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Chemical Engineering Division, American Society for Engineering Education

American Institute of Chemical Engineers

Nicholas A. Peppas

... of the University of Texas at Austin

SPECIAL ISSUE:

AIChE CENTENNIAL CELEBRATION

Also . . .

and ChE at . . .

The University of Illinois at Urbana-Champaign

Author Guidelines for the LABORATORY Feature

The laboratory experience in chemical engineering education has long been an integral part of our curricula. CEE encourages the submission of manuscripts describing innovations in the laboratory ranging from large-scale unit operations experiments to demonstrations appropriate for the classroom. The following guidelines are offered to assist authors in the preparation of manuscripts that are informative to our readership. These are only suggestions, based on the comments of previous reviewers; authors should use their own judgment in presenting their experiences. A set of general guidelines and advice to the author can be found at our Web site: <http://che.ufl.edu/~cee/>.

c Manuscripts should describe the results of original and laboratory-tested ideas. The ideas should be broadly applicable and described in sufficient detail to allow and motivate others to adapt the ideas to their own curricula. It is noted that the readership of CEE is largely faculty and instructors. Manuscripts must contain an abstract and often include an Introduction, Laboratory Description, Data Analysis, Summary of Experiences, Conclusions, and References.

- An Introduction should establish the context of the laboratory experience (e.g., relation to curriculum, review of literature), state the learning objectives, and describe the rationale and approach.
- The Laboratory Description section should describe the experiment in sufficient detail to allow the reader to judge the scope of effort required to implement a similar experiment on his or her campus. Schematic diagrams or photos, cost information, and references to previous publications and Web sites, etc., are usually of benefit. Issues related to safety should be addressed as well as any special operating procedures.
- If appropriate, a Data Analysis section should be included that concisely describes the method of data analysis. Recognizing that the audience is primarily faculty, the description of the underlying theory should be referenced or brief. The purpose of this section is to communicate to the reader specific student-learning opportunities (e.g., treatment of reaction-rate data in a temperature range that includes two mechanisms).
- The purpose of the Summary of Experiences section is to convey the results of laboratory or classroom testing. The section can enumerate, for example, best practices, pitfalls, student survey results, or anecdotal material.
- A concise statement of the Conclusions (as opposed to a summary) of your experiences should be the last section of the paper prior to listing References.

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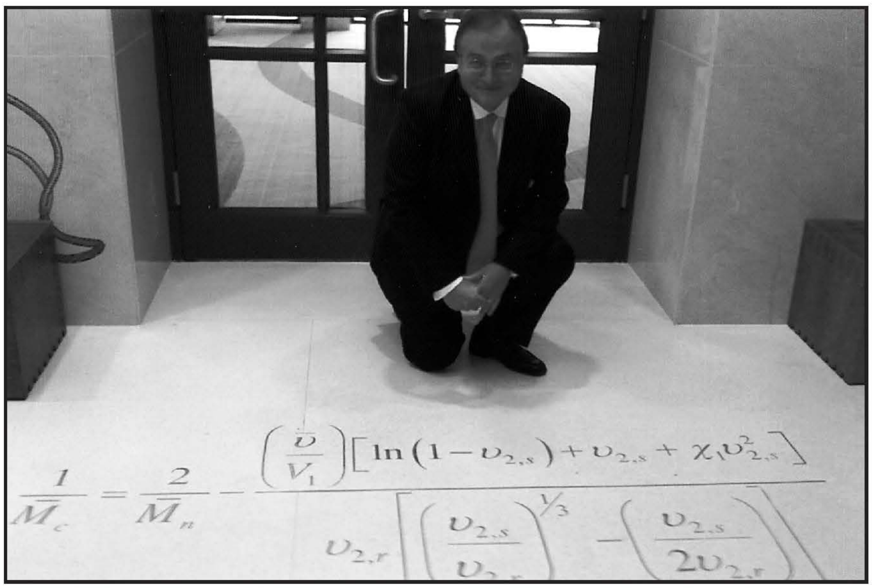
Nicholas A. Peppas

of the University of Texas at Austin

JENNIFER SINCLAIR CURTIS
AND CHRISTOPHER N. BOWMAN



Nicholas poses above the Peppas-Merrill equation for the analysis of gels, which is engraved in an entry of the atrium of the new BME Building at the University of Texas.

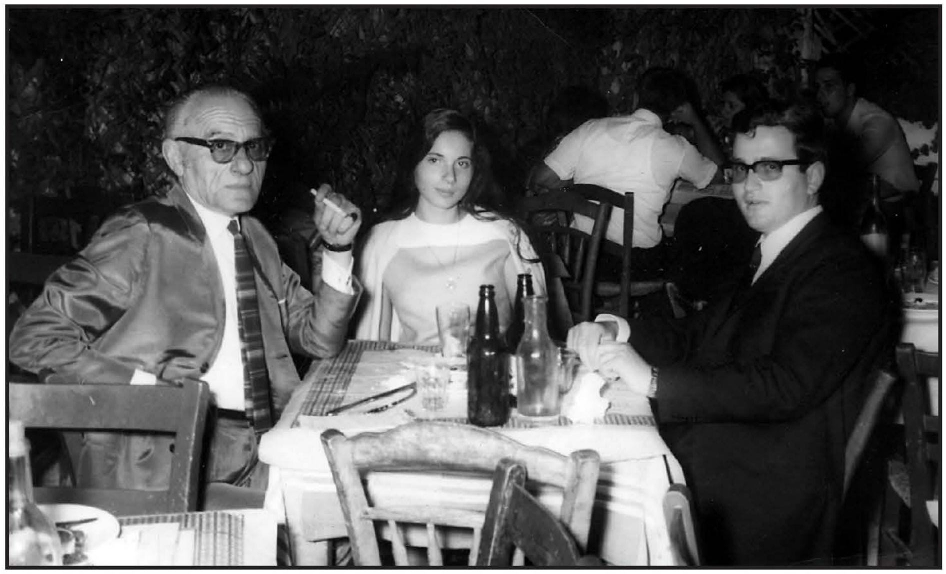
It is quite rare to encounter a person with a commitment to excellence that spans the personal and the professional, education and research, science and engineering, fundamentals and applications, chemical engineering and the broader academic fields, and language and culture. Nicholas A. Peppas is just such an individual, having made exceptional contributions with breadth and depth that span the chemical engineering field. Were one to write an article that described each award and recognition that he has received in even the briefest manner, it would readily fill this issue of *Chemical Engineering Education*. While if one allowed each of the undergraduate and graduate students whose lives he has touched to write briefly about Nicholas's influence on their careers, it would span numerous issues. By committing himself to quality and strongly supporting those who come into his sphere of influence, Nicholas Peppas shines in every aspect of his life.

THE EARLY YEARS

Nicholas A. Peppas was born on Aug. 25, 1948, in Athens, Greece. He was the eldest of two children born to Athanasios and Aliki Peppas. His parents were educated in economics and classics and taught him at an early age to appreciate classical education as well as learning and discovery. They stressed balance in life and also modeled perseverance, hard work, and dedication to life goals that remain hallmarks of his personal traits to this day.

Early on, Nicholas was fascinated with medicine and the inventions of the pioneers in engineering, while simultaneously developing a passionate interest in opera. While in high school he studied Byzantine music in the Hellenic Conservatory of Music, and he also began his studies of Greek and Byzantine history. His interest in history was initiated through the influence of several family members who were archaeologists or historians, including his father.

Knowing that he did not want to practice medicine, Nicholas decided to pursue engineering and he received his Dipl. Eng. degree in chemical engineering at the National Technical University of Athens in 1971. Although he worked in industry for all three summers during his undergraduate days (including a stint with Shell in Rotterdam, the Netherlands), he chose an academic career. His family has a rich history of academicians with professors of chemistry, history, and plant physiology, as well as archaeology—going back to Göttingen, Heidelberg,



Left, in the summer of 1954, 6-year-old Nicholas rides his favorite American bicycle—sent from New York by his aunt. Right, in 1959, standing amid confetti from Carnival in Athens. Above, with his father, Nassos, and sister, Louiza, in the summer of 1970, Athens.

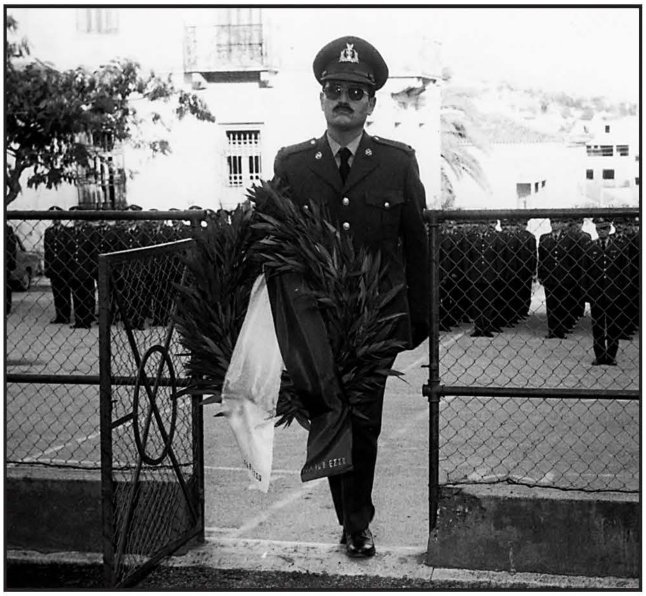
and Königsberg—so this was a very natural path for him. Before he left Greece in 1971, he knew he wanted to do something novel and unusual in his career, and to practice it as a pioneer in the field. He emigrated to the United States at the age of 22 and continued on for graduate work in chemical engineering at the Massachusetts Institute of Technology. He chose to work in the research group of Edward W. Merrill, a great role model, AIChE Founders' Award recipient, and pioneer in the field of bioengineering—a field that combined Nicholas's love of both engineering and medicine, as well as his strong desire for the novel and unusual. For his research, Nicholas worked on developing a series of nonthrombogenic biomaterials that could be used for artificial organs.

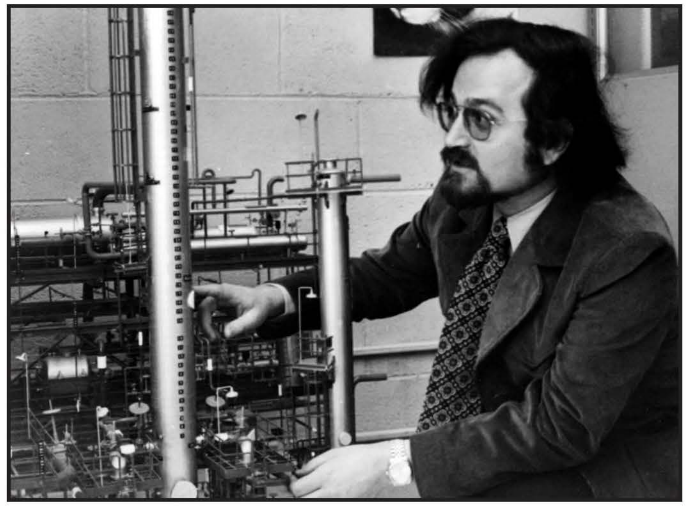
Nicholas continued with his balanced interests during his graduate school days and pursued a minor in comparative linguistics with studies of French, German, Italian, Spanish, Dutch, and Russian. Nicholas spent a little over two years in graduate school, receiving his Sc.D. degree in chemical engineering in October 1973. The highly remarkable speed with which he completed his Ph.D. was just one of the early indications of the amazing productivity and impact that characterizes his entire career. While at MIT, he became best friends with classmates Mike Sefton (a fellow Ph.D. student in Merrill's group, now a professor at the University of Toronto) and Bob Langer (a Ph.D. student in Professor Clark Colton's labs and now a professor at MIT). Along with sharing lofty research interests, in their down time all three cultivated a keenness for two simpler things: ping pong and ice cream. The odd combination added up to many good times, and his deep friendship with these two individuals endures to this day.

After finishing at MIT, Nicholas did two years of military service as a second lieutenant in the Greek Army. At this point, Nicholas was completely sure that he wanted to get more involved in biomedical engineering. So, he returned to MIT as a research associate in the Department of Chemical Engineering and the Arteriosclerosis Center, serving as a post-doc with Clark Colton (himself a former Ph.D. student of Ed Merrill) and Ken Smith. His research involved understanding the mechanisms of arteriosclerosis—how the transport of blood and the cholesterol and lipoprotein components in the blood contribute to plaque formation.

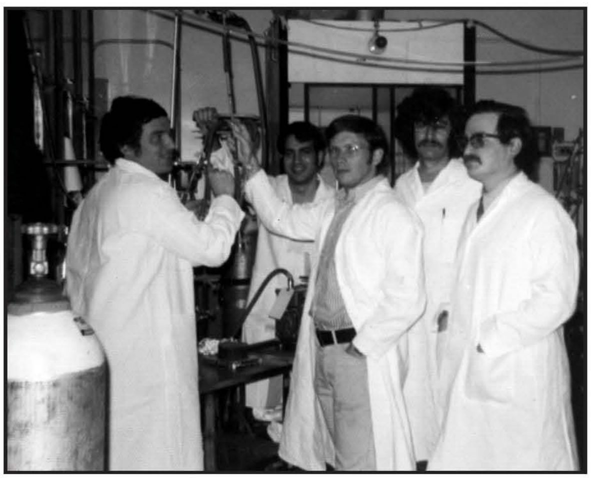
PURDUE UNIVERSITY: 1976 - 2002

Following his post-doctoral appointment at MIT, Nicholas was committed to a career as a faculty member in chemical engineering, seeking the opportunity to perform research while simultaneously educating students in the classroom and in the laboratory. From his first day at Purdue through today, Nicholas has been committed to education, research, and the general improvement of his profession.





Above left, Nicholas as a second lieutenant in the Greek Army in 1974. He served two years following completion of his Ph.D. Below left, lab mates in Ed Merrill's lab at MIT in 1972 (from left to right, Steve Rose, Hussein Banijamali, Tim Burke, Mike Sefton, and Nicholas). Above, as a young assistant professor at Purdue, 1976.



Nicholas was hired at Purdue as an assistant professor in 1976 and rapidly promoted to associate professor after just two years. His research program began by looking at two themes that continue through his research today. Todd Gehr (now head of nephrology at Virginia Commonwealth) and William Bussing (until recently a VP of BP in Singapore) completed their master's theses under Nicholas's supervision in 1978, with both doing polymerization reaction engineering—including in Bussing's thesis an examination of the importance of crosslinking reactions, while Gehr's thesis examined copolymerization reactions appropriate for hydrogel production and subsequently developed techniques for heparinizing these hydrogels to improve biocompatibility. Simultaneously, Nicholas was initiating programs on diffusion and mass transfer in polymers and membranes, including his first Ph.D. student, Ming-Shih Yen, who was jointly supervised by Prof. Schoenhals in mechanical engineering.

By 1982, Nicholas had been promoted to full professor and his first batches of chemical engineering Ph.D. students began to graduate. The cohort of Lucy Lucht, Richard Korsmeyer, and Donald Miller completed their doctoral theses in 1983 and 1984 in research themes that focused on applying the fundamentals of polymer science and transport phenomena to fields as broadly ranging as the macromolecular structure of coal, synthetic gels, solute release, and biocompatibility. These first doctoral students represented only the tip of the iceberg, as Nicholas has now supervised 83 completed doctoral theses. Further, along with Robert Gurny (a post-doc who started in 1977) these students and Nicholas were building the foundation of and initiating his work in the fields for which he has become best known: biomaterials, controlled drug delivery, and hydrogels. Throughout the late '70s and early '80s, Nicholas worked extensively on enhancing the fundamental understanding of transport phenomena in polymeric materials. In particular, Nicholas worked to develop and apply knowledge of how penetrants are transported through polymer networks where the size of the diffusing molecule relative to the mesh size of the network dictates transport. Further, in work begun by Richard Korsmeyer and Jennifer Sinclair (an undergraduate researcher at the time) and followed up on by many others through the years, Nicholas analyzed the transport of penetrants into glassy polymers. Here, the transport relationships are dramatically complicated by the strong concentration dependant diffusion coefficient, arising from the glass transition that occurs in the polymer.

In 1982, he went to the University of Geneva as a visiting professor and was also selected to be the editor of the journal *Biomaterials*—a position he kept for 20 years, transforming the publication into the premier journal of the field. His work during this period was highlighted by the completion of Raymond Davidson's doctoral thesis

Above, Nicholas poses with best buddy Bob Langer, left, and Bob's wife, Laura, at the first U.S.-Japan Drug Delivery Meeting, in Maui, Hawaii, in 1991. Above right, Nicholas and Lisa with Terry Papoutsakis in Basel, Switzerland, in August 1988—just days after Nicholas and Lisa's wedding, in which Terry served as best man.

in 1985 that provided a foundation from which to predict drug release from swollen polymeric systems and drug-delivery devices. The targeted application of this work was the burgeoning field of controlled drug delivery that Nicholas was leading along with his good friend (and fellow fan of ping pong and ice cream) Bob Langer at MIT.

In the early to mid 1980s, Nicholas recruited an exceptional group of students that comprised Andy Tsou, Tony Mikos, Ronald Harland, Steven Lustig, Lisa Brannon, John Klier, and Alec Scranton. Nicholas worked with these students to expand the breadth and depth of his impact by focusing on hydrogel materials and transport phenomena in glassy polymers. He examined the formation and network properties of the hydrogel through reaction engineering and structural modeling of the polymer network while extending his previous work to examine the effects of pH, hydrogen bonding, and various other intra- and intermolecular interactions that could be used to control drug release from or swelling in these hydrogel materials. From the early to mid 1980s Nicholas was developing smart, responsive hydrogels that were ultimately used to produce pH- and temperature-sensitive polymer networks for the delivery of streptokinase and other enzymes. At this same time, in 1984 Nicholas's parade of awards began in earnest as he was selected to receive the Materials Engineering and Sciences (now CMA Stine) Award from the American Institute of Chemical Engineers in recognition of his outstanding contributions to materials science. A few years later he also received the Food, Pharmaceuticals, and Bioengineering Award of AIChE.

In the 1986-87 academic year Nicholas took sabbaticals first at the University of Paris, then at the University of Parma, where he was a visiting professor. At Parma, Nicholas established one of his longest and most productive collaborations, with Professor Paolo Colombo—a collaboration that has produced more than 25 refereed journal articles and several jointly supervised students and student exchanges.

At around this same time of the late 1980s and early 1990s Nicholas's group underwent another major expansion with more than 20 graduate students and post-doctoral researchers in the laboratory at various times during this period. His group also led the field into several new areas by beginning research projects focused on bionanotechnology and molecular imprinting, while significantly expanding his focus on controlled drug delivery by targeting several specific diseases and clinical needs. His program was recognized repeatedly throughout this period with numerous awards, including the 1988 American Society for Engineering Education's Curtis McGraw Award for Outstanding Research that is awarded to the most outstanding researcher from any engineering discipline under the age of 40. Nicholas also was recognized for his excellence by several nonengineering organizations during this period—a testament to his focus on interdisciplinary work that has broad impact across traditional boundaries. The awards include the Controlled Release Society's Founders' Award (1991), the Society for Biomaterials Clemson Award for basic research (1994), the Research Achievement Award in Pharmaceutical Technology (1999), and the Dale Wurster Award from the American Association of Pharmaceutical Scientists (2002). Purdue recognized Nicholas by naming him the Showalter Distinguished Professor of Biomedical Engineering in 1993, and in 1999 and 2000 Nicholas received honorary doctorates from the Universities of Ghent, Athens, and Parma in recognition of his distinguished career-long achievements and his valued contributions to those institutions.

THE UNIVERSITY OF TEXAS AT AUSTIN: 2003—PRESENT

During the 2002-03 academic year, Nicholas sought a change in direction for a variety of personal and professional reasons and found the ideal fit at the University of Texas at Austin. There, in 2003, Nicholas became the Fletcher Stuckey Pratt Chair with appointments in the Departments of Chemical Engineering and Biomedical Engineering as well as the College of Pharmacy. His move was bittersweet, with fond memories and strong collaborations at Purdue but with exciting opportunities availed by his new location and colleagues.

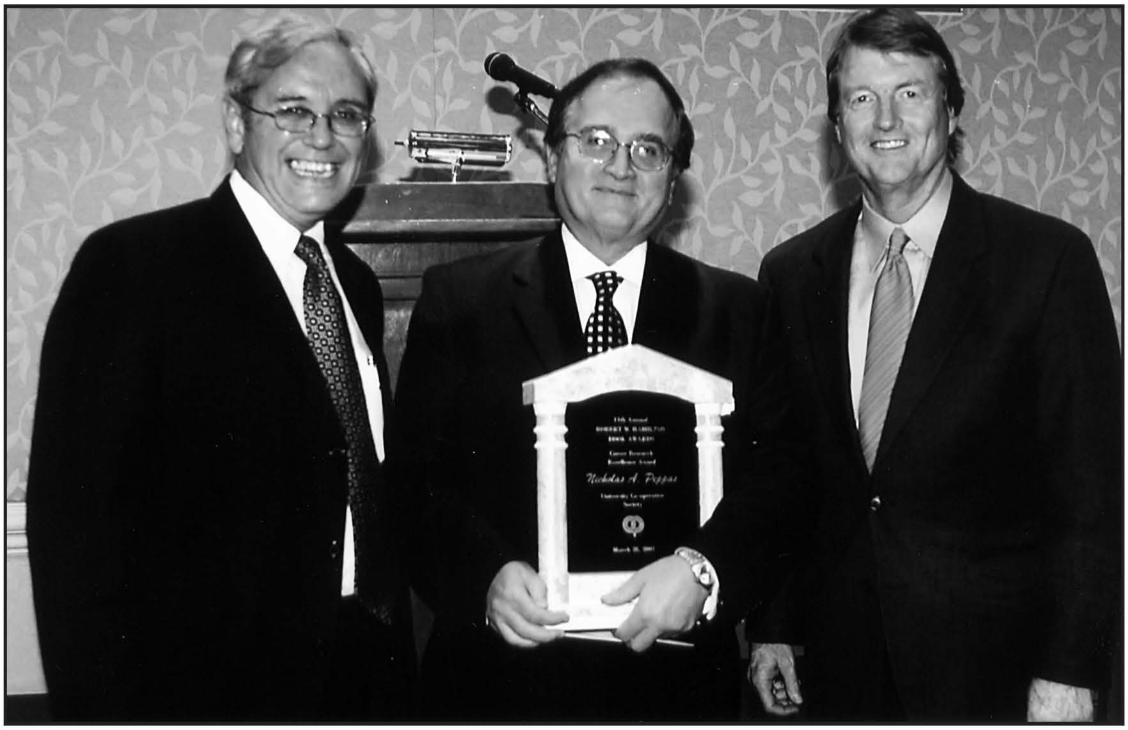
At Texas he made the transition as smoothly and as rapidly as possible, transferring many students and picking up new ones such that he has already had more than 10 students complete their doctoral theses at Texas in just six years there. Nicholas's research programs have also taken on new and expanded directions since his move, although he has continued to focus on biomaterials. In particular, his work on molecular imprinting and selective molecular capture and release from synthetic hydrogels has led to great successes in intelligent polymer therapeutics. A recent focus of his group is the combination of hydrogel technology with micro- and nanotechnology for single cell delivery devices, for biomimetic systems, and for nanovalves and other micro- and nanostructures.

Since his move to Texas, the national and international recognition of Nicholas's research accomplishments has been astounding. He has been elected to the National Academy of Engineering (2006), the Institute of Medicine of the National Academies (2008), and the French Academy of Pharmacy (2005), in addition to receiving the AIChE William Walker Award (2006) and the Jay Bailey Award (2006), and being named the Institute Lecturer by AIChE (2007) and receiving its Founders' Award (2008). Last year he was also selected one of the 100 Chemical Engineers of the Modern Era by AIChE and became an associate editor of the *AIChE Journal*. Nicholas also received the 2008 Pierre Galletti Award from the American Institute of Medical and Biological Engineers. This is the highest award given by this organization, recognizing exceptional career achievements in the medical and engineering arenas.

Over the course of his career, Nicholas has established himself as one of the preeminent polymer scientists and biomedical engineers of our time, particularly in the area of creating new fundamental knowledge in regard to polymer science and engineering and subsequently translating those results into practical knowledge and viable commercial systems. As noted, Nicholas's ability to apply polymer science to a wide variety of bioengineering fields has been recognized by numerous international, interdisciplinary organizations. In fact, the interdisciplinary nature of Nicholas's work is highlighted by his selection as a fellow of nine diverse organizations that span engineering, science, physics, materials, biomaterials, and pharmacy, while also being named a founder of three of these organizations (AIChE, the Society for Biomaterials, and the Controlled Release Society). He has regularly demonstrated a unique talent for achieving significant fundamental insights into polymer materials fabrication and modification, polymer thermodynamics, polymerization kinetics, and transport behavior—and then applying that knowledge to the development of improved materials, material performance, and biomedical devices. Nicholas's ability in this area is highlighted by the more than 1,000 manuscripts that he has published, the more than 18,000 citations of his work, his H-factor of 72, and his impact on practical devices and companies.

Nicholas, circulating amid the hundred guests at his surprise 50th birthday party in 1998, passes the table of friends and colleagues Balaji Narasimhan of Iowa State and Mike Sefton of the University of Toronto.

Nicholas's fundamental achievements have been translated into more than 20 commercial medical products, each in collaboration with his students and frequently with others as well. For example, he has developed, patented, and/or commercialized materials for vocal cords, intraocular lenses for cataract patients, nanodelivery systems for oral administration of insulin to type I diabetic patients, systems for oral delivery of calcitonin for treatment of postmenopausal women suffering from osteoporosis, and devices for oral delivery of interferon-beta for multiple sclerotic patients. His work with Professors Colombo and Conte in collaboration with several companies has resulted in hydrogel controlled-release devices, and his more recent work at UT has led to the Affinimer™, TheraSmart™, TabletSmart™, BeautySmart™, AppiForm™,



Nicholas, center, receiving the 2008 Career Research Excellence Award—the highest UT recognition for a professor. Flanking him are University of Texas Vice President for Research Juan Sanchez, left, and University of Texas President William Powers, right.

and other technologies for smart, programmed, and responsive/recognitive delivery of drugs, proteins, and cosmetic and consumer products.

Nicholas's research record obviously places him at the absolute top of his peers in this generation of polymer and biomaterials researchers—yet that is only one of his many contributions to our field. Nicholas has trained more than 95 past or current Ph.D. students and hundreds of undergraduate researchers. These students have gone on to have an ever-expanding impact on the chemical engineering, polymer science, pharmaceutical engineering, and biomaterials fields, with more than 30 having entered academia and numerous others having become corporate leaders. In just the last eight years, Nicholas's former students have received five different AIChE Institute-level awards, and the 2008 and 2009 ASEE Chemical Engineering Lectureships have both been awarded to former undergraduate or graduate students of his. In conversations with Nicholas, it is clear that his greatest pride lies in his students—those he has advised in the lab as well as those he has taught in class.

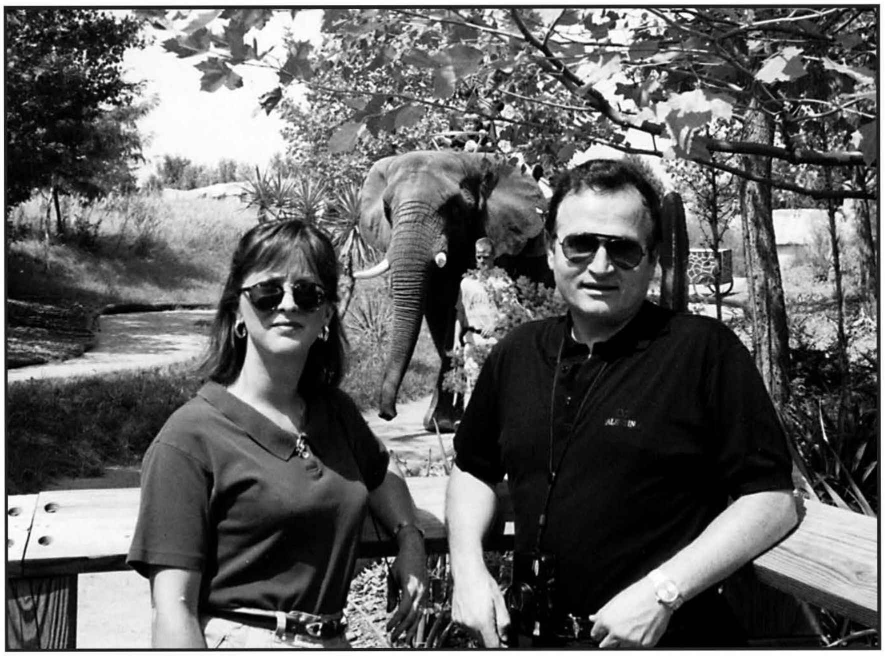
COMMITMENT TO EDUCATION

At work, first and foremost, Nicholas is committed to students and their education. In a recent interview for the January 2009 issue of the *Controlled Release Society Newsletter* (to go along with his 2008 election to the Institute of Medicine of the National Academies of Science), Nicholas was asked what he regarded as his most significant achievement of his career. His response was "my contribution to the education of the younger generations of chemical engineers, biomedical engineers, pharmaceutical scientists, and especially industrial and academic leaders in drug delivery, controlled release, biomaterials, and nanobiotechnology." Anyone who has participated in his research group or has ever been a student in one of his classes can verify how his actions line up with his answer to the interviewer's question.

In the classroom, he is a very animated teacher and his lectures incorporate the latest research advances. Students in his classes learn first-hand how fundamental knowledge of engineering concepts can translate to products or devices that help people and society. Because he conveys such excitement for learning and discovery, students are highly engaged in his classes and are eager for knowledge. As a result of his excellence in classroom instruction, Nicholas has received numerous teaching awards including the engineering-wide teaching award at Purdue (the Potter Award) three times, and the chemical engineering department teaching award at Purdue (the Shreve Award) five times. In 2007 he was voted the "Best Faculty Member in Chemical Engineering" by the students at UT-Austin.

In addition to authoring more than 20 educational papers, Nicholas has combined his love of history and chemical and biomedical engineering by writing several historical books and articles on the chemical and biomedical engineering profession. One of his first history books along this line was a book about how chemical engineering developed at Purdue and what Purdue's contributions were to the chemical engineering field. This book was published in 1986 on the occasion of the 75th anniversary of the department. After that, Nicholas started to write books and articles on how the fields of chemical engineering and biomedical engineering developed, including his 1988 Kluwer book, *History of Chemical Engineering*. Just last year, he completed another article, "The First Century of Chemical Engineering," for the Chemical Heritage Foundation and the AIChE Centennial celebration.

Not only is Nicholas an excellent teacher, but as a mentor and advisor he is unsurpassed. Undergraduates flock to his research group; they want to be a part of the excitement. He takes in students who know nothing about research or academia, but are interested in learning. Not only does he actively mentor them in technical matters, he cares about their families, their personal lives, and their aspirations. Due to his holistic approach to advising, and perhaps in part because of the nature of his research field, Nicholas's group is always filled with female students. It has been that way even since the early days of his independent research program in the late 1970s, when it was very rare to find any females at all in chemical engineering research. With his continuous, lifelong support and mentoring, many of Nicholas's female students have gone on to the very top positions in industry and academia. He has always been one to lead the way in breaking the glass ceiling!



Lisa and Nicholas at the Indianapolis Zoo in 1996. Both are avid supporters of various zoo projects and efforts to protect endangered species.

To date, more than 500 undergraduate students have participated in research projects supervised either directly by Nicholas or by one of his graduate students. This number is staggering and shows his unwavering commitment to enhancing the quality of undergraduate education through the involvement of chemical and biomedical engineering undergraduates in research. The undergraduates who work in his research group get a taste of all of the same experiences as his graduate students—undergraduate students are co-authors on his journal and conference publications, present at national scientific meetings, and even participate in proposal preparation. Five of Nicholas's patents even have undergraduates as co-inventors! When undergraduates are brought into Nicholas's group, they are treated as full members of the research team and are expected to perform as such. They are given a defined project and a high level of responsibility. Because of this approach, students typically rise to the challenge and learn to become productive and effective researchers. Nearly two-thirds of all students participating in Nicholas's group have gone on to further their educations with an advanced degree.

For his successes in mentoring and advising, he has received the Myron Scott Best Counselor Award at Purdue and the national AIChE Counselor Award associated with his service as the faculty advisor for the Purdue AIChE Student Chapter for 15 years. The American Society for Engineering Education has also recognized him with all its major awards including the 1992 George Westinghouse Award for teaching, the 2000 General Electric Senior Research Award, and the 2006 Dow Chemical Engineering Award for both educational and research accomplishments, as well as election as an ASEE fellow in 2008.

Nicholas's mentoring and connectedness with his students do not end when a student graduates or leaves his group. He proactively keeps up with his former students' careers and personal lives via periodic "what's up?" / "how are you doing?" e-mails and phone calls. He will always do whatever he can to help a former student at any time in their career if they call on him for assistance. Nicholas also keeps his former students —affectionately known as "peppamers"—connected with each other. He sends out regular e-mail blasts to his students letting the others know about any successes or recognition any one of them has achieved.

Because Nicholas gives so much of himself to his students, he is very much loved and honored in return. For his 50th birthday in 1998, about 100 friends and former students gathered in Indianapolis for a surprise party. Recently, for his 60th birthday, a research symposium and party in his honor was held at the University of Texas at Austin and was attended by more than 200 people, many from his MIT and Purdue days.

NICHOLAS AND LISA—THE DYNAMIC DUO

Nicholas met his wife Lisa when she (then Lisa Brannon, now Lisa Brannon-Peppas) was enrolled in the Ph.D. program

Pride and joy: Nicholas with his children, Alexi and Katia.

in chemical engineering at Purdue. They were married in 1988 after she completed her degree. Nicholas will readily tell you that not only does he love Lisa deeply, but that he is also madly "in love" with her even after all their years of marriage. Nicholas and Lisa make quite a team as two ambitious and highly successful chemical engineering professionals. As Nicholas told *AIChE Extra* in a Chemical Engineering Progress article (February 2000), "I am very, very lucky to have met Lisa in that respect. When I go home, I am grateful to have someone I can share my work with." They both agree that science is certainly one of the big topics that comes up at the dinner table.

After finishing her Ph.D., Lisa worked at Eli Lilly for three years. She then founded her own company, Biogel Technology, Inc., in 1991, where she served as president for 11 years. During that time, she made significant research contributions in the areas of biomaterials, controlled drug delivery, drug targeting, biodegradable materials, and the structure-property relationship of polymers. One of her key accomplishments was developing targeted delivery systems to treat breast cancer using biodegradable nanoparticles. In 2003, Lisa also joined the University of Texas at Austin faculty, as a research professor and as director of the Center of Biological and Medical Engineering. While there, she received a biomedical engineering department teaching award as well as several research awards for her work in biomaterials. In 2008, Lisa decided to leave academia and is currently vice president of Appian Laboratories, LLC, in Austin.

Lisa is a fellow of the American Institute of Medical and Biological Engineering (in fact, she was the youngest fellow ever elected

Nicholas and Andreas Acrivos (of CUNY), two of the prestigious list of "100 Chemical Engineers of the Modern Era," honored at the AIChE meeting in 2008.

to the Institute at the time of her election) and a fellow in biomaterials science and engineering of the Society of Biomaterials. Most recently, she received the very prestigious national 2008 AIChE Award in Chemical Engineering Practice for outstanding contributions in the industrial practice of the profession—right alongside Nicholas, who received the 2008 AIChE Founders' Award for outstanding contributions to the field of chemical engineering. Nicholas and Lisa have both served as directors of AIChE as well as chairs of the Materials Engineering and Sciences Division of AIChE. They truly are a dynamic duo!

Besides Lisa, the deepest joys in Nicholas's life are his children Katia (Katherine), an 8-year-old, and Alexi

A lifelong lover of opera, Nicholas poses outside the entrance to an opera concert in Busseto, Italy, prior to attending the event on the exact day of famed composer Giuseppe Verdi's centennial.

(Alexander), who is 5. Nicholas is very clear—no matter what the demands on his time, his family always comes first. So that Nicholas can spend more time with his family, he has become very judicious in his choice of opportunities to travel.

Nicholas and Lisa have an active social life with many interests. They are avid supporters of various zoo projects including the protection of endangered species. Before kids, their travel schedule was extensive—many wonderful sites and much fine cuisine. An itinerary incorporating trips to places like Paris, Las Vegas, and Japan back-to-back was not uncommon. Now, family travel typically involves trips to the beach with lots of sun, sand, and swimming. They also take a family vacation to Maui, Hawaii, every other year along with their participation in the U.S.-Japan Symposium on Drug Delivery Systems.

AWAY FROM WORK

Nicholas is a true renaissance man. His interests are unbelievably broad with music and history dominating the scene. For music, opera is his love and helps him relax. As Lisa says, "He'll drop any chemical engineering project for opera." Nicholas has spent more than 40 years writing about Italian, French, and romantic German opera. He has published hundreds of critiques, essays, and articles on opera and classic music performances on various Web sites and in magazines including *Fanfare*, *High Fidelity*, *Stereo Review*, *International Opera Record Collector*, and *The Record Collector*. He has even published two books (*Vasso Argyris: The Great Greek Tenor of the Interwar Years* and *Greek Light Music of the 1935-1975 Period*).

For history, his main interest is the Byzantine Empire based in Constantinople, especially the period of 976 to 1025, which is in the middle of a series of emperors known as the Macedonian Dynasty. He has published 26 articles on the Byzantine Empire, the history of Attica, and related subjects. Another historical topic of key interest for Nicholas is ocean liners and 19th- and 20th-century immigration to the United States. He has written some 300 short articles on these topics in various sites.

Nicholas has also contributed articles to various literary journals and newspapers. For example, he was a major contributor to the 1968 and 1978 *Tourist Guides of Greece* (Institute of Tourist Publications, Athens, Greece). He has also contributed articles in the magazines *Eleusinian* and *Hellenic Chronicle*, and the Greek newspapers *Daily* and *The Tribune*.

Nicholas speaks Greek, French, German, Italian, and Spanish, can read/write in Russian, Portuguese, and Dutch, and can read several other languages. He has even taken classes in Hebrew and Japanese (especially because of his sabbatical leaves to Hebrew University and Hoshi University) although he admits these are extremely difficult languages for him. Aiding Nicholas in his mastery of all of these languages is his encyclopedic memory. Lisa says that the only thing he ever forgets are the items he hints at during the year that he might like for Christmas presents. Therefore, when he receives his presents at Christmas, they are a surprise to him! Lisa also says that Katia appears to have inherited Nicholas's encyclopedic memory, but does not forget about her Christmas present hints! Nicholas's organizational skills are also incredible—these skills go hand-in-hand with his amazing productivity and memory. He believes there is a place for everything and everything in its place. He can lay his hands on any piece of paper or any electronic file within seconds.

Nicholas is a collector of opera and classical music CDs. Lisa says that if there were space, he would have a CD of every opera ever published. Other extensive collections include operatic 78-rpm records—including many rare records from the period of 1898 to 1912—history books in every possible language, nutcrackers, and old maps.

Also among his collections is an assortment of silver serving pieces. Nicholas actually likes cleaning them. While others might dread the tedious task, carefully polishing each piece pleases him, he says, because he very much appreciates seeing the results of his labor—fine silver with a beautiful shine. For an educator, mentor, and researcher for whom the success of his students is the brightest reflection of a brilliant career, it's a fitting image. ❒

Chemical Engineering at . . . the University of Illinois at Urbana-Champaign

Edmund G. Seebauer, Paul J.A. Kenis, and Marina Miletic

The Roger Adams Laboratory North Entrance, at the University of Illinois at Urbana-Champaign, the primary home of ChBE.

Chemical engineering education at Illinois is unique. That uniqueness springs in part from the nature of the state of Illinois and its university system, and from the unusual administrative structure of our department.

The University of Illinois at Urbana-Champaign is the Morrill-Act land-grant institution of the state. In fact, the land-grant idea was conceived by Jonathan Baldwin Turner of Illinois College and driven mainly by the Illinois Congressional delegation. The state of Illinois at that time hosted an exceptionally diverse economy including manufacturing, transportation, agriculture, and services. New universities were needed especially "to promote the liberal and practical education of the industrial classes in the several pursuits and professions in life."[1] The economy of the state continues to be very diverse today, and it supports 11 million residents—yet only two public chemical engineering departments reside within the state. These factors lead to an extraordinarily large, talented, and socioeconomically diverse undergraduate student pool.

Our department is administratively unique by maintaining strong structural connections with two colleges: Engineering and Liberal Arts and Sciences. Indeed, Chemical & Biomolecular Engineering (ChBE) is formally housed within the School of Chemical Sciences (together with the Department of Chemistry) in the College of Liberal Arts and Sciences. Yet the department participates in virtually all College of Engineering affairs except budget, and throughout most of the 1990s, the dean of the College of Engineering was from the Department of Chemical Engineering. Sitting astride these two colleges promotes an outlook among the faculty and students that emphasizes both technical strength and the appreciation of the social context, history, intellectual flexibility, and lifelong learning that represent core values of the liberal arts.

EDUCATION: INNOVATIVE AND EFFICIENT

Our department operates within a public research university, one of many such institutions that face long-standing challenges of balancing strong teaching and research within a changing framework of state and corporate support. Within that context, ChBE frames its mission as follows:

> *To improve the human condition through the study and practice of chemical engineering by education, research, economic development, and engagement with and service to the profession and society.*

We strive to educate leaders who are rooted deeply in the technical foundations of chemical engineering science, yet have cultivated the intellectual scope, flexibility, and determination to apply knowledge in novel ways throughout life. That we have succeeded is demonstrated by our family of living alumni, which boasts three individuals who have served as chief executives of Fortune 500 companies, four executive vice presidents, and one university president.

Undergraduate Education: Holistic

Central to the ethos of a public research university is enhanced access to education at modest cost: Such institutions are geared to educating large numbers of students. Yet for decades, our department has chosen to keep the number of faculty relatively low. The number of tenured/tenure-track faculty oscillated between about six and nine in the 1970s, and has grown to its record size of 15.5 only in the past year (one is shared with another department). Even that number remains small compared with the undergraduate student enrollment of 425, leading to a student/faculty ratio in the high twenties. The small faculty size encourages a degree of coordination and integration that becomes more difficult for large departments, but it also requires special attentiveness and creativity by the faculty to foster a high-quality learning environment. Efficiency is paramount, with only the design and unit operations courses taught more than once per year. Many elective courses are taught in simultaneous graduate and undergraduate versions that have one set of lectures but homework and examinations attuned to the different degree levels.

The environment is intellectually diverse, stimulating, and demanding, and requires students to take considerable responsibility for their own education and to be personally invested in their future success. Graduates of the curriculum cultivate a disposition and skillset that make them exceptionally successful in either graduate school or entry-level corporate jobs, and also throughout their careers. Figure 1 shows placement statistics by job function averaged over the past decade.

ChBE's close administrative alignment with the chemistry department promotes a strong emphasis on basic science in education. Indeed, Figure 2 shows that the undergraduate curriculum includes 23% chemistry in the total course content, which is significantly higher than most chemical engineering programs. Students take two required courses in analytical as well as physical chemistry in addition to organic and general chemistry. This emphasis on chemistry provides not only a strong conceptual base in diagnostic methods, analysis, and quantum mechanics but also lots of hands-on experience through laboratory courses.

Consistent with the strong science base in the department and the research mission of the overall university, many undergraduate students are actively involved in research. Over time, 50-75% of undergraduates have worked on at least one individual research project. Typically, 60-70% of these projects involve ChBE faculty.

ChBE's administrative alignment within the College of Liberal Arts and Sciences and geographical location near central campus (separate from most other engineering departments at the north end of the campus) fosters an environment wherein our students routinely rub shoulders with many nonengineers.

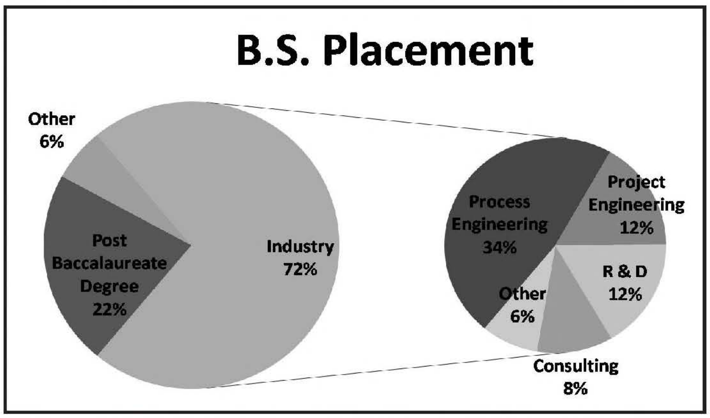


***Figure 1.** Placement statistics for Illinois ChBE graduates by job function averaged over the past decade.*

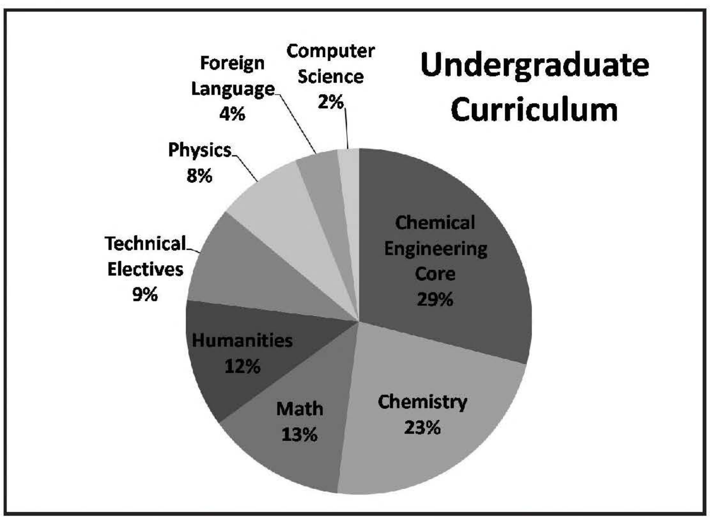


***Figure 2.** Distribution of subject material in the Illinois undergraduate curriculum. Chemistry, mathematics, and other sciences are represented particularly strongly.*

The relationships thus formed also stimulate increased intellectual breadth and scope among the ChBE undergraduates.

The curriculum is unusually holistic in the sense that it proves a great deal of chemistry, mathematics, and physics as a foundation for hands-on, practical, and real-world rigorous capstone courses. The curriculum strongly emphasizes the development of technical problem-solving skills in the senior year. Students learn open-ended process and product design and control with cost optimization, technical communication, theory, statistical analysis, equipment troubleshooting, plant safety, engineering disaster prevention, equipment design, the Kepner Tregoe problem-solving process, and case study analysis.

A strong foundation is laid in chemical engineering for all students starting with the first year. Engineering is introduced early in the freshman year through Engineering 100: Introduction to Engineering and ChBE 121: The Chemical Engineering Profession. Students complete a chemical engineering group project, and are encouraged to join such professional organizations as the student chapter of AIChE, Omega Chi Epsilon, and the Society of Women Engineers. This strong foundation helps students successfully adapt to the curriculum and stay in the program.

Rigorous experimentation and data analysis comprise the unit operations course in which statistics and model creation meets troubleshooting, process scale up, and economics. Students study everything from the internals of pumps and compressors to experiment design and creative problem solving. Each project builds on the previous one and requires critical analysis of the prior group's results. The laboratory course has evolved to include new experiments such as polymer extrusion, liquid-liquid extraction, ideal reactor optimization, and bioreactors and fermentation. The course revolves around characterizing systems, creating models, performing statistical and profitability analysis, and troubleshooting equipment.

The capstone design course is one of the most rigorous and demanding in the curriculum, with a strong emphasis of chemical engineering fundamentals integrated with process simulation, hazard and operability studies, economics, sustainability, and optimization. Through group and individual reports students create a process that produces a commodity chemical safely and efficiently with little wasted energy or physical resources. Each design becomes more detailed than the previous, including more safety and economic optimization.

Overall, students in the senior year write eight individual and group reports and give about five hours of group presentations. Students work in a variety of groups with and without team leaders to implement shared project ownership, efficient decision making, delegation, constructive peer feedback, and self-reflection. All students complete a multi-stage qualitative and quantitative peer- and self-performance review. Presentations are reviewed live by peers. Students critique their own presentations and create performance goals for subsequent projects.

In response to student requests, we introduced in 2002 a formal Biomolecular Engineering concentration to the chemical

Lecturer Marina Miletic (standing) teaches undergraduates in the unit ops lab.

engineering bachelor degree. The concentration allows students to enhance their understanding of bioprocessing, food processing, systems biology, and biomolecular engineering through their choice of technical electives.

Our graduates continue to find excellent places to embark on their professional careers, although placement distribution continuously evolves with societal needs. After many years of a steady increase in the fraction of graduates joining food, personal care, and consumer products industries, the oil/energy companies are now re-emerging as a major destination.

Graduate Education and Research

Our department recognizes that well-educated graduate students constitute a "product" of the research endeavor as much as discoveries and technical results. That is, the quality of research is determined as much by the quality of the mentoring relationships between students and faculty as by the factual content generated by those relationships. Accordingly, graduate education at Illinois emphasizes continually developing and exercising an integrative thought process.

Graduate students in discussion with Professor Huimin Zhao (second from left). The group's focus is on ways to engineer proteins enabling the production of biofuels.

The U.S. education system has long internalized the basic notion that linking doctoral education with research strengthens both.[2] This idea traces back to the 19th-century German principle of *Bildung durch Wissenschaft* (education through science) advanced by Wilhelm von Humboldt. Yet elevating the importance of the mentoring relationship represents a key development. In the original formulation of the German philosophy Idealism, the purpose of education was to find "absolute truth as such,"[3] so that society could be rationally ordered on the principles thus discovered. The subject matter rather than the person received the most attention. Faculty teaching reflected the search for objective knowledge, while students were left to learn independently, with minimal direction.

At Illinois we feel that the focus on the student is especially important to properly justify research in a public university. As Harvey Brooks wrote over a quarter of a century ago,

> *"The public… is now more skeptical that the universities are the best locale for basic and generic applied research, especially when that research is being justified for its benefits to the market economy rather than for its benefits to public sector responsibilities such as health or environmental protection. The idea that the universities are the principal locale for virtually all forms of research in the public domain needs restatement and updating."*[4]

As public research universities currently seek to face the challenges they confront, we believe an important aspect of "restating and updating" the justification for research should include this focus on students.

Accordingly, our graduate curriculum is structured carefully. The doctoral degree requires a total of eight courses. All students take applied mathematics to build a solid foundation in the development of mathematical models and be exposed to modern mathematical methods currently used in the solution of chemical and biomolecular engineering problems.

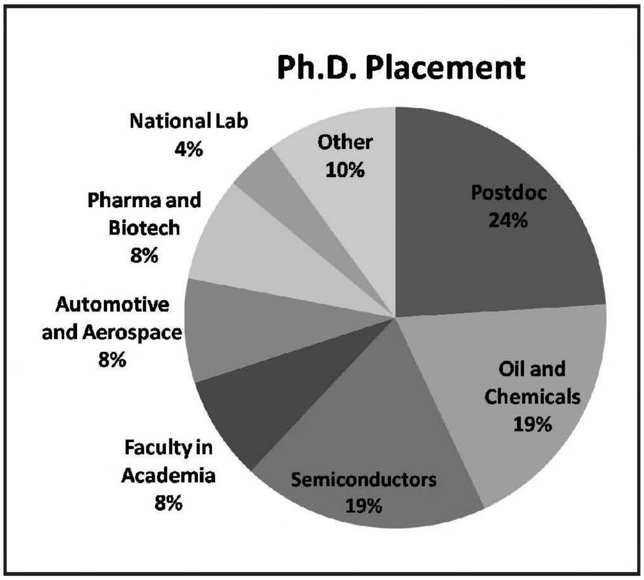


Figure 3. *Placement of Illinois Ph.D. students by sector.*

Furthermore, they are required to take one graduate-level transport phenomena course and at least one graduate-level course on kinetics, reaction engineering, or thermodynamics. The remaining five courses can be chosen based on the student's research needs and personal interests within science or engineering. As part of these technical electives, all students need to take at least one bio-related course and one graduate-level course outside our department in recognition of the interdisciplinary nature of today's research enterprise. The recent increase in the number of ChBE faculty overall, as well as the number of faculty with research interests in "bio" and/or "micro/nano," has led to new graduate electives in Techniques in Biomolecular Engineering, Systems Biology, Microelectronics Processing (lecture and lab), and Microchemical Systems.

Consistent with ChBE's alignment in the College of Liberal Arts and Sciences, many of our graduate students choose to broaden their horizons in nontechnical directions. Students take courses in such topics as economics, finance, statistics, leadership, and proposal writing. Some also obtain formal teaching and leadership certificates. The faculty actively seek to show by example how to broaden one's intellectual scope. For example, a textbook on ethics in science and engineering emerged from the department earlier this decade.[5]

To emphasize breadth and flexibility, the qualifying examination for doctoral study comprises two components: a written exam on coursework concepts and an oral presentation on proposed research. Both are normally completed within the first year of study. The written exam is offered in January, and students must correctly answer eight questions out of a selection of 16-22 total questions on undergraduate and graduate course work. At least four must be chosen from the "core" list, which comprises all traditional undergraduate chemical engineering topics. The remaining questions are drawn from all graduate electives offered in recent years.

The flexibility in required coursework as well as in selection of questions for the qualifying exam ensures also that graduate students that enter our program with a nonchemical engineering background [*e.g.*, bioengineering, (bio-)chemistry, mechanical engineering] have no trouble fulfilling these requirements, while still ensuring basic knowledge of chemical engineering principles. This has become particularly important over the last decade as the percentage of applicants with nonchemical engineering undergraduate degrees has grown steadily, to about 25% of the applicant pool.

The oral part of the qualifying exam entails a presentation of proposed research to a committee of faculty in April. The students need to (i) demonstrate a coherent understanding of their research area in general; (ii) describe and justify their particular project; and (iii) unfold a research plan for the next six to twelve months. We introduced this component in 2004 with the aim of helping graduate students think critically about their research project early, so they will have a much quicker start. Indeed, this exercise has induced students to take charge of their project and they seem to become independent more quickly.

The graduate program has grown recently to its present size of about 110 graduate students. In addition, 30 or so students from other graduate programs pursue their Ph.D.'s with ChBE faculty. More than 94% of the graduate students that enter our program successfully obtain a Ph.D. degree, with most of the few remaining students leaving with a M.S. degree. Upon graduation our Ph.D. graduates embark on a wide variety of careers, spanning academia, national labs, and various industries. Figure 3 shows the placement of these students by industry sector averaged over the past decade.

ChBE's research directions exemplify the diversity of the chemical engineering discipline today, encompassing fundamental and applied efforts in long-standing areas such as microelectronics and complex fluids as well as a wide range of emerging efforts in energy and biomolecular engineering. Demographically, the department is young, with slightly over half the faculty at the assistant or associate professor level in 2008. Thus, it is easy to cultivate an environment that fosters collaboration to address subjects of immediate societal interest. The department seeks to provide ample room for fundamental science investigations, while providing every opportunity for the outcomes of fundamental science to translate into inventions that lead to new tools for scientific study and ways to address society's most daunting challenges. Reflecting this commitment, the department has major research efforts in human health, energy/sustainability, and advanced computation for applications.

Many of our research efforts require an inter- or multidisciplinary approach for which the Illinois environment is exceptionally well-suited through the Beckman Institute for Advanced Science & Technology, the Institute for Genomic Biology (IGB), the National Center for Supercomputing Applications (NCSA), the Materials Research Laboratory (MRL), the Energy Biosciences Institute (EBI), and the Micro- and Nanotechnology Laboratory (MNTL). Not only do these research institutes provide an environment for faculty to come together and pursue collaborative multidisciplinary projects, they also house a suite of world-class instrumentation facilities.

This environment has fertilized extraordinary research quality and breadth within the department. As one indication, ChBE faculty have enjoyed nine elections to Fellow status within six different professional societies over the past half-dozen years or so. The primary areas of endeavor are as follows.

• ***Human Health***

Professors **Leckband, Kenis, Kraft, Masel, Zhao, Price**, and **Schroeder** are developing a range of experimental and computational approaches to unravel the genetic and molecular basis of many complex diseases such as cancer and AIDS or to develop new tools to detect such diseases, or even environmental threats. Many of our faculty are active in the development, manufacture, and delivery of pharmaceuticals. For example, professors **Braatz**, Kenis, and **Zukoski** are studying pharmaceutical crystallization for screening for appropriate solid forms of active pharmaceutical ingredients and for the selective manufacture of desired polymorphs at industrial scales. Braatz, **Pack**, and Zhao are pursuing novel approaches for the controlled-released delivery of drugs and gene delivery. In addition, Zhao and **Rao** are developing new approaches for treating infection caused by antibiotic-resistant bacteria. As part of the Regenerative Biology and Tissue Engineering research theme at IGB, several of our faculty, including **Kong, Harley**, Kenis, Pack, Rao, and Braatz are unraveling the fundamentals of tissue regeneration and developing clinical strategies for cardiovascular and bone repair.

• ***Energy and Sustainability***

Professors Kenis, Masel, and **Seebauer** are pursuing a wide range of studies to design better catalysts and electrodes for more efficient energy conversion, and they apply these in fuel cells for portable electronics or transportation applications. These efforts already have led to two startup companies that are pursuing the commercialization of these microfuel cell technologies. Looking ahead, they are taking on the intertwined challenges of climate change and energy security by converting carbon dioxide back into chemical intermediates presently derived from fossil fuels. Another active area of study in our department is alternative energy based on biofuels. As part of the EBI established by the oil company BP in collaboration with the University of California-Berkeley and Lawrence Berkeley Laboratory, professors Zhao, Rao, Schroeder, and Price are engineering micro-organisms for

Graduate students and Professor Paul Kenis (center) testing a microfluidic chip for membrane protein crystallization.

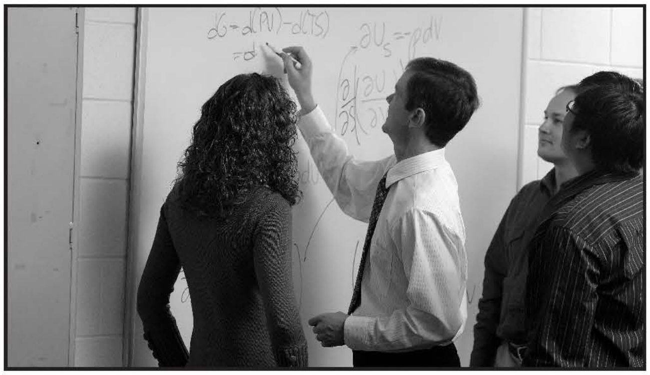
efficient production of novel biofuels such as ethanol, butanol, and alkanes from nonfood crops. Related protein engineering and metabolic engineering efforts are also being used for the green synthesis of fine chemicals via biocatalysis.

• ***Advanced Computation***

Professors Braatz, **Higdon**, Price, and Rao are creating theoretical and computational tools for the modeling, design, simulation, optimization, and control of complex chemical and biomolecular systems. Frequently, widely generalizable tools are used to address specific problems in the chemical, energy, microelectronics, biomedical, and pharmaceutical industries. Many of these efforts rely upon collaboration with scientists and engineers in academia and industry.

Global Programs

The original conception of the research university in the 19th century was tacitly local, meaning that the university and its branches were rarely geographically distant from each other. With the advent of easy telecommunication and air travel, however, the time has arrived for a globalized research university that permits the formation of new alliances to improve education and research. Accordingly, over the past decade ChBE has established an increasing number of department-level connections with universities around the globe. Such connections have progressed furthest at the doctoral level with the National University of Singapore, with which



Professor Ed Seebauer reviews semiconductor defects for microelectronics applications with three of his graduate students.

ChBE established in 2009 a multi-institutional doctoral degree with the counterpart department there. Students are jointly advised by faculty at both institutions, split their time evenly between the locations, take courses almost interchangeably between the two universities, and ultimately receive a single degree bearing two seals.

PUBLIC ENGAGEMENT

The nature of engineering is often poorly understood by the general public. Technological literacy yields citizens who can make informed decisions, and workers who ensure long-term economic health. Among the engineering disciplines, chemical engineering is sometimes the least understood. As W.H. G. Armytage has put it, "The artistry of a bridge-builder is obvious to the naked eye, but the activities of the chemical engineer are not, until the products are bottled, batched, or baled. Both profoundly affect the progress of mankind."[6] Given our society's pervasiveness of products and energy that are chemically derived, it is especially important to make chemical engineering intelligible to the general public.

ChBE is one of the few engineering departments in the United States to take this public engagement mission seriously enough to host a faculty member whose main purpose is its pursuit. **Bill Hammack** uses mass media to communicate engineering to the public, and has received numerous awards for his efforts. He has created a remarkable public radio series called *Engineering & Life*, in which he shares the wonders of engineering while also emphasizing the responsibilities associated with technological change. His hundreds of radio pieces have been heard on public radio's premier business program *Marketplace*, which has an audience of 8 million, and around the globe on Radio National Australia's *Science Show*.

ECONOMIC DEVELOPMENT

The department's research activities have led to tangible economic development for societal benefit. In the past five years ChBE faculty have filed more than 10 patent applications per year, a significant increase from, on average, 1-2 applications per year prior to 2000. Much of the intellectual property has been licensed to companies. In addition, four startup companies have been created recently with ChBE faculty involvement: two in energy, one in microanalysis systems, and one in tissue engineering.

SUMMARY

We are deeply conscious within ChBE of our role as a department within a public research university, and we seek to be distinctive in the ways we fulfill that role. Our undergraduate education ranks among the best in the United States even with a large student/faculty ratio. The curriculum emphasizes chemistry, laboratory experiences, and practical creative problem solving in a unique way. The program offers extensive opportunities for undergraduate research, and features a biomolecular course option taught by leaders in the field. In graduate education, the department features an extraordinary dedication to collaboration across disciplines and with many individual faculty spanning a wide range of areas. The large proportion of early-career faculty sharpens the focus on current-day research problems, and also fosters an environment of especially close mentorship of graduate students. The department exhibits a rare willingness to build global graduate education programs at the level of a multi-institutional doctoral degree, and to embrace public engagement efforts to interpret the engineering endeavors to the society at large.

Looking ahead, we believe public research universities need to re-envision themselves in the changing social and economic landscape. As a discipline, chemical engineering must recognize that its reach extends with particularly broad scope into the pressing problems of our day, in areas of human health, energy, and sustainability, and in a milieu where access to powerful computational tools becomes widespread. Large numbers of students at both the undergraduate and graduate levels are seeking to enter these areas for the benefit of the common good, and chemical engineering departments in public research universities must embrace those students in a spirit of both innovation and efficiency.

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INTRODUCTION

TO THREE SPECIAL ISSUES OF PAPERS FROM THE

AIChE Centennial Celebration

> **"History never looks like history when you are living through it."**
>
> —John W. Gardner

DAVID L. SILVERSTEIN, *Chair of AIChE Topical Conference on Education*
PHILLIP C. WANKAT, *Proceedings Editor*

Marking where chemical engineering education emerges in history is a challenge. Perhaps it should be traced to the growing practice of industrial chemistry courses during the 19th century. Some would cite the formation of the first degree program in the field at MIT in 1888. Doubtless, the formation of the American Institute of Chemical Engineers in 1908 marked a significant milestone in the rapidly developing profession of chemical engineering. During the Institute's 2008 Annual Meeting in Philadelphia, we celebrated the centennial anniversary of AIChE's role in chemical engineering and in the education of chemical engineers.

As part of the Centennial Celebration, the Group 4 (Education) Programming Committee of AIChE sponsored a Topical Conference entitled "Chemical Engineering Education: Past and Future." The theme was a "retrospective look forward" at many topics that form the chemical engineering curricula. Highlights included: "200 Years of Chemical Engineering Pedagogy: Reflecting on the Past, Designing the Future"; a comprehensive history of the ASEE ChE Division Summer Schools for Chemical Engineering Faculty; sessions on core areas of chemical engineering featuring some of the most prominent people in their fields; a joint education session with the Indian Institute of Chemical Engineers; and a full program of traditional education sessions. In an effort to further disseminate and preserve the collected knowledge, experience, and advice offered in the Centennial education sessions, extended abstracts were requested of all presenters. These abstracts are available in the Proceedings published by AIChE and on the *CEE* Web site, <http://cee.che.ufl.edu>.

While the planning for the Topical Conference was ongoing, another significant education initiative was under way in AIChE. In an effort to expand the role of chemical engineering education in AIChE, an Education Division was formed with probationary status. The Education Division seeks to provide resources faculty need to teach well; promote the scholarship of engineering education; and provide an opportunity for all of those interested in chemical engineering education to become involved in a meaningful way to shape the practice of chemical engineering education. In addition to continuing to provide an innovative and useful technical program, current Division projects include: a partnership with the Chemical Engineering Division of ASEE for a special session on "Fundamental Research in Education"; an annual multi-national survey on how chemical engineering courses are taught; and an expanded sequence of career development workshops targeted at new and prospective faculty.

It seems natural that the Education Division would partner with *Chemical Engineering Education*. Authors submitting extended abstracts to the AIChE Proceedings were invited to submit an article to *CEE*. These papers went through the normal, rigorous *CEE* peer-review process. This issue is the first of three featuring these papers. We hope to forge closer links between AIChE's Education Division and *CEE*, and expect to see additional special issues of *CEE* based on AIChE Education Division programming in the future. ❐

IMPLEMENTING CONCEPTS OF PHARMACEUTICAL ENGINEERING
Into High School Science Classrooms

HOWARD KIMMEL, LINDA S. HIRSCH, LAURENT SIMON, LEVELLE BURR-ALEXANDER, AND RAJESH DAVE
New Jersey Institute of Technology, Newark, NJ

Engineering plays a major role in shaping the world today. The application of science, mathematics, and technology into engineering benefits people and makes the world we live in possible. Most students are unaware of the benefits that engineering provides people in their daily lives.[1, 2] One of the more critical reasons most students, particularly those from underrepresented populations in urban school districts, are not interested in pursuing careers in engineering is that they are not exposed to topics in engineering during their K-12 studies. Most K-12 teachers have not been trained to incorporate engineering and technology topics into their classroom lessons and there is a lack of high-quality curricular materials in these areas.[3] Comprehensive professional development programs are needed for teachers to address the new skills and knowledge necessary for improved classroom teaching and learning[4, 5] if we expect them to integrate engineering concepts into their classroom practice.[6-8] One perspective on the features influencing effective professional development outcomes is provided by a Council of Chief State School Officers report,[9] in which five features were considered: three core features (active learning, coherence, and content focus), and two structural features (duration and collective participation). With this in mind, the Research Experiences for Teachers (RET) program was designed to include each of these five features: 1) **Active Learning:** Teachers were involved in discussion and planning, as well as research; 2) **Coherence:** Activities were built on what they were learning, and led to more advanced work; 3) **Content Focus:** Content was designed to improve

Howard Kimmel *is a professor of chemical engineering and the executive director of the Center for Pre-College Programs at the New Jersey Institute of Technology. He has spent the past 30 years designing and implementing professional development programs and curricula for K-12 teachers in science and technology. At the college level, he collaborates on projects exploring teaching methodologies and assessment strategies in first-year college courses in the sciences, engineering, and computer science.*

Linda S. Hirsch *is the program evaluator in the Center for Pre-College programs. She has a doctoral degree in educational psychology with a specialty in psychometrics and a master's degree in statistics. She has been involved in all aspects of educational and psychological research for 15 years. Dr. Hirsch has extensive experience conducting longitudinal research studies and is proficient in database management, experimental design, instrument development, psychometrics, and statistical programming.*

Laurent Simon *is an associate professor of chemical engineering and the associate director of the pharmaceutical engineering program at the New Jersey Institute of Technology. He received his Ph.D. in chemical engineering from Colorado State University in 2001. His research and teaching interests involve modeling, analysis, and control of drug-delivery systems. He is the author of* Laboratory Online *(available at <http://laurentsimon.com/simon/>), a series of educational and interactive modules to enhance engineering knowledge in drug-delivery technologies and underlying engineering principles.*

Levelle Burr-Alexander *is a project manager responsible for the Education and Training Institute of the Center for Pre-College Programs at NJIT. She has a B.S. degree with thesis in chemistry from Stevens Institute of Technology, an M.S. degree in biomedical engineering from NJIT, and is pursuing a Ph.D. in education specializing in instructional and curriculum leadership from Northcentral University. Her work and research interests focus on STEM education for students and educators through curriculum, instruction, and assessment of learning at the secondary-school level.*

Rajesh N. Dave *received a B. Tech. degree in mechanical engineering from Indian Institute of Technology, Bombay, in 1978, and M.S. and Ph.D. degrees in mechanical engineering from Utah State University in 1981 and 1983, respectively. He is a distinguished professor of the Otto York Department of Chemical, Biological, and Pharmaceutical Engineering at NJIT. He has published extensively in two main research areas, particle technology/engineered particulates and fuzzy pattern recognition.*

and enhance teachers' knowledge and skills; 4) **Duration:** Professional development for the teachers extended over six weeks during the summer and continued during the school year; and 5) **Collective Participation:** Teachers met in teams and as a group to discuss strategies and content as well as to develop approaches that they presented to their peers.

A focus is needed on content in currently available curriculum materials that creates connections between the science used in engineering applications in the real world and the science curriculum standards for which teachers and administrators are held accountable.[3, 10, 11] While substantial energy has been devoted to developing standards-based curriculum materials and achievement tests, little is known about new lesson planning, teaching, and student activities needed in a standards-based classroom. O'Shea and Kimmel[12] have developed a protocol for standards-based lesson planning that allows teachers to systematically assess learning outcomes that are aligned with state content standards.

RET programs are seen as a vehicle for introducing engineering into secondary-school curricula to increase students' interest in engineering, and ultimately increase the number of qualified students pursuing engineering degrees,[13-15] but many programs lack follow-up and\or effective evaluation.[13, 14]

An RET program at the New Jersey Institute of Technology (NJIT) has been designed to provide high school science teachers with a professional development program that enhances their research skills and their knowledge of science and engineering concepts—enabling them to incorporate real-world applications (*e.g.*, pharmaceutical engineering) into high school science curricula. As part of the program teachers developed instructional modules they could use to integrate engineering principles into their classroom teaching. The project also focused on helping the teachers refine their instructional planning skills and providing them with an effective protocol for developing standards-based lesson plans.

THE SETTING

The RET program at NJIT is a collaboration between the Engineering Research Center for Structured Organic Particulate Systems (ERC-SOPS) and the University's Center for Pre-College Programs (CPCP), initiated under an NSF-sponsored four-university project. The goal of the program is to educate high school teachers in the opportunities and challenges involved with manufacturing pharmaceutical products, and thus help educate future generations of students—helping create a strong pipeline of talented students interested in pursuing careers in engineering and science.

The ERC-SOPS is a four-university project, involving about 30 faculty members, with a central systems-oriented theme of developing a model-predictive, integrated framework for systematically designing materials, composites, and the processes used to manufacture them. The NJIT ERC includes seven faculty members, who mentor research projects aligned with three main research thrusts: 1) a New Manufacturing Science for Structured Organic Particulates, 2) Composite Structuring and Characterization of Organic Particulates, and 3) Particle Formation and Functionalization.

The Center for Pre-College Programs (CPCP) at NJIT has been working with the public school systems in Newark and others across the state of New Jersey for almost 40 years.[16] The mission of the center includes the planning, development, and assessment of STEM education programs, and the development and coordination of academic programs to serve elementary- and secondary-school teachers. Among the many successful programs at CPCP is the Pre-Engineering Instructional and Outreach Program (Pre-IOP), established to raise awareness about the importance of pre-engineering concepts in science and mathematics curricula.[7, 17] Pre-IOP included the development of pre-engineering curriculum modules (aligned with the New Jersey Core Curriculum Content Standards) for use in secondary mathematics and science classrooms. Teacher professional development programs were established to train teachers how to integrate the pre-engineering curriculum into their classroom teaching as a way for their students to apply classroom lessons to real-life problems. The pre-engineering curriculum in science, mathematics, and technology classroom was found to improve students' and teachers' attitudes toward engineering and knowledge of careers in engineering.[18, 19] The RET program at NJIT continued the work of Pre-IOP by incorporating pharmaceutical concepts into the high school science curriculum.

THE RESEARCH EXPERIENCE

The 2007 NJIT RET program provided the opportunity for nine high school science teachers (chemistry, biology, and physics) to engage in a six-week experience in a research group of the Center for Structured Organic Particulate Systems (C-SOPS). Participating teachers were selected from local urban schools with whom NJIT already had working relationships. Working side-by-side with university research faculty, graduate students, and undergraduate students (participating in a parallel Research Experience for Undergraduates, or REU, site program) in discovery-based, hands-on research projects, teachers developed basic knowledge and skills in the area of pharmaceutical particulate and composite systems that could be incorporated into their teaching practice. Implicit was the opportunity for intellectual professional growth for the teachers.

The first week of the program was an orientation, which included an introduction to NJIT and ERC-SOPS's research activities, methodologies, instrumentation, and safety procedures, as well as the scientific tools, protocols, and equipment necessary to gain meaningful hands-on experience in the laboratory. Teachers were trained to become contributing members of their research team and given instruction in how to develop standards-based lessons/modules for use in their classrooms.

An introduction to the technical literature and methodologies for searching the Web to support their research activities was included. Ongoing discussion during the summer experience focused on the development of lesson plans.

RET projects were small sub-projects within the research at ERC-SOPS, in recognition that much of the research deals with concepts that can be difficult to translate into laboratory and instructional activities for high school classrooms. Simplified versions of the basic concepts in a research project were developed. For example, dissolution of particles can be related to basic concepts of solubility, equilibrium, and rates of processes by developing simple experiments that involve observing dissolution of sugar crystals of varying size, with or without stirring or agitations. Teachers worked in teams of two that also involved at least one graduate student and one undergraduate REU student. The REU students will have had several weeks of experience by the time the RET program begins, and hence the team consisting of one graduate student and one REU student will be well-versed in the research project.

For example, in one research project, a method for dry particle coating was used to deposit a very small amount of nano-size additives with a high degree of precision onto drug or excipient particles to change their flow and other properties. RET participants examined the application of this technique on improvement, control, and characterization of flowability of cohesive powders in a predictive manner through dry particle coating. A lesson was designed to introduce the topic of nano-technology so that students may acquire an understanding of what it means to be that small. First the students were given a sense of what it means to be as small as micro- and nano-size, as compared to larger objects. Then the students explored why ultra-small size matters to scientists and engineers with examples of the applications making use of it in various industries, including pharmaceuticals. The students were also introduced to some of the problems encountered when working with very small particles. To help students think about how different micro- and nano-size particles are when compared to people, students compared objects that are 6 and 9 orders of magnitude apart in size, including atoms and molecules and the wavelength of light in the electromagnetic spectrum. The lesson included hands-on activities and demonstrations that used meter sticks, micrometers, and finely ground or powdered substances such as sugar, sand, and flour, to demonstrate properties of particles as well as compare sizes of objects and flow rates of fine particles.

Another research project focused on crystallization—the most common method used in the pharmaceutical industry for generating particles of active substances or intermediates. Teachers examined the role of agitation on crystal size as part of a study of the hydrodynamics of a stirred-tank-impeller assembly, with particular attention being paid to solid dispersion and the determination of the minimum agitation speed for off-bottom solid suspension, both in the presence and the absence of an impinging jet apparatus. A lesson was developed on the crystallization of ultrafine (nano and micro) particles of active pharmaceutical ingredients using a liquid anti-solvent technique. The lesson was used to demonstrate the principles of solution mixing and crystallization and related engineering themes, by having students determine the optimum concentration for crystallization and effect of surfactants. The students were introduced to the liquid anti-solvent method of crystallization, which involves the formation of nanoparticles of different compounds. The lesson focused on how to make crystallized particles of a substance from a given solution using an anti-solvent. In the first part of the lesson, students in groups discuss the various crystallization methods and advantages of the liquid anti-solvent method. Next, using solutions of aspirin and ibuprofen in acetone, they find the amount of anti-solvent needed to precipitate the given amount of drug substance. They do so by first finding the volume of anti-solvent needed to precipitate the given amount of aspirin, and then finding the volume of anti-solvent needed to precipitate the given amount of ibuprofen. The students could then plot a graph of concentration of drug substance vs. amount of anti-solvent needed for precipitation of aspirin and ibuprofen, and determine the optimum concentration of the active pharmaceutical ingredients in acetone.

Development of the instructional modules was critical to the RET program. Teachers and their mentors met frequently to develop a simple topic that is closely related to the pharmaceutical industry as well as the research they were conducting. To be effective, the modules had to address important issues including: the real-life implications of the research; which experiments would best relate the information to students in an exciting, insightful way; whether the materials and methods required to perform these experiments are accessible in high school laboratories; the insurmountable safety issues in planning such experiments; the step-by-step procedure for disseminating the information to students in a logical way; and the assessments to be used to show that students have internalized the information.

Because there was an odd number of teachers, one of the teachers served as a "swing teacher" working jointly with each team to monitor progress and communicate with the mentors. The swing teacher developed an instructional module that encompassed the research projects of the other teachers, "A Step Toward Discovery: Inquiry Skills in Science," designed to help students think like engineers and scientists, while connecting relevant mathematics and science skills.

STANDARDS-BASED LESSON PLANNING

Curricular materials in support of the integration of engineering into science instruction have been made available through organizations such as NASA, ASME, and IEEE, as well as through university- and teacher-developed lesson plans. Only concepts included in state content standards are taught in the classroom, however, as teachers believe they will only be accountable for what is in the standards.[12] As a result, the only curriculum materials usually considered, let alone implemented, are those that reinforce state content standards, since student achievement (and schools' and districts' achievement) is measured largely by student performance on the statewide assessment tests.[20] So, if teachers are to make engineering principles a part of their instruction for student learning, then engineering principles must be part of the state science standards. Translation into standards-achieving lessons is critical.[3] Curriculum topics aligned to standards alone are not sufficient, however.[12, 21] Alignment with standards must also include the assessment of student achievement of the skills and knowledge defined by the standards.

Research suggests that lesson and unit plans are essential and powerful tools for instructional improvement and increased student achievement.[21] When teachers prepare truly standards-based lessons, their teaching is focused on student achievement in relation to specific standards.[22, 23] A protocol for the creation and implementation of standards-based lesson plans has been developed at CPCP and used in previous and current professional-development programs.[12] The protocol includes identification of measurable learning objectives, specification of the corresponding statement from the content standards, adaptation of the activity that provides the student the opportunity to acquire the skill and/or knowledge specified by the learning objective, and the expected student performance that provides the evidence that the student has acquired the skill and/or knowledge. The RET participants were introduced to the protocol and a template was developed for use in the development of their instructional modules.

EVALUATION

Teachers' Concerns About Integrating Engineering Skills Into Classroom Teaching

Teachers' concerns about integrating engineering skills into their classroom teaching were measured using The Teachers' Concerns Questionnaire (TCQ) adapted from the Concerns Based Assessment Model (CBAM).[24] Repeated administrations of the TCQ are used to identify teachers' concerns and track changes in their concerns as they engage in educational reforms, focusing on how they progress through seven stages of concern: Awareness, informational, personal, management, consequences, collaboration, and refocusing. Teachers completed the TCQ at the beginning and end of the RET program and again several months into the school year after they had time in their classrooms. All three sets of responses were examined by graphing teachers' percentile scores across the seven stages. The highest percentile score indicates the stage teachers are focused in.[24] Initially, the teachers showed low levels of awareness and\or some were not very interested (see Figure I).

By the end of the program most teachers increased their awareness and many had moved into the information-gathering stage (indicated by a moderate decrease in the percentile score for the Awareness stage such that it was lower than the score for the Information stage). Not until a few months into the school year did the teachers begin shifting toward whether the new curriculum would help their students learn math and/or science. Three teachers completed the TCQ toward the end of the school year, expressing fewer personal and management concerns about the time commitments required to implement their new instruction modules. The teachers were focused on how the implementation may have impacted their students and appeared to have shifted into the collaboration stage indicated by the high percentile score.

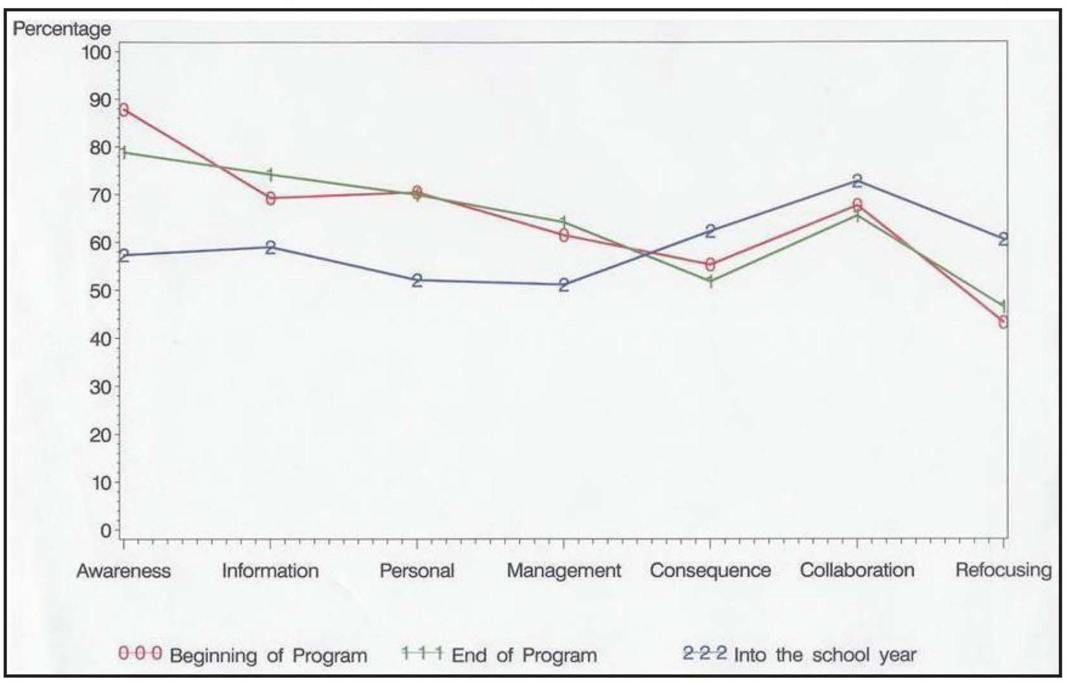

Figure 1. *Teachers' concerns profile.*

Teachers' Readiness to Teach

At the end of the RET program teachers completed a Readiness to Teach Questionnaire (RTQ). The RTQ[18, 19] requires teachers to indicate how ready they feel they are to teach lessons on new topics and\or skills they have learned on a scale from 1 to 4 where 1 is "I would have to start from scratch"; 2 is "I would need more training to teach this topic"; 3 is "I would have to look at my notes to do this"; and 4 is "I can teach a lesson on this topic tomorrow." For example, one item asks "How ready are you to teach the concept of steady state?" Teachers were asked to complete the RTQ again a few months into the school year after they had some time in their classrooms. At the end of the summer program average scores for the 13 topics ranged from 2.8 to 3.8, indicating that most of the responses were 3 or 4. Only one teacher gave any responses that indicated 1 ("I would have to start from scratch"). For many topics the percentage of teachers that indicated 4 ("I can teach a lesson on this topic tomorrow") was over 50%. Average scores for most of the topics increased slightly a few months into the school year; ranging from 3.2 to 3.8. The average scores for two of the topics did not change and only one topic, Drug Release From a Lozenge, showed a decrease in the average response from 3.1 to 2.8. This was due mostly to a few teachers indicating 3 ("I would have to look at my notes") the second time rather than their initial response of 4 ("I can teach a lesson on this topic tomorrow"). Again, three of the teachers completed the RTQ a third time toward the end of the school year. Their average scores ranged from 3.5 to 4.0 indicating that at least these three teachers could teach all of the topics even if they had to look at their notes.

Attitudes to Engineering

Teachers completed the Teacher Attitudes To Engineering survey (TATE) at the beginning of the RET program and again a few months into the school year after they had completed the program and had some time in their classrooms. The TATE, developed as part of the center's Pre-IOP program, measures teachers' overall attitudes toward engineering as well as their knowledge of careers in engineering and their self-efficacy for assisting students who might want to study engineering.[18, 19] Teachers' attitudes toward engineers and engineering as a career were fairly high, even at the beginning of the program. All nine teachers agreed with the statement that "skills learned in engineering are useful in everyday life" and disagreed with the statement "I would not like any of my students to be engineers." Their average TATE scores increased from 3.9 at the beginning of the program to 4.2 during the school year. See Table 1 for a sample of items from the TATE that appeared to show the most change in the teachers' attitudes toward engineering.

Most teachers were somewhat informed about how to help prepare students interested in studying engineering. Most agreed they would "know where to find the necessary information to help my students if they wanted to become engineers" but most disagreed with the statement "I have all the information I need to help prepare any of my students who may want to be an engineer." Only a few indicated they knew of summer programs to help students learn more about careers in engineering. Average scores on the items that assess teachers' self-efficacy for helping students who might want to study engineering were low, only 3.0, at the beginning of the program, but increased to 4.3 during the school year.

TABLE 1
Changes in Teachers' Attitudes to Engineering and Self Efficacy for Helping Students

Attitudes toward engineering	Start of program	End of program
I think that engineering could be an enjoyable career.	3.6	4.5
Engineers have little need to know about environmental issues.	1.9	1.6
I would not like any of my students to become engineers.	2.7	2.1
The rewards of becoming an engineer are not worth the effort.	2.2	1.7
To be an engineer requires an IQ in the genius range.	2.5	2.2
My students would have no problem finding jobs if they had an engineering degree.	3.6	4.4
Engineering plays an important role in solving society's problems.	4.4	4.8
A woman can succeed in engineering as easily as a man of similar ability.	3.9	4.3
Engineers spend most of their time doing difficult mathematical calculations.	3.6	2.7
Most of the skills learned in engineering are useful in everyday life.	4.2	4.7
From what I know engineering is boring.	1.8	1.4
Self-efficacy for helping students		
I feel I have all the information I need to help students who may want to become engineers.	3.0	3.0
I suggest engineering as a possible career if students do well in math and science.	2.8	3.9
I suggest medicine as a possible career if students do well in math and science.	4.1	4.0
I think I know what engineers do.	3.6	4.5
I am aware of grade-appropriate information on engineering careers for my students.	2.6	3.6
I actively encourage my students to consider engineering as a career.	1.9	3.2
I know of summer programs that would help students prepare for an engineering career.	2.7	3.8
I have discussed engineering as a possible career option with my students.	2.6	3.4

Knowledge of engineers and careers in engineering is measured using a multiple-part, open-ended question that requires teachers to "name five different types of engineers" and to "give an example of the work done by each type." Each type of engineer is coded '1' for correct or '0' for incorrect. Possible total scores range from 0 to 5. Each example of the work they do is coded '2' for completely correct, '1' for partly correct, or '0' for incorrect. Possible total scores range from 0 to 10. At the beginning of the program only five of the nine teachers were able to correctly name five different types of engineers and two were able to name two types correctly. Only one of the teachers was able to give correct or partly correct examples of the work done by all five types of engineers, receiving 7 points. One teacher did not give any examples and the rest were only able to give one, two, or three partly correct examples. When the teachers completed the survey again a few months later results showed that teachers' knowledge of engineers and engineering as a career had increased. Six of the teachers were able to correctly name five different types of engineers, two teachers named four types, and the last teacher named three. All of the teachers were able to give at least some partly correct examples of the work done by the types of engineers they named, most scoring at least 5 points; a few scored 8 or 9 points.

Teachers' Feedback on Program Effectiveness

Periodically during the program teachers were asked to provide written feedback on how they felt the program was progressing. Teachers were asked to rate each activity or learning experience by indicating how useful they felt it was to them as a teacher (2 = very useful, 1 = somewhat useful, 0 = not useful) and the value they felt it had for student learning (2 = high value, 1 = some value, 0 = no value). The average rating for a majority of the activities was at least 1.5. See Table 2 for a summary of the average ratings for the major topics and activities.

Two activities—poster presentations to share their research experience with others and the mentoring process—had an average rating of 1. Many of the teachers just did not find the poster presentation very useful. Two of the teachers rated the mentoring process as not useful. Unfortunately one of the two teachers reported that their mentor had "not been available" during the program. The teachers found a majority of the activities to have a high value for student learning, with average ratings of at least 1.6. The activities that teachers did not find useful for their students—scoring an average of 1 or less—were things such as tours of laboratories, poster presentations, and discussions of ongoing research.

TABLE 2
Teachers' Feedback on Program Effectiveness

	Average usefulness for:	
	You as a teacher	Student learning
Introduction to pharmaceutical engineering, discussions, demonstrations	1.8	1.6
RET mentor presentations	1.7	0.6
What we can bring to the classroom? Q & A	1.8	1.6
Information literacy: research and communication skills	1.4	1.2
Brainstorming sessions with RET mentors	1.2	0.7
Skills necessary for pharmaceutical manufacturing	1.6	1.4
Various lab tours, presentations on lab techniques, safety	0.8	0.3
Teamwork on project and planning of educational module	2.0	1.6
Team presentations of projects	1.8	0.9
Project management: presentation preparation w\RET mentors and research facilitators	0.2	0.1
Poster presentations, discussion of ongoing research	0.9	0.2
Individual research	2.0	1.8
Module development: lesson planning discussion of progress	1.9	1.6
Undergraduate symposium	1.8	1.0

CONCLUSIONS

Teachers found the RET program useful to them as instructors and found a lot of value in the experience for their students. This conclusion is exemplified by the response of one teacher to a survey on their implementation of what they learned into their classroom practice:

> *"I have seen significant gains in basic skills as a result of student willingness to risk failure. In my estimation I've done a horrible job of harnessing this new power, being completely unprepared for how successful it might be. I've got freshmen handling vector math and multiple-step equation manipulation problems but there's more I can do. I can't wait for next year so I can apply what I've learned from this first attempt. Since the approach focuses on the students' skills and self-improvement they've gotten some benefit in other classes as well. My freshmen are doing very well. They apply engineering principles to their own student behavior and are actually taking pride in improving themselves. As we might expect, their initial efforts in the laboratory were disastrous, but they have begun to avoid blame and self-doubt. It has completely changed their concep-*

tualization of failure—they are now seeing failure of method instead of failure-as-a-person; not surprisingly they are trying very difficult things, since they can take pride in success and not feel guilty about failure. As one example, I did a week-long unit on technology and engineering awareness, focused mainly on career opportunities and the roles of engineering in society. I also ran a task-oriented laboratory in which advanced chemistry students were asked to separate chicken soup into its component parts, having been informed of separation techniques but without specific instructions or previous complex separation experience. The laboratory experience was designed to show 'failure,' as well as success in solving engineering problems. The students found that such a process was indeed quite difficult to carry out."

Participation in the RET program increased teachers' attitudes toward engineering, their knowledge of engineering careers, and their self-efficacy for helping students who might be interested in studying engineering. Many of the teachers expressed an interest in repeating such an experience.

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WIKI TECHNOLOGY AS A DESIGN TOOL FOR A CAPSTONE DESIGN COURSE

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Web 2.0 technologies allow sharing of information and are designed to enhance creativity, communication, and the overall collaborative functionality of the Internet. These Internet tools, like wikis, are becoming an integral part of the upcoming generation's (the Net Generation) social and academic life.[1] Educators and students alike benefit from incorporating these technologies into the classroom.[2] With wiki technology, student interaction, idea collaboration, and organization of information can be improved compared to traditional ways of teaching.[3]

A wiki is a Web site where users add, view, and edit content as needed. Different users can add content and review material added from other users allowing for collaboration and sharing of information within groups.

According to a survey conducted by the Educause Center for Applied Research (ECAR), the use of information technology and Web 2.0 technologies is astonishingly high.[1] Out of the 20,000-plus students surveyed, engineers spent more time online (an average of 21.9 hrs/week) than any other discipline. Specifically pertaining to wiki usage, 41.7% of all of those surveyed access or use wikis on a weekly basis. According to the conductors of the study, this number may be understated because the students may not know what a wiki is or realize their Internet searches direct them to a wiki site. An additional factor is the survey does not distinguish between access and contribution. Another part of the survey reported 32.6% of the students liked learning through contribution to wikis and blogs. Again, this number may be skewed due to the ignorance of what constitutes a wiki.

Although technology is an integral part of the Net Generation's social and professional life, educators should show restraint when incorporating technology into the classroom. The main question to keep in mind when deciding to include new technology (or a new approach in general) is "will it benefit the students?" According to Oblinger and Oblinger,[4] even though the Net Generation values what older generations consider new technology—wikis—what they value most is interaction. Professors can't replace interaction with technology, but must augment and enhance interaction using technology.

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Interaction and learning are the keys when bringing something new into your classroom.

Of course, it is hard to know whether or not something new will enhance interaction or learning, which served as the motivation of the study discussed here. The goals were to understand how to introduce wikis to students and what their value was as a design tool. This article presents a description of wikis, the details of the wiki study, what was learned from the study, and suggestions for further wiki use in the engineering classroom.

WIKIS AND THEIR FEATURES

Wiki is a Hawaiian word for quick, but in the context of this study it is a type of Web site any user can view and edit like any word processor without the knowledge of html or similar programming languages. An appropriate illustration of wikis and their potential can be found online at <http://doiop.com/wiki-che>. There are many wiki hosts on the Web, but we chose to use <www.pbwiki.com> (version 1.0), because it was very user-friendly and it was free. Wikis have a number of features appealing to engineering and engineering education. First, there is a complete revision history for each page in the wiki. From the student's perspective, they can go back to any version and not only see what has been changed, but they have access to make it the current version if mistakes were made later. From an educator's perspective, a professor can track the progression of the project through the students' eyes. Also, the teacher can observe specific changes between versions.

Every saved change to a page can be tracked to a specific user and that change is time-stamped. This means a professor can really enforce accountability with respect to each team member. If Jean and Tom say Billy isn't working, the professor can go to the wiki and confirm Billy made four minor additions to the wiki. In addition, a professor has verification if a group is being lazy or if they are procrastinating.

A final feature is the ability to add comments. If the educators don't feel comfortable editing a student's work, they can leave a comment on a page of interest. Instead of meeting at key points in the semester, a professor can go to the wiki and look at how things are going. If something of concern exists or if the students have questions or concerns, the professor can address those concerns or notify the group of his/her concerns. The ability to do this ties directly into the goal of integrating technology into the classroom, while promoting interaction between students and the faculty.

SENIOR DESIGN PROJECT AND WIKI STUDY DETAILS

The participants of the study were the seniors enrolled in the Chemical Engineering Process Design course at Vanderbilt University. Their final project was the 2008 AIChE National Student Design Competition project: to design a process to convert coal into methanol and perform a complete economic analysis.

Ten groups of three students were given 30 days to complete their design and present their results to the rest of the class. At the start of the project, the teaching assistant (TA) introduced how to use wikis and displayed their potential to the students and encouraged (but did not require) them to add content to the wiki as part of the project. Each group's wiki was set to private, so only the professor, the TA, and the group members could view and edit the content. The class was also provided with a class hub wiki to post common questions, to see an example page, and to have links to pbwiki tutorials.

Each week, the professor received weekly reports from each group, some directly from the wiki, and the group's progress was discussed in a weekly meeting with the main instructor. In addition, throughout the project, the TA and the professor would monitor the wiki of each group and add comments, questions, or concerns when necessary and reply to comments or questions expressed by the group within their wiki.

At the end of the project, 25 out of the 30 students were given a survey asking about their experience with the wiki, their opinions of the wiki's use, and their suggestions for further use. Within the survey, there were three sections: positive and negative statements requiring a numerical allocation from the student on a 6-point Likert scale, a list asking which project items were included in the wiki, and open-ended questions about the good and bad points of the wiki and its implementation.

SURVEY RESULTS

The first section of the survey contained 12 statements, and the students were asked to circle a number between 1 and 6 to describe how much they agreed with the statement, where a choice of 1 indicated strong disagreement and a choice of 6 indicated strong agreement. To prevent a neutral response, an even number was chosen for the maximum. Also, a mix of positive and negative responses was included to ensure valid results from those surveyed.

The scores were analyzed and (for the most part) students liked the use of wikis in the design course. One group didn't add any content to their wiki in any form, and their responses were negative with respect to the wiki. The members of that group provided helpful open-ended comments, but their responses were excluded from the numerical analysis of the survey. We decided the absence of their participation didn't qualify them for a valid opinion about the implementation and general opinion of the wiki.

The first step in evaluating wiki use in a design course was taking the average score for each statement. If the score was greater than 4.0 or less than 3.0, we considered that score to have a significant positive or negative agreement. The statements with values between 3 and 4 were regarded as a neutral response. Table 1 lists the average score for each statement and as you can see, the students agreed with six statements:

- *(I.) They will tell others about wiki technology for collaboration.*
- *(II.) They would like to use a wiki in their future career.*
- *(III.) They recommended use of the wiki for other senior design courses.*
- *(V.) They used the wiki only because it was required.*
- *(VI.) The wiki helped organize their work and findings.*
- *(XII.) There was more interaction from the professor and the TA in this project than others in the past.*

In addition, the students disagreed with three of the negative statements:

- *(IV.) Adding to the wiki took more time than it saved.*
- *(IX.) The wiki overcomplicated the project.*
- *(XI.) The wiki was confusing, and it made the project more difficult.*

There was not a definitive agreement as to whether the wiki was a key component to finishing the project (VIII.), if the wiki helped them finish the project more efficiently (VII.), or if the student had better understanding of their team members' progress because of the contributions to the wiki (X.).

Taking these numbers into account, statement V. was the only one expressing a negative opinion toward wikis. From the rest of the statements, the benefits outweigh the shortcomings. The authors speculate the students may have realized this if the project was longer term and/or involved more members per group who didn't have a history of working with each other. Also, in our opinion, the neutral statements may have shifted toward a positive response if the project was changed with respect to the two factors mentioned in the previous sentence.

Another criteria for acceptance of the wiki was average individual and group scores for each statement. For the negative statements, the scores were adjusted by reflecting their value across the median of the Likert scale. The score for each statement was summed. We looked at the average score for all of the statements to evaluate if an individual or group had a positive response to the implementation of the wiki, as shown in Figures 1 and 2, respectively. On an individual basis, six students had a negative response (including the three who didn't use the wiki), eight had a neutral response, but a third of the class (11 students) had a positive response with four individuals having an average score of 5 or greater. On a group basis, half of the groups had a positive response, four had a neutral response, and the group that didn't use the wiki had a negative response.

The frequency, volume, and quality of content added to a group's wiki correlates with the average opinion of the group. In other words, the groups who utilized their wiki liked using the wiki and those who didn't use the wiki had a neutral opinion about its usefulness. But it is difficult to evaluate cause and effect with respect to recommendation of the wiki and wiki contribution. We hypothesize, however, that if the wikis were implemented throughout the entire senior design course vs. a 30-day project, the students might have begun to see the appeal of the technology and have a more positive reaction.

From our data, we have seen the students agree the wiki is a good organizational tool. With a larger-scale project, we expect more data, more ideas, more decisions, and more files would be generated from a group. As such, as a project supervisor or a professor, we would require more robust documentation and suggest use of the wiki. We hypothesize if the students use the wiki, they will see its potential and begin to hold it in high regard. We have other ideas as to what might have increased the positive opinion of the use of wikis in design, but those are discussed in a later section.

Table 2 summarizes student use of the wiki or the typical content of the wiki. From the open-ended responses, the ability to have a central hub for shared files like Excel files or Aspen files was a very appealing feature of the wiki. The students also used the wiki to organize their meetings and update the

TABLE 1
Average Scores for Survey Statements

Number	Statement	Score
XII.	The interaction/involvement of Dr. Debelak and Kevin in this project was more productive to my progress than the involvement of other professors and teaching assistants in the past.	4.8
III.	I believe the wiki should be implemented in next year's senior design course.	4.5
V.	If it wasn't required, I wouldn't have used the wiki.	4.3
I.	I will tell others about wiki technology for collaboration.	4.2
II.	I would like to use a wiki in my future career.	4.0
VI.	The wiki helped organize our work and our findings.	4.0
VII.	This design project was finished more efficiently than other school projects.	3.6
X.	I had a better understanding of my team members' progress because of their individual contributions to the wiki.	3.4
VIII.	The wiki was a key component to finishing this project quickly and thoroughly.	3.2
IV.	Adding to the wiki took more time than it saved.	2.9
IX.	The wiki overcomplicated the project.	2.8
XI.	The wiki was confusing, and it made the project more difficult.	2.2

specifics of the group's timeline and task allocation. Finally, most of the students utilized the capability of the wiki to quickly make links to important references.

POSITIVE REACTIONS TO WIKIS FROM THE STUDENTS' AND EDUCATORS' PERSPECTIVE

The last section of the survey asked open-ended questions regarding their likes and dislikes of the wiki, in general, and its integration into senior design. A lot of what the students liked about wikis didn't surprise us. The main thing commented on was the wiki serving as a central hub for files and information. They said it diminished inconsistencies in the content of files (*i.e.*, weekly reports) and everybody had easy access to the most up-to-date files. Finally, in cases where certain individual tasks of the project overlapped, students could find the necessary details in their partner's added content to help steer the progression of their portion of the project.

Another appealing feature to the students was the dynamics of the wiki. Instead of sending multiple e-mails, it was much easier to come to a consensus on meeting times or have discussions without having to schedule a formal group meeting. Within an instant, the students could add little pieces to a discussion or make slight alterations to a plan (meeting schedule) until the group was satisfied with the final result. Compared to other discussion mediums, the whole discussion is automatically recorded and archived.

The other thing related to the appeal of the dynamics of the wiki was the interaction from the authors of this article. Students felt their questions and concerns were addressed frequently and in a timely manner. The wiki provided more interaction on this project compared to other projects. It is crucial to reiterate what was said in the introduction about new technology in the classroom. Students perceive enhancement of interaction as a main requirement when deciding to integrate technology into a class.[4] From the responses to the survey, wiki use seems to have met this requirement.

The addition of wikis to the class had a big impact on project evaluation by the professor compared to previous offerings of

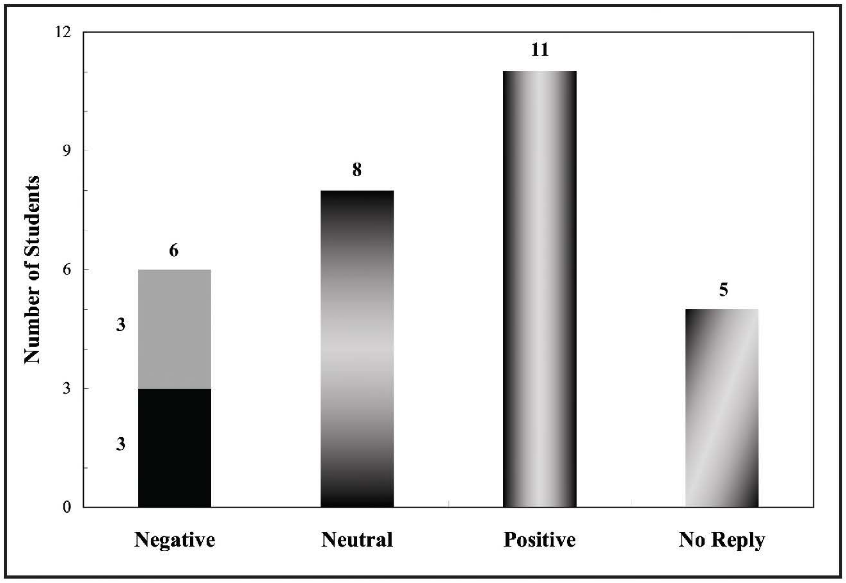

Figure 1. *Comparison of the number of individual students with a negative opinion (black/grey), a neutral opinion (horizontal gradient), and a positive opinion (vertical gradient) of the wiki. The grey region represents the group who didn't use their wiki, and the black region represents the students who used the wiki but had a negative opinion.*

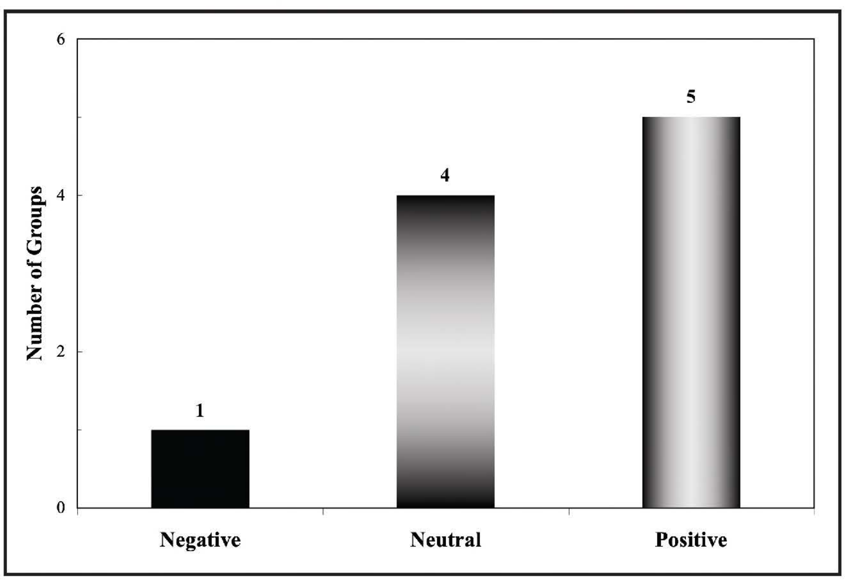

Figure 2. *Comparison of the number of groups with a negative opinion (black), a neutral opinion (horizontal gradient), and a positive opinion (vertical gradient) of the wiki.*

TABLE 2
Summary of how many groups included each item in their wiki

Wiki item	Number of occurrences
Timeline/calendar	8
Attaching files (*e.g.*, Aspen)	8
Meeting notes	8
Links to references	7
Group/professor discussion	7
Task allocation	6
Coordinate meeting times	6
Pre-meeting agenda	3

From a pedagogical standpoint, wikis provide a great potential for study. Wikis allow easy sharing of information among a group. A professor may get a lot more information about what went on throughout the semester compared to solely reading weekly or final reports.

the class. In the past, students kept paper folders containing documentation of their design work analogous to an artist's or architect's portfolio. Evaluating the content of the design folders was cumbersome and could only be done at the end of the semester and during one-hour meetings. With the groups' content stored on a wiki, evaluation of the design and student progress was drastically more convenient.

With respect to the wiki acting as a central hub for information, the wiki content could be viewed at the educator's convenience, the evolution of the design can be observed in real time (and suggestions to redirect the group can be made, if necessary), and shared electronic files for process simulations or design calculations can be downloaded and evaluated by the professor. With the students adding content, the wiki documents what options the students were exploring, what decisions were being made, and, occasionally, why those decisions were made.

Although not a perfect indicator of student progress, the wiki program sends the instructor an e-mail every time the wiki is changed—documenting when and how often the students are working on their project. The e-mail alerts also highlight the type of changes (additions/deletions), who made them, and when they were made, providing a summary of progress made.

Another reason we believe wikis make a great tool for students is that the faculty interaction with the wiki better simulates the interaction they'll receive in practice. In industry, an engineer doesn't collaborate solely by writing a report every month or at the end of a project. The supervisor keeps constant tabs on a group's progress, so the project gets completed on time and the results are valid. With respect to the students' comments about the frequency of interaction from the professor and the teaching assistant, it was easy to address concerns and questions raised by the students. If a student/group posted a question or uncertainty about their design in their wiki, it took no more than 15 minutes to see the question and to answer it in a place where all of the members could see it, and it was easy to find what information was shared at a later time vs. hunting through a slew of e-mails. In addition, knowing their progress was being monitored; these students were more on task than students of previous semesters.

From a pedagogical standpoint, wikis provide a great potential for study. Wikis allow easy sharing of information among a group. A professor may get a lot more information about what went on throughout the semester compared to solely reading weekly or final reports. Also, because of its revision history, we can observe the dynamics of the design process from the students' point of view. If the students use the wiki and add content as information is gathered and decisions are made, an outside observer can start to see the thought process of the designers. Another appealing piece of the revision history is the record of who added what and when. As observed by Heys, individual accountability can really be enforced.[7] Early in a project, if there is a lack of content added or participation by an individual, the group or teacher can take steps to prevent further laziness or problematic procrastination. The content of the wiki may also serve as a source of learning assessment. If interpretations are provided within the content, the educator and outside evaluators can determine the quality and accuracy of that interpretation and conclude if the students apply the fundamentals correctly.

NEGATIVE RESPONSE TO THE WIKI

A main goal of this study was to investigate the benefits and the potential pitfalls associated with implementing wikis into the classroom. Although most students had a positive opinion of the wiki and recognized its utility in design, hurdles existed that prevented use of the wikis. From the opinions pointing out the flaws of the wiki and its implementation, constructive decisions could be made about what to change in the future and how.

The students' three main arguments against the use of the wiki involved the preference for e-mail, the small size of the groups, and the small scale of the project (amount of work required and time to finish). A large percentage of the students commented on how they "prefer to use e-mail." They thought the wiki was more work whereas it was easier to use e-mail. In addition, they thought it was easier to use e-mail because of the size of the groups. It was much easier to meet up with two other people or e-mail two other people, than to add their content to the wiki. Another factor related to the size of the groups was the familiarity of the group members. Each group member shared at least two (if not more) classes with their teammate, they socialized in their personal time, and they saw each other outside of group meeting times very often.

With the project lasting only 30 days, the students didn't think it was worth adding content to the wiki. One student is quoted as saying, ". . . given more time than four otherwise busy weeks with graduating and major life changes approaching, we would have had time to use it for effective group and time management." Because there was no requirement for the content added, some students minimized the content added to save them time.

There were other hurdles preventing or discouraging the students from adding to their wikis. The students began the study with minimal familiarity with wiki technology. Some embraced the new technology, but others stayed away from it because it was new. This is consistent with what was seen in the ECAR study.[1] That study found that students who considered themselves early adopters of new technology had a greater affinity to using wikis in the classroom than those who utilize technology at the same rate as the average population.

Other hurdles were the organization of the wiki, the allocated amount of file storage, and full group participation. Some students thought the wiki could be a great tool if the information gathered throughout the project was organized, but the time required to organize the information was more than the time saved by having the information organized. With respect to the amount of storage, the free pbwiki account only allows a maximum of 15.0 MB worth of files to be uploaded. There is no limit on the amount of content added directly to the wiki, but pictures and actual files saved to the wiki count toward the maximum. Finally, there was at least one group where one of the members didn't attempt to contribute to the wiki, discouraging the rest of the group from adding to it.

SUGGESTIONS FOR FUTURE USE

In general, we believe the wiki is a good design tool for students and recommend it to all design groups in education and in industry. The authors have been communicating with the design team at pbwiki.com to improve what the wiki has to offer. Since the beginning of this study, some of our suggestions for changing pbwiki have been implemented into the newest version, or the feature is being tested as a beta version, *e.g.*, the file limit of the free version of pbwiki 2.0 now has a maximized capacity of 2.0 GB, as opposed to 15.0 MB.

The suggestions for change try to address all of the things that prevented students from embracing the wiki. To address the problems with organization, the authors suggest having a prebuilt skeleton structure for the wiki. The designers have come up with a way to make this very easy for an educator. First off, any previously made wiki page can serve as a template for future pages made. Another feature in beta is the ability to "clone" a wiki. In this fashion, not only does the structure of one page get copied (as in a page template), but all of the links, all of the pages, and the whole structure of the wiki Web site can be made as an exact replica. Using these two new features, we plan on making one wiki whose pages contain suggested headings and space for new additions in a manner we, as supervisors, prefer. We will clone all of the pages of the wiki Web site to make each group's beginning wiki exactly the same. An example of a "skeletal" wiki can be found at <http://vandyskeleton.pbwiki.com>.

Being able to give the students a skeleton structure of the wiki helps alleviate a lot of problems with how the wiki was initially implemented. The biggest benefit is organization. The students can appreciate this, because they don't have to spend as much time organizing, and can spend more time adding content. The teacher can use this organization to allow finding exactly what he or she wants, *e.g.*, the results of a decision matrix. The teacher won't need to go through page after page looking for the justification for the use of a piece of technology. Another helpful aspect of the preconstructed wiki is how it will take away the intimidation of wiki technology and de-emphasize students' lack of familiarity with it by giving them a head start on the project.

Changing the logistics of the project could solve the other issues with the use of the wiki in the class. To address the issues discovered from this study, the following are plans for further offerings of the course using wikis as a design tool:

- *Increase the number of members in each group to four or five.*
- *Randomize the members of the group to reduce familiarity based on class rank.*
- *Increase the scale of the project to last the whole semester and assign it the first day of class.*
- *Require specific entries into the wiki (not just weekly reports).*
- *Require equal contributions to the wiki by all members through a participation grade.*
- *Incorporate other departments for an interdisciplinary design project.*

Considering factors the students said prevented their wiki contribution, we think the above will alleviate those problems.

Being digital immigrants, we didn't enforce using wikis above e-mail. Throughout the project, some students would e-mail us with their concerns and questions (vs. putting them on the wiki) and we would reply using e-mail. The main advantage of wikis over e-mail is the centralization of data and its organization. By responding to the students via e-mail, we decentralize correspondences and add to the disarray of information. By posting the question and the response on the wiki (vs. an e-mail), the conversation is recorded and can be easily referenced for later use. In short, a project manager or professor needs to be consistent about adding to wikis if all group members are expected to use wikis rather than e-mail.

CONCLUSIONS

Wikis have a lot of potential in the classroom. Heys[7] used wiki technology for a class project to improve the learning of his Mass & Energy Balances class. Some educators are using wikis as a replacement for traditional textbooks, where the students add problems and edit the educational content.[3] In this study, we used wikis as a design tool.

Overall, the students liked using the wiki and recommended it for further use. They liked how the wiki improved interaction among group members, the professor, and the TA. In addition, they utilized how a wiki can centralize their findings and its dynamic nature for collaboration. They didn't like taking the time to organize their wiki and prefer using e-mails for a variety of reasons. E-mail can be used for collaborating, but for a large design project, we think organized wikis are more beneficial. As a result, we have suggested changes for further use of the wiki in a design course.

Finally, we think wikis have great potential for pedagogical research and learning assessment. If the students properly add content to their wikis, we can delve into how students approach and implement a design project. In addition, research can explore what factors affect group productivity and design quality. The content of the wikis can also be used as a way to assess proper application of previous course material.

Web 2.0 technologies like wikis have great potential in the classroom for the Net Generation. These technologies, however, should be used with caution. We as educators can't integrate these technologies into our classes simply because we want to seem novel and up-to-date, but we should integrate them if the desired result is to improve student learning. By doing studies like the one from this article, we can decide the best way to involve technology in lectures and teaching design. From this study, wikis were established as a good design tool, but changes must be implemented in the future to encourage their use.

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Design Course for
MICROPOWER GENERATION DEVICES

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The chemical engineering field of study is undergoing changes, with more focus on emerging areas in molecular chemistry and biology, product design, and micro- and nanotechnology. On the other hand, design courses are still considered the capstone of an undergraduate chemical engineering program. This article describes a recently developed course for the Department of Chemical Engineering at the Massachusetts Institute of Technology (MIT) and the Aachen Institute for Advanced Study in Computational Engineering Science (AICES) at the RWTH Aachen. The course considers the design of microfabricated fuel cell systems for man-portable power generation.

The term man-portable is defined as: capable of being carried by one person, typically over long distance, without serious degradation of the performance of that person's normal duties. Efficient alternatives to batteries for man-portable power generation are necessitated by the ever-increasing use of portable electric and electronic devices. The desired power level is in the order of 0.5 to 50W. There are several reasons for replacing batteries. In addition to their high cost and large life-cycle environmental impact, batteries have relatively low gravimetric (Wh/kg) and volumetric (Wh/l) energy density. State-of-the-art rechargeable batteries reach only a few hundred Wh/l and Wh/kg. Battery performance has significantly improved over the last decades, but it is believed that the upper limit on performance is being approached, because the list of potential materials is being depleted. A promising alternative is to use common fuels/chemicals such as hydrocarbons or alcohols as an energy source.

There is significant research activity in the area of microchemical systems.[1] Chemical units such as reactors, separators and fuel cells with feature sizes in the submillimeter range have been considered for a variety of applications, due to their advantages compared to macroscale processes, such as the increased heat and mass transfer rates.[2] The replacement of batteries for electronic devices requires man-portable systems and therefore the use of microfabrication technologies is plausible since a minimal device size is desired.

There is great military[3] and civilian interest in developing battery alternatives based on common fuels/chemicals such as butane. As a consequence, a lot of research projects have been undertaken in academia and industry (see, for example, References 4–6 for reviews). While there are well-established microchemical courses with emphasis on microfabrication, the author is not aware of any course with emphasis on process synthesis, process design, or optimization. Such a course is proposed herein; in addition to covering technological aspects of exciting topics (microchemical systems, fuel cells) it combines process and product design. This is important in view of recent trends for product-oriented design.[7–12] The course developed is based on several research publications of the Process Systems Engineering Laboratory at MIT.[13–21] In the

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remainder of the article, first the contents of the lectures are described in Section 1, and then the project tasks are summarized in Section 2. The article concludes with the skills gained by students, scope of improvement for the class, and summary of the experiences from teaching the class.

1. LECTURE CONTENTS

The course duration is six weeks, with three hours of lectures per week. No textbook is available for the course, but the material covered in Reference 6 is the primary reference. Other useful references are books on microchemical systems, design, and thermodynamics.[22-26] Approximately one week of lectures is reserved for software tutorials and discussions of issues raised by the students during the project execution. The remaining five weeks are devoted to five topics, namely the introduction and motivation, aspects of fuel cells, process synthesis, selection of alternatives, and process optimization. These topics are summarized in the following.

1.1 Introduction, Motivation, and Project Description

The first week of lectures is devoted to a description of the project as well as an introduction. These lectures are intended to give the students the big picture of the project and help them understand the goals of their tasks. First, the motivation for micropower generation is given. This is done by comparing the trends in power consumption by portable electric devices and electronics to the performance characteristics of batteries. Pricing and performance of batteries are discussed, along with their environmental impact. A common critique to fuel cell-based systems for micropower generation is that they are deemed too dangerous. To put these claims into perspective the safety issues of batteries (fire, explosions, etc.) are discussed and demonstrated by pictures and movies.

The next step in the introduction is the definition of the key metrics for man-portable power generation devices, namely the gravimetric and volumetric energy densities

$$e^{sys}_{grav} = \frac{\tau_{mission}\,PW}{M^{sys}}, \qquad e^{sys}_{vol} = \frac{\tau_{mission}\,PW}{V^{sys}}, \tag{1}$$

where the mission duration $\tau_{mission}$ (h) is the time between refueling or recharging, PW (W) is the power output (assumed constant for simplicity), M^{sys} (kg) is the mass of the system, and V^{sys} (l) is the volume of the system. These metrics are typically the objectives to be maximized by the process synthesis design and operation. In cases where the mission duration is very long and the device miniaturized, the size of the system is dominated by the fuel cartridge, in which case the simpler metrics of fuel energy density can be used:

$$e^{fuel}_{grav} = \frac{PW}{3600\sum_i MW_i N_{i,in}}, \qquad e^{fuel}_{vol} = \frac{PW}{3600\sum_i MV_i N_{i,in}}, \tag{2}$$

where $N_{i,in}$ (mol/s) is the inlet molar flowrate of species i, MW_i (kg/mol) is the molecular weight of species i, MV_i (l/mol) is the molar volume of species i at storage conditions, 3600 is the conversion factor from hours to seconds, and the summation is taken over all stored fuels and oxidants.

In man-portable power generation the most important advantage of microfabrication is device miniaturization. Microfabrication techniques are outside the scope of the course. On the other hand, various examples from microchemical systems are analyzed with emphasis on entire systems as opposed to components. The importance of physical phenomena at the microscale is analyzed and compared to the macroscale; for instance, it is shown that viscous forces dominate over inertial forces and that heat transfer (and loss) has much more importance than in the macroscale. Various alternatives for man-portable power are summarized, such as microturbines[27] and devices based on man-power.[28]

A common critique of micropower generation devices, and particularly of high-temperature systems, is that they pose safety threats and generate a lot of heat. These concerns are analyzed via back-of-the-envelope calculations. It is argued that these concerns are partially true and partially misconceptions resulting from macroscale experience. The high energy density of the fuels is of concern, as is the use of toxic fuels. On the other hand, the use of high-temperature devices is not a safety hazard, because of the low heat capacity and the insulation.

1.2 Fuel Cell Working Principles and Types

Both the batteries and the fuel cell systems studied, *i.e.*, the product to be replaced and the proposal for replacement, rely on electrochemical reactions. Electrochemistry is covered in some undergraduate curricula, but not in sufficient detail for performing and understanding the project tasks. Therefore, the principles of fuel cells are briefly summarized, along with a repetition of the relevant concepts from reactor engineering and thermodynamics. Then, the thermodynamic limits of fuel cell performance are analyzed and compared to heat engines.

Several fuel cells technologies have been proposed over the last decades. Some of the fuel cell types have a potential for scale down, such as solid-oxide fuel cells (SOFCs), polymer-electrolyte membrane fuel cells (PEMFCs) operating with hydrogen, direct methanol fuel cell (DMFC), proton ceramic fuel cells (PCFC), and membrane-less fuel cells, *e.g.*, References 29–31. Miniaturization has been performed for some of the fuel cell types, often with the use of microfabrication technologies. These fuel cell types are analyzed with an emphasis on advantages, disadvantages, and operating characteristics.

1.3 Conceptual Process Design at the Macroscale

Process synthesis at the macroscale is typically included in undergraduate curriculum. In the proposed course a brief summary of the techniques and methodologies is given, with emphasis on superstructure-based approaches.[25] This is deemed helpful for the students to be able to compare the challenges with the selection of alternatives at the microscale. For instance, the discussion of heat exchanger network synthesis demonstrates that at the microscale the challenges are very different: no utility streams are available, and the operating conditions of various components are not independent from each other due to the pronounced heat transfer. In addition, having this short summary allows students from different disciplines to attend the course. The lectures also briefly discuss some of the mathematical and algorithmic background used in conceptual process design. The emphasis is on the material that is relevant to the project tasks.

1.4 Selection of Alternatives

A major challenge in the system design of micropower generation processes is the selection of alternatives, in particular which fuel to use for power and/or heat generation, what fuel cell type to select, whether a fuel reforming path should be followed and how heat integration should be performed. This selection of alternatives at the microscale is analogous in principle to macroscale process synthesis. Moreover, some of the mathematical techniques used in macroscale process synthesis can also be used for the selection of alternatives. There are several major differences, however, including different objectives and constraints and the fact that the unit operation paradigm must be replaced by that of highly integrated components in a system.[32] An additional challenge is the early stage of technology development.

The lectures describe the large number of alternative processes arising from the large choice of fuels, fuel reforming reactions, and fuel cells. The advantages and disadvantages are discussed and a system-level approach for modeling is detailed.[13, 14] This modeling approach is then used in one of the projects offered, see Section 2.1. The advantage of this methodology is that the most promising alternative(s) can be selected without detailed knowledge about the technological details, such as the catalysts used or the reactor configuration. The disadvantage is that some parameters, which in principle can be calculated, are viewed as input parameters—*e.g.*, the fuel conversion in the reforming reactor for a given operating temperature and residence time.

1.5 Optimization of a Given Process Alternative

Once a promising alternative has been chosen, the design and operation can be optimized via models of intermediate fidelity.[15-19] The spatial discretization results in problems with (partial) differential-algebraic equations. The models employ spatial discretization when necessary and are based on first-principle models. As a consequence they are predictive and can be used to find the optimal sizing of units (reactor, fuel cell, etc.) as well as operating variables (voltage, temperature, flowrates, etc.). A drawback is that the development of such a model takes significant effort and requires knowledge of kinetic rates.

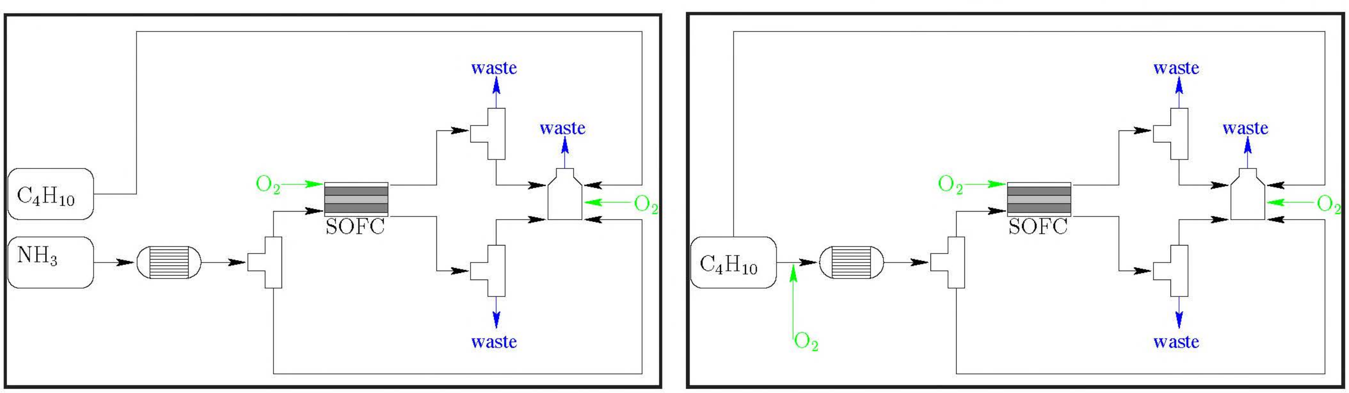
For the optimization of design and operation, algorithms from mathematical programming with differential-algebraic equations (DAEs) embedded can be used. These techniques are briefly described in the lectures along with techniques for the simulation of DAE systems. The state-of-the-art in dynamic optimization, however, is such that the use requires significant mathematical background and computational experience, and is deemed limitedly suitable for an undergraduate class in chemical engineering. Instead, in the project (Section 2.2) the optimization is based on a simulation approach, in which the students must specify the degrees of freedom. To simplify the problem, some variables (such as the operating temperature and voltage) are prespecified. On the other hand, to give some experience in the use of advanced methods, the simpler problem of parameter estimation is given as a subtask to be solved with an optimization algorithm.

2. DESCRIPTION OF PROJECTS

Two alternative projects are offered. The recommendation is to offer these in alternate years. Offering both projects in parallel (to different groups of students) is also possible, however it complicates logistic considerations significantly, since the material necessary for the project must be covered in class prior to the project assignment. A third alternative would be to assign both projects, and extend the course duration.

2.1 Selection of Alternatives

Two main processes are considered, see Figures 1. Both are



Figures 1. *Process flow sheets for project on selection of alternatives.*

based on a solid-oxide fuel cell (SOFC); one of them uses NH_3 as the fuel for power generation while the other uses C_4H_{10}. All units are modeled using stoichiometric reactors, *i.e.*, a fixed conversion is assumed for each reaction. As a consequence, relative rough estimates for the process performance are obtained; however, these estimates are sufficient for a comparison of alternatives. All units are microfabricated on a single silicon chip; as a consequence they share the operating temperature of T = 1000K. The entire process operates at ambient pressure. The gas phase is assumed to be ideal. A power production of 10W is requested. The enthalpy of the inlet streams is calculated at ambient conditions and the gaseous phase. For the outlet streams a temperature of T_{out} = 600K is assumed, based on heat recovery.

The models for the processes are given to the students as a Jacobian[33] input file. The students must perform additional calculations, such as the calculation of energy density based on the calculated flow rates. For these calculations the students have the choice of using Jacobian or a software tool of their choice.

2.1.1 Project Tasks

The first task is to optimize the processes based on NH_3 and on C_4H_{10}. The operational variables are the flow rates of fuel and the split fractions in the 3 splitters. The flow rates of air are a direct consequence of the fuel flow rates and a specified stoichiometric ratio. The objectives are to maximize the volumetric and gravimetric energy density; the device mass and volume can be ignored, but the fuel cartridges must be accounted for.

The second task is to compare the optimized processes with a conceptual process based on methane, stored at ambient temperature. An overall efficiency (power produced divided by chemical energy consumed) of 50% is assumed. The main challenge is to calculate the required cartridge thickness and volume as a function of pressure for various container types, *e.g.*, plastic or steel.

The third task is to compare the optimized processes with a process based on an H_2 generator, such as a hydride. The goal of this task is to identify the storage properties (hydrogen volume % and density) required to match the best process in terms of both gravimetric and volumetric energy density. To do so, an overall efficiency of 70% is assumed.

2.2 Optimization of NH_3-Based Process

The project task is to optimize a micropower generation device for the production of PW = 10W. A fixed process is considered based on NH_3 cracking to H_2 and electrochemical oxidation of the produced H_2 in a solid-oxide fuel cell (SOFC). The device comprises two parallel lines, namely the NH_3 line for power generation and the C_4H_{10} line for heat generation, see Figure 2. These two lines are not independent, because they are microfabricated in a single silicon chip; as a consequence they share the operating temperature of 1000K. The entire process operates at ambient pressure. The gas phase is assumed to be ideal. The model considers one-dimensional spatial discretization and a kinetic model for the catalytic reactions. All assumptions for the model have been shown to be valid (see Reference 15).

2.2.1 Project Tasks

The first project task is to determine appropriate values for the constants in the kinetic rate of NH_3 cracking, by fitting to a set of experimental values. The students are given a postulated kinetic mechanism along with experimental data of conversion as a function of residence time for four different temperatures. The kinetic mechanism has two adjustable parameters and the data contain random error. The students must extend an example provided to them. This task is relatively simple, thanks to the estimation capabilities of Jacobian.

The main task of the project is to maximize the energy density of the device; this is done by optimizing the volumes of the device components and the flowrates of fuel and air. There are four design variables, namely the volumes of the reactor, SOFC, hydrogen burner, and butane burner. In addition, there are also four operational variables, namely the feed flowrates of fuel (NH_3 and C_4H_{10}) and air (to the SOFC and to the butane burner). The temperature and voltage have been fixed. The optimization is a challenging task, in which the students can only succeed if they employ a systematic procedure for varying the variables. The achievable energy densities are significantly higher than in state-of-the-art batteries; however this requires successful optimization of the process design and operation.

The final task is to analyze potential improvements to the process. This analysis includes the comparison of the chosen process configuration with alternatives, such as using stored oxygen and having a fresh-air stream to the burner instead of using the cathode effluents. The students are also asked to comment on the effect of increasing or decreasing the temperature and the voltage. The process relies heavily on catalysts, and not surprisingly the performance of catalysts significantly

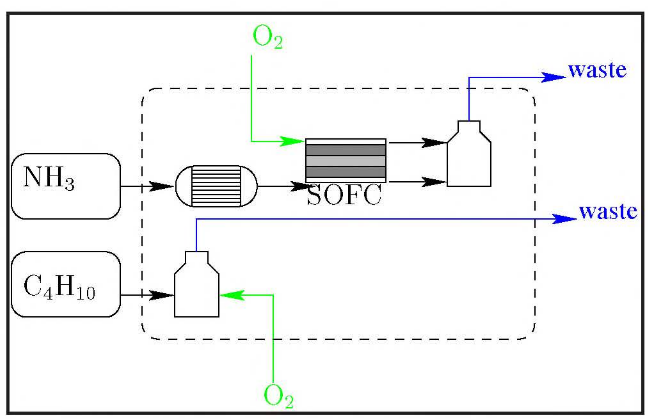


Figure 2. *Process flow sheet for project on process optimization.*

affects the overall process performance; the students are asked to identify which component is the most important to optimize (reactor, burner, or fuel cell). Finally, the students are asked to explain how a doubling of the desired power demand level will affect the process design and operation.

3. CONCLUSIONS

A new course on the design of microfabricated fuel cell systems is offered for chemical engineering students.

The course is project-based and spans six weeks. The theoretical material needed for a successful project execution is covered in three lectures per week, each one-hour long. The students learn several skills through the lectures and project. Likely the most important skill is learning how to work in a team, as in any course based on group projects. The most important technical skills are process and product design, and in particular their interaction. The students have a chance of integrating the knowledge acquired in their preparatory classes, especially thermodynamics and reactor engineering. Finally, the students are familiarized with the exciting technologies of fuel cells and microchemical systems.

The course was developed for chemical engineers. The class was first offered in Spring 2008 at RWTH Aachen. The format of the class was a seminar for graduate students with backgrounds in mechanical and chemical engineering. Approximately five students attended the lectures, which is a typical size for seminars. No project was offered. The full class, including the project, is currently offered at MIT. It is one of the elective modules in Integrated Chemical Engineering. More than 20 students, corresponding to approximately one third of the class, chose this module. This is a success, given that the course is offered for the first time. Class evaluations are not available yet, but the preliminary informal feedback from the students is also very positive. A potential extension would be to aim at interdisciplinary class. In particular it would be interesting to consider teaching joint classes in chemical, mechanical, material, and electrical engineering.

In the lectures and project, material and structural considerations are taken into account as simple constraints, *e.g.*, a maximal operating temperature. It would be interesting to incorporate the interaction of these considerations with process design and optimization more thoroughly. This is currently not possible, since the effect has not been examined sufficiently in the literature. Moreover, incorporating such structural and material considerations in a chemical engineering class would be very challenging.

A common critique of micropower generation devices, and particularly of high-temperature systems, is that they pose safety threats and generate a lot of heat. These concerns are analyzed via back-of-the-envelope calculations. It is argued that these concerns are partially true and partially misconceptions resulting from macro-scale experience.

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IDEAS TO CONSIDER FOR NEW CHEMICAL ENGINEERING EDUCATORS

Part 1. Courses Offered Earlier in the Curriculum

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Although teaching is a critical mission of any college or university, today's faculty members are increasingly becoming involved in other scholarly activities. Thus, when teaching a new course, developing a good set of instructional materials can be a challenging, time-consuming task. In this paper we provide a review of some of what we consider the best practices in engineering education, applied to the following courses: Freshman Chemical Engineering, Material and Energy Balances, Fluid Mechanics, Introductory Thermodynamics, and Separations. Note that a companion paper covering those chemical engineering classes that normally occur later in the curriculum is planned.

The format used for each course is:

- ▲ *Brief description of typical course content*
- ▲ *Discussion about novel and successful methods used, including best practices and new ideas*
- ▲ *Listing of "toughest concepts" for the students (and how to address them)*

We note that most of this material was originally presented

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by the authors at the 2007 ASEE Chemical Engineering Division Summer School in Pullman, WA.[1] This work was originally published (and also presented) at the 2008 ASEE Annual Meeting[2] as paper number #AC 2008-1147.

FRESHMAN CHE COURSE

Depending on the school, this course is either a "stand-alone" introduction to chemical engineering or is part of a college-wide introductory course (with a portion devoted to chemical engineering). Ironically, many chemical engineering educators may never have taken such a course.

A major goal of the course, since it is for freshmen, should be to cultivate student interest in engineering[3] and motivate students to pursue an engineering career. This course can have a wide variety of formats, depending upon the number of credits and objectives of the course for a particular institution. For example, Brigham Young University has a three-credit course that introduces (via an integrated design problem) all of the aspects of the chemical engineering curriculum,[4] while Tennessee Technological University has a one-credit course that focuses more on hands-on experiments and information exchange.[5] Whatever the course, it is important for a department to identify why they have introduced or are teaching such a freshman course and whether (via specific assessment) the goals and objectives of the class are being met, from both the faculty and student standpoint.

In the rest of this section, we briefly highlight (as a resource) some of the novel work available on freshman courses in chemical engineering.

Best Practices / New Ideas

Some best practices that we have used (or discovered) for this course are:

- ▲ *The use of freshman design projects:*
  - *Design an economic analysis of a controlled-release nitrogen fertilizer plant*[6]
  - *Design, build, and test an evaporative cooler*[7]
  - *Design and build a pilot-scale water treatment plant*[8]
  - *Analyze and design sneakers with better material properties*[9]
- ▲ *Introduce in-class, hands-on experiments:*
  - *Melting chocolate and coating cookies*[10]
  - *Electrophoresis and brewing with microreactors*[11]
  - *Heat transfer scaling with hot dogs*[5]
  - *Human respiration process*[12]

One overlooked concept in designing this course is to consider the needs of the student from the *student* perspective. Recently, the University of Pittsburgh asked their freshmen engineering students to conduct a survey of other first-term freshmen engineering students on topics the students felt were important.[13] While the results of the surveys are interesting in their own right, the most useful result is the types of surveys the students developed. The top 10 types of surveys were as follows:

1. *Getting enough sleep?*
2. *Has high school prepared you for college?*
3. *Do you feel safe on campus?*
4. *Any new romantic relationships?*
5. *Is partying getting in the way of schoolwork?*
6. *Exercise more or less than in high school?*
7. *Homesick?*
8. *Favorite campus food options?*
9. *Susceptible to doing drugs / alcohol now?*
10. *Confidence in time-management skills?*

It is noted that there is nothing about a student's major listed in the top 10. Thus, a freshman engineering course requires a balance between what an instructor knows (or thinks) that a student needs, and what the students think they need. Therefore, while a freshman chemical engineering course must (obviously) contain information about the field of chemical engineering, it should also find ways to address non-chemical engineering related issues as well. Here, ample use of guest speakers in Counseling Services or similar offices on campus should be explored.

In addition to what has been discussed above, other ideas in freshman chemical engineering courses exist as well. Roberts discusses a course that focuses on, among other areas, communication skills.[14] Worcester Polytechnic Institute looks to mix writing with first-year engineering in a course shared by a ChE faculty member and a Writing faculty member.[15] Vanderbilt University describes a course where students are introduced to chemical engineering by "using examples from cutting-edge research to illustrate fundamental concepts."[16] At Youngstown State University they are demonstrating combustion principles to chemical engineering (and non-chemical engineering) students using a potato cannon.[17]

Trouble Spots

Trouble spots for this course include:

- ▲ *Most students do not know what chemical engineers do—one idea is to have teams of like-minded students investigate where chemical engineers work in a particular field. Each team will present this information to the rest of the class at the end of the semester. Also, The Sloan Career Cornerstone Center*[18] *has short "Day in the Life" interviews with various young chemical engineers in a wide variety of industries that are quite informative at emphasizing the diversity of career options accessible for B.S. chemical engineering graduates.*
- ▲ *Most students have only a vague idea as to why they are taking math—one idea is to have upperclassmen come into the class and tell them how they are using math in their courses. In fact, using upperclassmen as much as*

possible during the semester is a good idea as it indoctrinates the students more easily into the program.

- ▲ *Many students struggle with the transition from high school—one idea is to use upper-class peer mentors or speakers from on-campus who can discuss student-relevant issues. Having students conduct their own surveys, as discussed in a previous section of this work, might identify the most important issues for your students.*

MATERIAL AND ENERGY BALANCES

This course may also be called the Stoichiometry or Process Principles course by faculty. Students may refer to it as a weed-out class as some students drop and switch majors during or after completing the course. Much of this perception may be because it requires students to think at a higher level than in previous courses. A typical course will cover: units and dimensions, properties, measurements, phase equilibria, material balances, energy balances (nonreactive and reactive systems), and combined mass and energy balances. The course should prepare students to apply conservation laws to process simulation as the first source of modeling equations. The course is the foundation for the rest of the curriculum—it is all about planting seeds for the future!

Best Practices / New Ideas

Some best practices and useful tools that we have used (or discovered) for this course are:

- ▲ *Emphasize importance of communication in problem solving.[19] Requiring students to submit a solution or two that meets corporate standards can be a useful exercise in developing students' communication skills. Overuse of such a requirement can distract from the problem-solving objectives, so use sparingly.*
- ▲ *Teaching by analogy.[20] Using simple analogies for explaining confusing topics such as mass/mole fractions, steady-state, specific volume, saturated air, and others can help students grasp topics that might elude them from lecture and reading alone. Analogies provide a link between what the student already knows and what you are trying to teach them.*
- ▲ *Mass and energy balances on the human body.[21] In this module students are asked to measure flows and compositions using a medical gas analyzer while exercising and at rest. They then apply several ChE fundamental principles (ideal gas law, partial pressure, stoichiometry, relative humidity, heat of reaction, work, efficiency, and process simulation) to analyze their results.*
- ▲ *Starting the unit operations early in the curriculum.[22] The equipment is already in the laboratory, so why not use it within the material and energy balance course? This allows for introduction of measurement, application of conservation laws, and an introduction of the fundamentals of design. Any time students can apply knowledge to a real task, they learn better.*
- ▲ *Incorporating programming with templates.[23] Programming is an effective way of teaching students numerical methods. The problem with programming is that it often has significant overhead (input/output, user interface, etc.) that has nothing to do with the objectives of an assignment. Using templates, or "almost finished" programs lacking only the numerical method code, enables students to focus on implementing the numerical method and concentrate on the learning objectives for the assignment.*
- ▲ *Student-centered teaching.[24-26] These references provide a host of suggestions for the material and energy balance course, including: developing a well-structured team approach to homework, posting homework answers (but not solutions), giving open-book exams, and developing clear objectives and exam study guides to aid in student learning.*
- ▲ *Psychrometric chart applet.[27] This applet allows the user to calculate properties of humidified air, and helps students understand how to use the psychrometric chart. It also frees up valuable lecture time when assigned to students to study on their own and then assessed through in-class active-learning exercises.*
- ▲ *Richard Felder's* Resources in Science and Engineering Education. *This is a popular site containing a link to the stoichiometry course taught by the textbook[29] co-author. The site also contains links to Excel tutorials.[30] Furthermore, there are many links to information on using active learning in your courses.*
- ▲ *Graph paper Web site.[31] Assuming you still expect students to learn fundamentals of graphing such as use of logarithmic axes, these papers will come in handy.*

Trouble Spots

Trouble spots for this course include:

- ▲ *Reluctance to show work. Students should be required from the start to show clean, detailed solutions even on the easiest problems assigned earlier in the class. Significant point deductions for deviations early in the course help train students to clearly communicate with their problem solving.*
- ▲ *Reluctance to apply rigorous methods to simple problems. The grader must pay attention to the method and not just the final answer. Requiring students to start from the general material balance even on problems that can be solved intuitively will aid students in solving more complex problems later in the course.*
- ▲ *Misunderstandings about density / specific volume and* g_c. *Repetition, drills, quizzes, and clear examples help to clear up some of these common misunderstandings. Warning students that these can be challenging issues may help a few pay more attention. Keeping a reference page at the beginning of their notebook or in the cover of the textbook with notes on these and other key subjects can also help.*
- ▲ *Trouble with thermodynamic diagrams. Students will not grasp these diagrams without working with them.*

One approach is using online interactive tutorials. Another effective approach is to bring copies of charts (even if they are in the text) for students to use in working problems either with the instructor, or better still, in small groups. They will only learn how to use these charts if they practice using the diagrams.

▲ *Reluctance to apply rigorous methods to simple problems. Yes, this problem is significant enough to mention twice.*

▲ *Lack of integration of "old" material into subsequent chapters. Students are going to tend to compartmentalize knowledge from each chapter (or each homework assignment, each exam, etc.) and not internalize the concepts into their problem-solving repertoire. Blending lectures in a manner that bridges the chapter divide, using problems that draw extensively on previous topics, and even giving quizzes on material covered earlier in the course can help develop anchors to key elements in a course as they move on to new topics.*

FLUID MECHANICS

Fluid Mechanics has an interesting history within chemical engineering programs.[32] It developed from steam and gas technology for industrial chemistry and chemical engineering needs. From this evolved Unit Operations, which helped make chemical engineering a unique field. Meanwhile, fundamental studies in fluid mechanics were quite popular (and remain so) in the literature. This research work became integrated into the chemical engineering curriculum mostly due to the *Transport Phenomena* text.[33]

Best Practices / New Ideas

One major advantage of teaching a course in fluid mechanics is the visualization that could be easily brought into this course. Some best practices that we have used (or discovered) for achieving this in the fluids course are:

▲ *Ford's paper on "Water Day"[34] developed several observation stations so that students can visualize continuity, the Bernoulli equation, conservation of linear momentum, the vena contracta effect, and relative and absolute velocities.*

▲ *Incorporate high school outreach into the course*
- *Using pressure concepts[35]*
- *Using a tank-tube viscometer experiment[36]*

▲ *Use unit operations and/or research laboratories*
- *Unique experiments have been developed by Fan[37] who discusses flow surrounding a bubble, two-phase theory, flow segregation, phenomena of bubble-wake dynamics, and computational fluid dynamics of particulate systems).*
- *Particle technology is a field that offers a large number of simple experiments that can be brought into the classroom.[38] These include wet-powder systems (single-particle settling, hindered and lamella settling, sedimentation and flocculation, interparticle force effects on colloidal suspension rheology, wetting behavior of dry powders, and granulation coalescence behavior) and dry particle systems (hopper flow, consolidation effects of powder flow, particle dilation, wall friction, segregation during hopper flow, vibrational segregation, fluidization, and flow improvement due to powder agglomeration). There are also a CD[39] and Web site[40] available with additional powder-technology education information.*
- Golter, et al.,[41] *have developed a methodology to teach students fluid mechanics and heat transfer inductively. Many of their modules are see-through to aid in visualization. These include Reynolds dye/flow-through clear pipe, pressure drop through fittings and valves, flowmeters (Venturi, orifice, and Pitot tube), extended surface heat exchangers, kettle boiler / steam condenser, 1-2 shell and tube heat exchanger, fluidized bed (compressed air through sand), and a double-pipe heat exchanger.*
- Wright, et al.,[42] *introduced bioseparations through a three-part laboratory experiment. This includes bed expansion characterization under fluidization conditions, tracer studies, and protein adsorption studies.*
- *Other experimental unit operations that could be demonstrated include agitation and aeration,[43] solid/liquid and liquid/liquid mixing,[44] and compressible flow analysis.[45]*

▲ *Use fluid mechanics videos from the Web*
- *Most notable is the "Fluid Mechanics" video series starring Prof. Hunter Rouse of the University of Iowa. These videos are available online at the Iowa Web site.[46] General topics include the introduction to the study of fluid motion; experimental principles of flows; characteristics of the laminar and turbulent flows; fluid motion in a gravitational field; form drag, lift, and propulsion; and effects of fluid compressibility.*
- *There is also the "National Committee for Fluid Mechanics Film Series"[47] with sample topics: aerodynamic generation of a sound, cavitation, channel flow of a compressible fluid, deformation of a continuous media, Eulerian Lagrangian description, and flow instabilities.*

▲ *Use commercially available software*
- *Computational Fluid Dynamics (CFD) case studies in the fluids course[48] and for fluid-particle flow[49]*
- *COMSOL modules for fluid dynamics and heat and mass transfer applied to fuel cells[50]*
- *Use of Mathematica[51] to analyze non-Newtonian flow systems*

Trouble Spots

Trouble spots for this course include:

▲ *Students may possess weak math skills. Instructors can develop handouts to step students through difficult* solution processes (such as solving differential equations). Have them practice with in-class problems and homework before testing them.

- ▲ *Difficulty in connecting highly theoretical content to real industrial applications—if there is an Internet-connected computer and projector in the classroom, instructors can use online and/or laboratory demonstrations to make a strong connection. This connection can also help students with their subsequent classes.*
- ▲ *Students often do not know order-of-magnitude values for pressure drops, velocities, Reynolds numbers, etc. The teacher can provide them with general values on a handout they can paste in the front of their textbook.*
- ▲ *Students struggle with when to eliminate terms in the governing equations. If they are provided with handouts to step them through difficult solution processes (such as solving differential equations), they will be prepared for more advanced homework and exam questions.*

INTRODUCTORY THERMODYNAMICS

This course is normally the first of two thermodynamics courses where fundamental thermodynamics concepts are introduced (first and second law of thermodynamics) while solution properties are normally not discussed. Processes and equipment are emphasized, including various thermodynamic cycles and the analysis of their components (turbines, compressors, throttling valves, etc.) The course enrollment can also include non-chemical engineering students, so the instructor must also be aware of issues that mechanical or civil engineers may encounter in their careers.

German Physicist Arnold Sommerfeld said it best when discussing the topic of thermodynamics:

> *"Thermodynamics is a funny subject. The first time you go through it, you don't understand it at all. The second time you go through it, you think you understand it, except for one or two small points. The third time you go through it, you know you don't understand it, but by that time you are so used to it, it doesn't bother you anymore."*

Best Practices / New Ideas

The subject of thermodynamics can be confusing due to a number of issues, but most notable is the lack of an intuitive feel for certain integral concepts, such as entropy, internal energy, fugacity, chemical potential, etc. Recently one of us observed, in research involving student-prepared study guides, that entropy and the second law of thermodynamics are the most confusing topics. In fact, students did not put much information, if at all, on their study guides for these two topics—not because they were comfortable with them, but because they had a poor understanding of the topics. This manifested itself in exam scores on problems with these concepts.[52]

One way to connect this concept for students is through unique, nonlecture methods. Kyle discusses the mystique of entropy, applied to a wide range of fields including cosmology, time, life, and art.[53] Müller integrates second law concepts into common life experiences and economic theories.[54] Foley presents a view of entropy as a quality of energy degraded.[55] There are also newer thermodynamic terms that are gaining in popularity, including exergy (maximum work done by a system that brings it into equilibrium with a reservoir) and emergy (the cost of a process or product in solar energy equivalents).

If chemical engineering (or any engineering) faculty were to work with calculus instructors to provide context to some of the math (students) are learning, this could potentially mitigate the need for the remedial work when students arrive in the classes that depend on this knowledge.

Another problem that students face with thermodynamics is the strong importance placed on the use of differential calculus concepts. While students have normally been exposed to all of these concepts in their calculus sequence, the act of placing it in a thermodynamic context often proves a significant barrier. Working with F=F(x,y) is, seemingly, different from working with P=P(T,v). Accordingly, the thermodynamics instructor has two options. The first involves re-teaching the fundamental concepts of differentials, partial derivatives, meaning of integrals, etc. within the thermodynamics course. The second is to work with the people who are teaching students these math concepts, which are Mathematics Department faculty members. If chemical engineering (or any engineering) faculty were to work with calculus instructors to provide context to some of the math they are learning, this could potentially mitigate the need for the remedial work when their students arrive in the classes that depend on this knowledge.

Other new ideas associated with this course include:

- ▲ *Incorporation of biological concepts in addition to traditional chemical engineering examples. For example, Haynie[56] describes the irreversible increase in entropy involved in how a grasshopper jumps. Additional problems are available in this area as part of the Bioengineering Educational Materials Bank.[57]*
- ▲ *Development of a Personalized Class Binder[58] that requires students to put class notes, handouts, in-class problems, quizzes, exams, and homework into a binder. The binder is graded at various points during the semester. Students are also required to rewrite or type*

the notes neatly for inclusion in the binder and to show reworked exams, quizzes, and homework. Finally, the binder will include brief biographies of the scientists mentioned in the course, which goes toward humanizing the subject matter.

- ▲ *Creative Expression Day, where students make posters to be placed above the chalkboard that contains various concepts or formulas important for the course. Students can then easily "view" this information during the whole semester.*
- ▲ *Extensive use of* NIST WebBook *for data to perform any of a number of comparisons of involving polar and nonpolar substances.*[59]
- ▲ *Earlier presentation of power cycles (such as Rankine) as motivation for studying and contextualizing turbines, efficiency, latent heats, etc.*

Do note that many articles in the journal *Chemical Engineering Education* have been written on thermodynamics problems, especially in the "Class and Home Problems" section. Some notable ones include a powerful example on energy consumption relating the second law, by Fan and colleagues[60]; an open-ended design estimation problem from Lombardo[61]; and the description of an experimental vapor-liquid equilibrium laboratory at the University of Delaware.[62]

Trouble Spots

Trouble spots for this course include:

- ▲ *Difficulty comprehending the second law of thermodynamics. One idea is to use the statistical nature of entropy as an introduction as well as the works of Foley*[55] *and Fan.*[60]
- ▲ *Difficulty translating concepts of mathematics into this course. Rather than assume knowledge of differentials, partial derivatives, etc., spend some time to remind students of these concepts.*

EQUILIBRIUM-STAGED SEPARATIONS

This course typically combines steady-state material and energy balances with phase equilibrium to form the student's first experience with equipment design. Students apply equilibrium relationships to the design of staged separations equipment. Typical operations include flashes, cascades, absorption, stripping, binary distillation, and extraction. This course may also cover rate-based processes such as membranes, adsorption, and ion exchange.

Graphical methods are used to learn conceptual relationships and for order-of-magnitude design. Analytical methods are then used as rigorous design tools and provide a foundation for simulation.

Best Practices / New Ideas

Some best practices that we have used (or discovered) for this course are:

- ▲ *Ask the experts. Sometimes we do not teach the courses for which we have the most relevant experience. Both* Chemical Engineering Progress[63] *and* Chemical Engineering Magazine[64] *routinely publish relevant articles on separations applications. They are often written at a level that students can understand better than their textbooks.*
- ▲ *Bring in the history of the field.*[65] *Separations have been performed for millennia. The earliest recorded use of distillation dates back to 50 B.C.; it was used in the 12th century for ethanol processing; and in the 16th century it was widely used for perfumes, vinegars, and oils. Occasionally interrupting terribly interesting technical lectures with historical anecdotes can renew students' interest in a lecture while giving them perspective on their current course of study.*
- ▲ *Use literature from industrial suppliers.*[66] *Many manufacturers and distributors of industrial equipment have useful applications papers describing not only their equipment in particular but general concepts as well. A Web search will easily find vendor articles such as "Factors Affecting Distillation Column Operation," "Evaporator Handbook," and "Liquid-Liquid Coalescer Design Manual." These are also written at a very accessible technical level.*
- ▲ *Wankat's "Why, What, How?" approach. Establish why you're teaching something (economics, core of chemical engineering), what exactly you're teaching (equilibrium staged separations), and then teach it using best pedagogical practices (lecture with simulation labs, inductively structure the course, using both graphical and then analytical methods, and then reinforce with laboratory exercises and design projects).*[67] *This process should lead to a deeper understanding of the subject.*
- ▲ *Levels of understanding.*[68] *Dahm combines Wankat's approach with Haile's Special Hierarchy of understanding to give a specific possible formulation of the levels of understanding in teaching separations.*
- ▲ *Separations using spreadsheets.*[69] *Working with students to develop an analytical approach to graphical separations on a spreadsheet forces a connection between the graphical methodology and the theoretical underpinnings. Automating shortcut separations develops an understanding of what is required to be known in what order.*
- ▲ *Use of commercial simulation.*[70] *Use of commercial simulators in the classroom enables a range of inductive exercises to be incorporated into a course. Instead of performing time-consuming laboratory exercises (which do have an esteemed place in the course) to explore a piece of equipment, experiments can be performed virtually with the simulator, enabling students to observe results and draw conclusions. When the theory is later discussed, students have a framework of understanding whereby they can assimilate the salient points of the discussion.*

Occasionally interrupting terribly interesting technical lectures with historical anecdotes can renew students' interest in a lecture while giving them perspective on their current course of study.

Trouble Spots

Trouble spots for this course can include:

- ▲ *Reluctance to show work; reluctance to apply rigorous methods to simple problems; trouble with thermodynamic diagrams. These are problems encountered in earlier courses and they have been discussed in the Material and Energy Balances portion of the paper.*
- ▲ *Looking for "answers" instead of trends. Students often fail to see that the point of solving model equations (outside of homework and exams) is not to find a particular number. Models are always approximations or subject to other forms of error. The real value of models is in simulation to determine answers to questions such as "What happens if my flowrates vary +/- 50%" or "What would be the effect of a malfunctioning thermocouple?"*
- ▲ *Expecting rigor in graphical approximate solutions. You will need to constantly remind and reinforce the fact that assumptions are being made throughout the course. Some of the assumptions may not be significant (equimolar counter diffusion for a binary distillation with similar substances) or may change the character of the entire separation (use of inappropriate thermodynamic models).*
- ▲ *Disconnect between theory and simulators. If students do not learn how to use a process simulator for separations as they learn theory, they will have difficulty reconciling the terminology used in their text and the input fields in the simulator. Fostering that connection throughout the course makes use of simulators more effective.*

USE OF ACTIVE LEARNING

The authors are all advocates of using active learning within their courses. As such, a brief background and listing of simple ideas on how to integrate active learning into a core chemical engineering course is provided.

Studies have shown[71-75] that students typically learn best in an active mode; however, engineering is usually taught as lectures. The use of active learning is underscored in teaching textbooks[71-72] and those intended for the new professor[73] as well as in numerous conference proceedings and engineering education archival publications. A good listing of references is presented by Smith[74] and by Dyrud.[75]

A great deal of information on improving student-teacher interaction through active learning is presented at the National Effective Teaching Institute (NETI)[76] and the Excellence in Engineering Education (ExcEEd)[77] workshops. One former attendee and active learning advocate is Ken Reid, who highlighted the positive experiences in his classroom,[78] and summarized simple ways that faculty can increase active and collaborative learning in their lectures and within the laboratory.[79]

Improving student motivation may also improve learning, as was recently illustrated by Newell—who developed a game based on the reality television show *Survivor* within a material and energy balance course.[80] Newell referenced the student motivation classifications of Biggs and Moore[81]:

1. *Intrinsic—learning because of a desire to learn*
2. *Social—learning to please others*
3. *Achievement—learning to enhance one's position*
4. *Instrumental—learning to gain long-term rewards*

Game-based active learning exercises certainly address the social and achievement components of Biggs and Moore.[81] In his study, Newell[80] found that the *Survivor* game addressed all four motivation categories and improved student learning.

There are other quiz shows and contests that can be used within the classroom. The chemical engineering education literature has described ways to integrate formats from game shows and games such as *Jeopardy*, "Trivial Pursuit,"[82] and *Hollywood Squares*,[83] as well as offered professor-created games such as "Green Square Manufacturing,"[84] "True Blue Titanium Game,"[85] "Chemical Engineering Balderdash,"[85] and the "Transport Cup."[86] Most of these games usually only address the knowledge or comprehension component of Bloom's taxonomy.[87]

Other simple-to-use active-learning methods include:

- ▲ *Think-pair-share—think for 1-2 minutes, talk with neighbor for 1-2 minutes, then share answers with the rest of the class*
- ▲ *Poll the audience—with a show of hands, colored notecards, or clickers*
- ▲ *Minute paper—the students write down 1-2 ways to do something, then the instructor solicits answers from the students. This is also a good way to get anonymous feedback on the course content, what the "muddiest" point of a lecture is, etc.*
- ▲ Engineering Education *articles from Rich Felder[28]—this site highlights recent teaching methods that have been proven to improve student learning*

CONCLUSIONS

This paper has described some of the best practices for use in the chemical engineering courses that traditionally occur earlier in the curriculum: Freshman Chemical Engineering, Material and Energy Balances, Fluid Mechanics, Introductory Thermodynamics, and Separations. A common thread is deviation from the traditional lecture format. When this happens, the students are given the opportunity to take ownership of their own learning. Popular methods include the use of in-class demos, hands-on activities, tours of the unit operations lab, and seeing a movie or simulation of a concept. Additionally, the softer skills of engineering are finding their way into the classroom, with the most popular ones being an increased emphasis on communication and on teamwork skills. It is noted that it is particularly important for instructors of beginning courses (freshman chemical engineering and/or material and energy balance courses) to understand the concerns facing the students as they begin their college careers. Incorporating novel methods into the classroom can increase learning as well as retention.

For copies of the presentation slides from the Summer School, contact one of the authors.

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THE HISTORY OF CHEMICAL ENGINEERING AND PEDAGOGY

The Paradox of Tradition and Innovation

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Despite the conservatism of ChE departments, chemical engineering has been at the forefront of helping new professors learn how to teach and individual chemical engineering professors have been leaders in the push for engineering education reform. Examples of chemical engineering leadership in pedagogy include the Chemical Engineering Division of ASEE Summer School every five years, the division's publication of the journal *Chemical Engineering Education*, and leadership in teaching professors how-to-teach. Individual efforts include the development of the guided design method, introducing Problem-Based Learning into engineering, laboratory improvements and hands-on learning, the textbook *Teaching Engineering*, and the championing of cooperative group learning. Despite these efforts, most ChE professors insist on lecturing.

This paper will provide a brief history of chemical engineering programs, curricula, and pedagogies.

INTRODUCTION AND EARLY PROGRAMS

In 1888 MIT started Course X (course refers to curriculum), which began as a mechanical engineering curriculum with time devoted to the study of chemistry, and eventually became chemical engineering.[1-3] MIT did not claim invention of chemical engineering but noted that similar engineers were active in Europe.[4] Davies[5] starts his history of chemical engineering with the ancient Greeks and continues to the 1887 series of lectures presented by George E. Davis at the Manchester Technical School in England. [The Manchester Technical School became the University of Manchester Institute of Science and Technology (UMIST) and in 2004 merged with the Victoria University of Manchester to form the University of Manchester.] These lectures, which were published over the next few years in the *Chemical Trade Journal*, are often considered the start of formal education in chemical engineering. Davis published the first *Handbook of Chemical Engineering* in two volumes in 1901 and 1902.[6] Since this is the 100th anniversary of the American Institute

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of Chemical Engineers, we will generally limit our comments to the American experience and refer readers interested in the history of chemical engineering in other countries to the many fine chapters in Furter.[7]

The historical role of MIT in starting chemical engineering education in the United States has been well documented.[1-4, 8] The initial Course X, founded by Lewis Mill Norton, was contained in the department of chemistry. Chemical engineering became a separate department in 1920 with Warren K. Lewis as the head. Perhaps the first American text in chemical engineering, *Elements of Fractional Distillation*, was published by MIT professor Clark Shove Robinson in 1922 as part of McGraw-Hill's International Chemical Series.[9] This was followed in 1923 by the seminal *Principles of Chemical Engineering* by William H. Walker, Warren K. Lewis, and William H. McAdams,[10] which laid the quantitative foundations of the discipline and used the concept of unit operations first recognized by George E. Davis (although not by that name)[3, 5, 6] and first delineated by Arthur D. Little in 1915.[1] MIT also developed the idea of intensive practical education through a graduate level practice school, but this innovation has not spread beyond MIT.[1, 11]

Although there were programs in practical industrial chemistry before 1888, MIT was the first school to use the title chemical engineering.[2] After MIT, the University of Pennsylvania introduced a four-year chemical engineering program within chemistry in 1892; although, a separate department was not established until 1951.[2] In 1894 Tulane started the third curriculum in chemical engineering followed by the University of Michigan and Tufts in 1898 and the University of Illinois-Urbana Champaign in 1901.[2] The first independent chemical engineering departments in the United States apparently were the University of Wisconsin in 1905[2] and Purdue University in 1911.[12]

CURRICULUM DEVELOPMENTS

Early curricula were often cobbled together from existing industrial chemistry and mechanical engineering courses, and it was common, as was the case at MIT, to have no courses labeled as chemical engineering.[2] As programs grew, professors of chemical engineering were assigned and specific courses in chemical engineering were developed.

AIChE became involved in studying the education of chemical engineers in 1919 through its committee on Chemical Engineering Education.[13] Between 1921 and 1922 the committee, chaired by Arthur D. Little, studied the programs at 78 schools that claimed to teach chemical engineering and decided that chemical engineering was based on the unit operations and involved industrial-scale chemical processes.[13] Although controversial, the report of Little's committee was approved in 1922, and a new committee chaired by H.C. Parmelee was given three years to determine which programs were satisfactory. This report, with the names of 14 acceptable programs, was given in June 1925, and constitutes the beginning of engineering accreditation in the United States.[13] The Engineers' Council for Professional Development (now part of ABET) was formed in 1932. Since AIChE was the only engineering society involved in accreditation at that time, the institute requested and received special status. One of these perks, that a copy of each ChE program's self-study report was to be provided to the AIChE committee, was not removed until the March 2008 meeting of the ABET Board of Directors.[14]

In 1925, AIChE recommended that 10.3% of the curriculum be devoted to chemical engineering courses. The recommended amount of engineering has increased over the years. In 1938, 15 to 20 percent of the curricula was expected to consist of chemical engineering courses[15] (Table 1). Currently, ABET does not spell out the percentages of chemical engineering courses

TABLE 1
Accreditation Recommended Percentage in ChE Curricula[15, 16]

Topic	AIChE 1938[15]	Topic	ABET 2008-2009[16]
Chemistry	25-30%	Math & Basic Science	25% minimum Sufficient material to be consistent with objectives
Math	12%		
Physics	8%		
Other Sciences	2%		
Mechanics	6%		
Chemical Engineering	20-15%	Engineering	37.5% Must include design and sufficient material to be consistent with objectives
Other Engineering	12%		
Cultural Subjects	15%	General Education	Complement other components and consistent with objectives
Total	~148 credits		~124 or more credits

TABLE 2 ChE Plans of Study at Purdue University[12]					
Topic	**1907-08**	**1923-24²**	**1936-37³**	**1965-66**	**Proposed 2009-10**
Chemistry	15.1%	23.7-29.9%	24.2-26.9%	16.7% 14.5%	
Math	16.8%	12.3%	11.8%	12.5%	14.5%
Physics	6.6%	4.9%	5.3%	8.3%	5.3%
Biology	1.0%	1.2-3.1%	-----	-----	2.3%
Mech. Draw.	3.0%	2.5%	2.6%	-----	-----
Mechanics	4.4%	4.9%	7.9%	2.1%	-----
Ind. chem./ tech.	11.0%	-----	-----	-----	-----
Chem. Engr.	-----	6.7-10.4%	18.3-20.3%	25.-25.7%	36.6%
Other Engr.	12.6%	12.3-19.0%	5.2%	8.3%	5.3%
Shop	7.0%	2.5%	2.6%	-----	-----
Tech. electives	-----	-----	-----	4.9-5.6%	2.3%
Military	3.0%	3.9-13.1%	4.4%	0-5.6%	-----
English/ Speech	5.6%	3.7%	5.9%	3.5%	5.3%
German	10.0%	7.4-9.2%	3.9%	-----	-----
Other humanities	3.8%	5.5%	2.0%	12.5%	13.7%
Other	-----	-----	4.0%	5.6-0%	-----
Total credits	398.5 pts¹	163-169 cr	152.7-154.7 cr.	144 cr	131 cr

¹ *1 point for each hour per week in courses with no outside work and 2.5 points for each hour per week in courses with outside work.*
² *Depends on options chosen. The 163 minimum was used to determine %.*
³ *Depends on options. The 152.7 minimum was used to determine %.*

but focuses on the skills required by graduates.[16, 17] The total engineering percentage has increased, however[16] (Table 1).

It is interesting to consider the historical development of curricula. The curricula for Purdue University, which has always had a fairly typical curriculum, are shown in Table 2.[12] While chemical engineering was still part of chemistry (1907-08), there were no courses identified as chemical engineering, and German was required since much of the chemistry literature was published in German (Table 2). In addition, a thesis was required for graduation. This plan of study was truly a combination of industrial chemistry and mechanical engineering. An increase in military training occurred during the First World War. After chemical engineering became a separate department, separate ChE courses appeared and the industrial chemistry courses disappeared (1923-24 in Tables 2 and 3). Although still required, the amount of German decreased. Both the 1907-08 and 1923-24 plans of study required a modest amount of biology. The other engineering courses included Electrical and Mechanical Engineering, plus Surveying. Descriptive Geometry, required in 1907, was dropped by 1923. The 1923-24 plan of study had insufficient chemical engineering courses to meet the recommendations of the AIChE Parmelee committee, and Purdue plus many other schools were not on the AIChE list of approved schools.

Purdue (and most other rejected schools) worked hard to satisfy AIChE requirements.[12] Purdue's 1936-37 plan of study (Tables 2 and 3) satisfied the AIChE recommendations (Table 1) and Purdue was first accredited in 1933. The 28 to 31 credits of chemical engineering shown for 1936-37 in Table 3 include 6 credits of Metallurgy, which was part of chemical engineering. Biology was no longer required although Mineralogy (listed as 2 % in "other") was required. The German requirement had been reduced to 6 credits and disappeared entirely by 1950. By 1965, Shop, Mechanical Drawing, additional science, and German had all been eliminated. The Military requirement was made semi-optional and the humanities requirement (elective with a few constraints) was increased significantly. Chemical engineering requirements were increased to 25% of the course load. The 1965-66 curriculum is fairly close to the "four-year compromise curriculum light in chemistry" discussed in 1969 by Morgen.[15] The proposed 2010-11 curriculum shows the inclusion of Biology, an increase in chemical engineering courses including more Design, and a change in when students take hands-on laboratory (1 credit each of Fluids, Heat and Mass Transfer, and Reactor Engineering are for laboratory). The molecular basis of ChE is taught in ChE, which only partially compensates for the reduction in Chemistry. This proposed curriculum has

TABLE 3
Chemical Engineering Courses at Purdue University[12]

Semester	1907-08	1923-24	1936-37[1]	1965-66	Proposed 2010-11
1	None	None	None	None	None
2	None	None	ChE/Met. . . . . .3 (optional)	None	None
3	None	None	None	ChE Calc. 3	ChE Calc. 4
4	None	None	None	Intro. Chem. Proc. Ind. 3	Thermo. . . . . .4 Stat. Model 3
5	None	None	None	Thermo. . . . . .3 Fluids & Heat Trans. 4	Separation . . . . 3 Fluids 4
6	None	Thermo . . 3 cr.	Thermo. . . . . 3 Elem. Unit Ops. 2	Mass Transfer . . . . 4 ChE Lab. 2	Heat/Mass Transfer 4 Rx Eng. . . . . 4 Molec. Eng. . . . . . . 3 Prof. Semin. 1
7	Indus. Chem. & Tech. Analy- sis . . 22 points	Elements ChE I . . . . . 3 Metallurgy . . .3 (optional)	Elem. Unit Ops . . . . 2 Unit Ops . . . . .3 Non-Ferrous Metallurgy . . 3 Pyrometry . . . . .2 Plant Des. . . . . .2 ChE Prob. 1	Rx Kinet. . . . . .3 ChE Lab. . . . . .2 Prof. Guid. & Inspection Trips . 1 ChE Elec. 3-4	ChE Lab. . . . . .4 Proc. Dynam. & Control . . . . .3 Des & Cost Analysis 3 ChE Elec. 3
8	Indus. Chem. & Tech. Analy- sis . . 22 points	Elements ChE II . . . . .3 Metallurgy . . .3 (optional)	Inorg. & Org. Tech. & Stoich. . . . . .3 Unit Ops. . . . . 3 Ferrous Metall. . . . . .3 ChE Prob. 1	Proc. Dynam. & Control . . . . .3 Proc. Des. & Economics . . . . . 3 ChE Elec. 3	Proc. Des. . . . . 2 ChE Elec. 3
Total	44 points	9-15 cr.	28-31 cr.	36-37 cr.	48 cr.

[1] *Shown for the General Chemical Engineering program (other options were Gas Technology, Metallurgy, Military, and Organic Technology).*

two ChE electives, an additional engineering elective, and a technical elective. Several options such as pharmaceutical engineering allow students to use their electives in an organized fashion. The Military requirement disappeared during the Vietnam War.

Although total credits have dropped through the years (Table 2), the student work load appears to have stayed constant or increased. The amount of chemistry in the curriculum (Table 2) has decreased significantly. Shop, German, Mechanical Drawing, Mechanics, Circuits, and Military have slowly been phased out of the curriculum. Although still available, these courses are selected by few students. Biology has done a boomerang and returned to the curriculum. Chemical engineering science courses replaced practical, but less scientifically oriented, courses after World War II.[18] The percentage of chemical engineering courses has steadily increased, and there has been a trend to move these courses earlier in the curriculum (Table 3). Although not obvious from Table 3 because of the years selected, the amount of design has oscillated back and forth and is currently waxing. Hougen's[19] analysis of the curriculum trends at the University of Wisconsin reveals patterns similar to those shown here, except that Wisconsin was often several years ahead of Purdue in making changes.

The current ChE curriculum at Purdue and most schools is extremely hierarchical. Starting with the first Calculus course, Purdue has a seven-semester sequence of required courses to graduation consisting of the Calculus courses and Differential Equations, which is a co-requisite for Fluids, which is followed by Heat and Mass Transfer, which is a co-requisite for the first of two ChE design courses. There are also several four-semester sequences of ChE courses starting with Mass and Energy Balances. Few of the other engineering programs have prerequisite requirements as strict.

A long-term change not readily evident from looking at curricula is who teaches chemical engineering. Initially, there were no chemical engineers and the courses were usually taught by chemists and mechanical engineers. Once chemical engineers had graduated and were available to become professors, most of the chemical engineering professors had significant industrial experience and rarely had a Ph.D.[8] Over the years an earned Ph.D. became a requirement and the expectation that engineering professors would have practical experience was lost. The current lack of practical understanding of industry and the practice of chemical engineering is obviously a problem in the education of undergraduate chemical engineers.[20, 21] The current interest in rewarding research makes it unlikely that this lack will be solved in the near future.

Similar to all fields,[53] most ChE professors lecture much of the time in class. Their teaching would improve if they heeded the oft-given advice, "Lecture less."

CURRENT CURRICULUM DEVELOPMENTS

There have been a number of recent efforts at national curriculum reform. The University of Texas-Austin Septenary committee did a major analysis of the curriculum in the early 1980s.[22, 23] The committee recommended the following: an overhaul of all the ChE courses to strengthen fundamentals and include computer calculations in all courses; inclusion of modern biology, economics, and business courses in the curriculum; sufficient electives to allow specialization; and an overhaul of teaching methods and tools including major revisions of all the textbooks. The recommendations of the committee to provide incentives for rewriting textbooks have been ignored, but many of the other recommendations made by the Septenary committee were adopted at Texas. The report also had some impact elsewhere. In particular, the need to integrate Biology and Chemistry into the curriculum has been widely understood.[24, 25] The use of options or tracks, which had been recommended previously,[26] does not appear to have been widely adopted. The current University of Texas-Austin curriculum[27] differs from Purdue's (Tables 2 and 3) by specifying humanities electives in American History and American Government and requiring a literature course. In addition, an Electrical Engineering course is required, and there are a total of six electives in science, technical, and engineering areas compared to the four electives in these areas at Purdue. Both programs now require Biology. Thus, the differences in these two curricula are rather small.

There has also been a push to focus chemical engineering education more on product engineering because the structure of the chemical industry has changed markedly. Many chemical engineers at both the bachelor's and the Ph.D. levels now work for companies that are not considered to be chemical companies,[21, 28-31, 32] and the world of chemical engineering continues to expand.[33] Many more chemical engineers will work in specialty chemicals instead of commodity chemicals. Specialty chemicals will require more chemistry, in particular structure-property relationships including the use of quantum mechanical software. Graduates will need to be comfortable with producing products that function based on their micro- or nano-structure. In addition, there will be more interest and need to teach batch processing. Our examples and textbooks need to be revised to include examples from a much wider variety of industries. Some detailed examples of product design are available.[30, 31] At least from course titles, product design does not appear to have become a required course at MIT,[34] Purdue (Table 3), University of Minnesota,[35] or University of Texas-Austin.[27] Perhaps professors are including product design as examples in their courses.

Another current curriculum revision initiative is called the Frontiers in Chemical Engineering Education Initiative[36-39] that started with meetings in 2002. The initiative looks to: 1. integrate Biology into the curriculum; 2. balance the diversity of research areas with a strong undergraduate core; 3. balance applications and fundamentals; 4. include both process and product design; and 5. attract the best students to ChE. The initiative proposes that the organizing principles of chemical engineering are molecular transformations, systems, and multiscale analysis. The new curriculum is supposed to be integrative and include the organizing principles plus laboratory experiences, examples, teaming, and communication skills throughout the course sequence. Unfortunately, most popular chemical engineering textbooks are not arranged around the proposed organizing principles and little material for teaching within this curriculum is available. Although the initiative has been led by an MIT professor, the current MIT curriculum[34] does not reflect this initiative. To be successful, this initiative will have to convince professors that the changes are necessary, train professors in new pedagogy, and sponsor the development of an enormous amount of teaching material. In a related effort that was started independently, the chemical engineering professors at the University of Pittsburgh appear to have been convinced that these changes are necessary since Pitt has instituted a "Pillars of Chemical Engineering" curriculum.[39-42] The six "Pillar" courses on foundations, thermodynamics, transport, reactive processes, systems & dynamics, and design are block scheduled to provide additional time. The courses include Molecular Insight and Modeling, Product Design, Multiscale Analysis, and a significant amount of simulations. Preliminary assessment data with concept maps and concept inventories shows that students are learning concepts better with the new curriculum.[41, 42]

A trend that so far has been generally ignored in curriculum revisions is the increasing number of engineers employed in the service sector in a post-industrial United States.[32] Chemical engineers are popular in these positions because they are intelligent people who voluntarily undertook one of the most rigorous undergraduate curricula. These graduates need less chemistry, more professional skills, and more global awareness. Wei[32] recommends that the current curriculum, with appropriate fine tuning, should not be changed to accommodate these students since it is usually unclear which path students will follow after graduation. To a large extent the ABET professional criteria—3d (multidisciplinary teams), 3f (professional & ethical responsibility), 3g (communication), 3h (global/societal context of engineering), 3i (lifelong learning), and 3j (contemporary issues)[16]—help prepare graduates for jobs in the service sector. Currently, strengthening these professional criteria in existing curricula is probably all that is needed to prepare graduates for service-sector positions.

Although local curriculum revisions are needed periodically, I personally do not believe that a national one-size-fits-all curriculum revision is wise. Schools should focus on their strengths and local needs, and not blindly copy what other institutions are doing. If an innovation makes sense and fits, then by all means adapt it to your institution. If an innovation does not fit your institution, keep doing what the institution is doing well.

TEXTBOOKS AND OTHER TEACHING MATERIALS

"The very boundaries of what we mean by chemical engineering are determined to a significant extent by the textbooks. The publication of *Principles of Chemical Engineering* by Walker, Lewis, and McAdams . . . shaped the field of chemical engineering for many decades afterwards."[43, p. 185] In addition to Walker, Lewis, and McAdams,[10] Professor Bird[43] cited the books by Hougen and Watson,[44] and Hougen, Watson, and Ragatz[45, 46] as particularly influential. We can certainly add Badger and McCabe[47] and many other books to this list. The McGraw-Hill series of chemical engineering books started in 1925 was also very important for a number of years. Although not a textbook, Perry's *Handbook*,[48] first published in 1934 with significant contributions from DuPont chemical engineers, has also been quite influential in chemical engineering education.

Textbooks can both constrain and open a discipline.[23] For example, Bird, Stewart, and Lightfoot[49] clearly helped open chemical engineering to a more scientific approach, but later helped constrain the discipline to a continuum approach. Extremely popular textbooks such as Felder and Rousseau[50] and Fogler[51] serve to standardize parts of the ChE curriculum across the country since the vast majority of students have used these books. Because they are so widely used, the popular books can enhance or impede curriculum changes depending on the interests of the authors.

One of the current problems in chemical engineering education is that, with very few exceptions, there are no young textbook authors. The first edition of most of the current ChE textbooks were written when the author(s) were in their forties or fifties, and many of these texts are in the 2nd, 3rd, or higher editions. Younger professors are more likely to be trained in new content that should be worked into the curriculum. Unfortunately, because the current reward system at research universities is based on research papers, standard advice for untenured professors is to not write a textbook.[23, 43, 52, 53] Professor Bird also advises, "Book writing should not be undertaken to gain fame and fortune."[43] Although a successful textbook can pay for the college education of the author's children, the other rewards are seldom commensurate with the effort required to write a good book.[43, 53] Most chemical engineering professors are not trained in pedagogy and a really good textbook has to be based on sound learning principles in addition to being technically correct. The soundness of the pedagogical approaches is one reason for the successes of Felder and Rousseau[50] and Fogler.[51] Training all professors how-to-teach[52] would reduce the amount of on-the-job-training in writing textbooks. There have been calls for more rewards for writers of textbooks,[23, 38, 43] but so far action has been sparse.

There have been attempts to use other materials besides textbooks for presenting teaching material. In the 1980s AIChE developed a series of six volumes of *Modular Instruction* (AIChEMI) under the overall direction of Prof. E.J. Henley. The six volumes covered Kinetics, Mass and Energy Balances, Process Control, Stagewise and Mass Transfer Operations, Thermodynamics, and Transport. Modules had the advantage that the effort to write a module was orders-of-magnitude less than writing a textbook. Unfortunately, the quality was erratic and the modules were not widely adopted. The effort has apparently disappeared since none of the modules appears in the current AIChE catalog.

Computer-aided instruction and educational games have enormous potential for improving technical education[53-56] particularly for students in the gamer generation.[55] Some of the leading ChE textbooks (*e.g.*, References 50 and 51) provide supplemental instructional software as either a CD bundled with the textbook or as a course Web page. Unfortunately, students often do not use the supplemental material even when required to do so.[57] Instructional games have considerable promise,[56] but, with current technology, developing a professional-quality educational game takes an order of magnitude or more effort than producing a textbook. The chemical engineering market is not large enough to support these efforts without subsidies. A major reduction in the time and cost required to develop instructional games is necessary before educational games can become economically viable to teach chemical engineering material. Chemical engineering students, however, may use these methods to learn Calculus, Chemistry,[56] Physics, Biology, Economics, and other large-enrollment subjects.

HIGHLIGHTS OF PEDAGOGICAL DEVELOPMENTS IN CHEMICAL ENGINEERING

Similar to all fields,[53] most ChE professors lecture much of the time in class. Their teaching would improve if they heeded the oft-given advice, "Lecture less." Instead of lecturing they could use various active and inductive learning methods that have been extensively studied by ChE professors.[53, 58-69] These methods include cooperative group learning, "clickers," guided design, problem-based learning, quizzes, laboratory improvements and hands-on learning, and computer simulations for part or all of the class periods. Chemical engineering professors have also been at the forefront of activities to make ABET requirements for assessment more meaningful.[70, 71] A paradox is that chemical engineering professors such as John Falconer, Rich Felder, Ron Miller, Mike Prince, Joe Shaeiwitz, Jim Stice, Charlie Wales, Phil Wankat, Don Woods, Karl Smith (an honorary ChE since his B.S. and M.S. degrees were in process metallurgy), and the entire ChE faculty at Rowan University have been at the forefront of developing and popularizing these techniques, but most ChE professors do not use them.

Chemical engineers have also been at the forefront of helping professors learn how-to-teach.[52, 72-75] The Chemical Engineering Summer School was first held in 1931 and then 1939, 1948, 1955, 1962, and every five years after that. The Summer School has included a how-to-teach workshop since 1987, and the popular and successful ASEE National Effective Teaching Institute is led by chemical engineers. In addition, the Chemical Engineering Division of ASEE publishes the highly respected journal *Chemical Engineering Education*, which covers new chemical engineering content and how to improve teaching and learning in chemical engineering. Teaching interested volunteers to be better teachers is relatively easy and effective.[72, 73] Because professors who take workshops find that they can improve some aspects of their teaching without devoting excessive time to it, they are motivated to use at least some of the methods learned in the workshop. Yet, it is doubtful that the majority of ChE professors have attended a formal teaching workshop or teaching course. In the past, teaching workshops and courses for engineering professors were not readily available, and the reward structure at most universities did not strongly encourage faculty to improve their teaching. In my opinion the single most effective action that can be taken to improve engineering education is to require all new engineering professors, and encourage current engineering professors, to take a course in how-to-teach.

Research in improving engineering education has very recently become much more popular. This is signaled by the increased attention paid to this research by ASEE and the National Academy of Engineering, the elevating of publication requirements by the *Journal of Engineering Education*,[74] the emergence of engineering education as a separate research field,[75] and the development of new engineering education Ph.D. programs.[76] Ultimately, this research should lead to better answers to important questions such as why students choose to major in engineering and why some leave engineering, how students learn engineering topics, and how to further improve the teaching of engineering. Chemical engineers have been at the forefront of many of these efforts. Because most engineering professors are not trained to do rigorous educational research, NSF has sponsored workshops to help interested professors start learning how to do rigorous educational research.[77]

CLOSURE

Chemical engineers active in improving engineering education are often asked why chemical engineering, which is not one of the larger engineering disciplines, has had a large impact on engineering education. I will close by speculating on the answer. Chemical engineers are interested in processes while most engineering disciplines have focused on products. Teaching and learning are processes. Thus, it is natural that chemical engineers would contribute to improving these processes. The other major engineering field interested in processes, albeit of a different type, is industrial engineering. Industrial engineering has been at the forefront of graduating Ph.D.s who did their research on engineering education. I believe that their interest in processes is a major reason that chemical engineers have been and will continue to be leaders in engineering education.

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NANOLAB AT THE UNIVERSITY OF TEXAS AT AUSTIN:

A Model for Interdisciplinary Undergraduate Science and Engineering Education

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Significant discussion has taken place in recent years about the future of the undergraduate chemical engineering curriculum, with consideration of how content might be revised and updated, how the degree program might be made more flexible, and how innovative teaching strategies could be incorporated.[1-5] A slightly different chemical engineering curriculum issue has also arisen, and that is, "What is the *broader* role of the chemical engineering faculty in educating science and engineering undergraduates at the university?" At the graduate level, this question has become important as chemical engineering research has evolved into a highly interdisciplinary effort with research projects straddling disciplinary boundaries. Chemical engineering Ph.D. students interact and collaborate with Ph.D. students and faculty outside of chemical engineering and as a consequence, require a diverse set of fundamentals and skills in a number of different disciplines. The successful education of chemical engineering students at the graduate level requires available and effective courses in several departments, and an educational infrastructure that promotes interdisciplinary learning. Therefore, chemical engineering faculty need to be heavily involved in curriculum development in science and engineering outside their home department, focusing on the university as a whole. One example of a specific graduate program that has been developed at UT Austin with this in mind is the Doctoral Portfolio Program in Nanoscience and Nanotechnology. The program is directed by a chemical engineering faculty member and chemical engineering played

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an influential role in the development of the program, but it was initiated by a grass-roots efforts of faculty from eight different departments.[6, 7]

In contrast, chemical engineering departments have remained relatively insulated from other departments with respect to the issue of the undergraduate curriculum. The chemical engineering curriculum itself has changed little in the past few decades. But there may be a new need for chemical engineering faculty to reach outside of the department and become involved in the broader educational goals of the university at the undergraduate level. As an illustration, new educational initiatives at UT Austin are being developed by the upper levels of administration, including the formation of an Undergraduate College, an undergraduate "core" curriculum, new interdisciplinary "signature" courses available to all incoming first-year undergraduates, and a proposal that all undergraduates will enter the university "undeclared" and then pick a major after their first year.[8] These initiatives have been driven in part by increasing pressures from the state and general public for public universities to move their curriculum away from a traditional, compartmentalized model focused on technical specialization toward a broader and more flexible education that provides more independence for the students and a broader perspective when they graduate.[9] This is forcing chemical engineering educators to reassess long-held assumptions about what "needs" to be taught—partly as a pragmatic matter at UT Austin since "signature" first-year and second-year courses may be added at the expense of more specialized departmental courses, and partly as a matter of self-preservation (and perhaps self-promotion) as the department will be directly competing with other departments to attract students to its major. Needless to say, the Department of Chemical Engineering at UT Austin is reassessing the broader educational role of its faculty.

In the fields of nanoscience and nanotechnology, the chemical engineering department is well-poised to play a particularly influential role in the broader educational mission of the

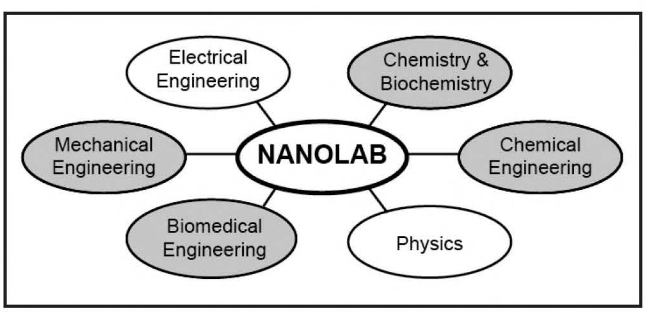

Figure 1. *Six different departments participate in NANOLAB. The first year was a trial period with the Departments of Chemical Engineering, Chemistry/Biochemistry, and Mechanical Engineering participating during the Fall semester. Biomedical Engineering joined NANOLAB for the spring semester. Physics will join in Fall 2009 and Electrical Engineering after that.*

university. One of the defining features of the contemporary field of chemical engineering is its interdisciplinarity—the research programs of its faculty now span biology, chemistry, physics, and engineering—and in the area of "nano," this interdisciplinarity is fundamental. At UT Austin, the chemical engineering faculty has begun to take on such a leadership role. With a recent financial boost provided by a Nanoscale Undergraduate Education (NUE) grant from the National Science Foundation, faculty and graduate students have developed an innovative new laboratory experience for undergraduate science and engineering students, called "NANOLAB." NANOLAB is a laboratory hub designed to serve six different departments and educate nearly 1,000 undergraduate science and engineering majors per year with a hands-on nanoscale science and education (NSE) experience. This paper describes the NANOLAB model for teaching NSE concepts across departmental boundaries, including how it was developed, and some of its successes.

WHAT IS NANOLAB?

There are many strategies for creating interdisciplinarity in the curriculum; for example, offering traditional course enrollment to students in other majors or cross-listing courses in multiple departments. These can be effective ways to educate students from other disciplines, but these efforts are not fundamentally interdisciplinary, as the information is taught from the perspective of a particular discipline. The NANOLAB is a genuine attempt to promote interdisciplinary learning, while introducing large numbers of undergraduate science and engineering students—nearly 1,000 per year—to NSE concepts that they will benefit from in their future careers. The NANOLAB is an upper-division undergraduate laboratory hub. It is unconventional because it is not a stand-alone course offered by a single department, but is instead integrated with existing laboratory courses sprinkled throughout six participating departments—Biomedical Engineering, Chemical Engineering, Chemistry/Biochemistry, Electrical Engineering, Mechanical Engineering, and Physics—across both the Colleges of Engineering and Natural Sciences. The NANOLAB is designed to serve the general science and engineering undergraduate population at UT Austin.

Figure 1 outlines how students from different science and engineering departments interface with NANOLAB. Students enroll in an existing undergraduate laboratory course, such as the physical chemistry laboratory, and then supplement their laboratory experience by performing one of the NANOLAB experiments during the semester. A chemical engineering student in the "fundamentals" laboratory does likewise. The NANOLAB experiments are then designed so that students work in multidisciplinary teams of two natural sciences and two engineering students. The NANOLAB is an autonomous teaching resource, providing a possible model for education in interdisciplinary areas that do not fit neatly into the pre-packaged departmental educational system. This article describes NANOLAB—how it was formed and what it is—with the hope that other universities may adopt a similar educational model for NSE, or may elect to incorporate one or more of the experiments into existing courses within their own departments.

THE NANOLAB EXPERIMENTS

NANOLAB consists of four 6-hour experiments: (1) Fabrication of gold nanoparticles using self-assembled templating; (2) Optical and redox properties of colloidal semiconducting quantum dots; (3) Acid-doped polyaniline nanofiber sensor for vapor detection; and (4) Gold nanorod synthesis and optical properties. Three of the experiments were designed and developed during the summer of 2007 by three chemical engineering graduate students, Andrew Heitsch, Shawn Coffee, and Navneet Salivati, and one materials science and engineering graduate student, Damon Smith. A fourth experiment was added for the Spring semester 2008 based upon student and TA feedback after the Fall semester. The experiment was developed by three other chemical engineering graduate students, Mike Rasch, Vahid Akhavan, and Danielle Smith. As described in more detail below, each NANOLAB experiment was designed to teach a different concept that is unique to the nanoscale: self-assembly, nanofabrication, and quantum confinement. Consideration in the design of the experiments was also given to how much time students would need to complete each experiment. One experiment must be completed in two 3-hour laboratory course periods by four students working together in a multidisciplinary team.[10] Figure 2 summarizes the experiments described below, showing students and TA's working in the NANOLAB and examples of data that are collected by the students.

(1) *Fabrication of gold nanoparticles using self-assembled templating:* A diblock copolymer is spun cast onto a substrate, annealed, and then etched to form an ordered array of cylindrical holes. This self-assembled polymer film is then used as a mask to deposit an array of gold nanoparticles by vapor deposition followed by lift-off. The Au particle arrays are examined by atomic force microscopy (AFM). The students learn about polymer self-assembly and the basics of masked film deposition, which is one of the process steps at the heart of the microelectronics industry. They also gain exposure to a scanning probe microscopy technique, which is one of the most important analytical tools in nanoscience and nanotechnology.

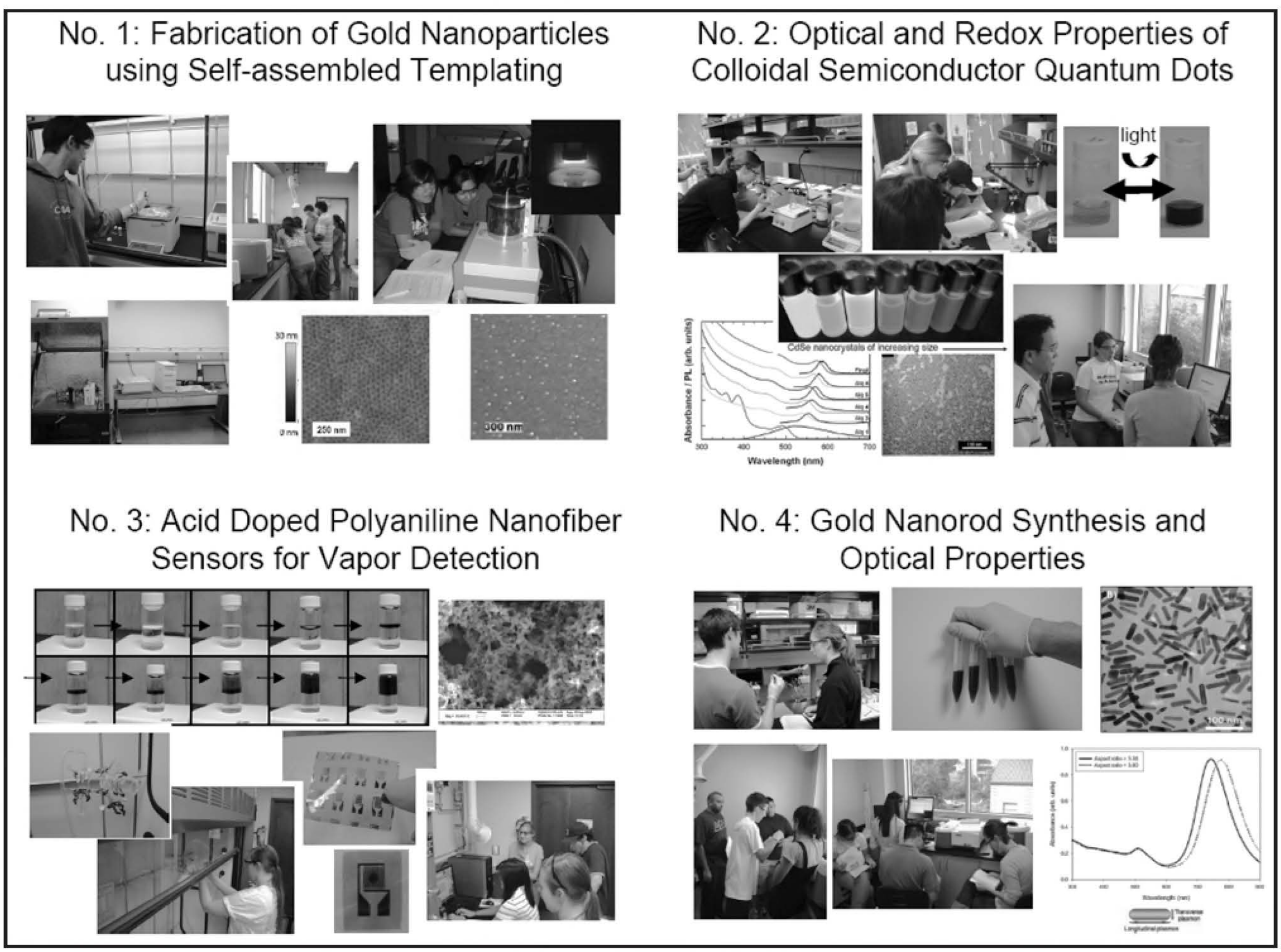

Figure 2. Images from the NANOLAB.

One of the defining features of the contemporary field of chemical engineering is its interdisciplinarity—the research programs of its faculty now span biology, chemistry, physics, and engineering—and in the area of "nano," this interdisciplinarity is fundamental.

(2) *Optical and redox properties of colloidal semiconducting quantum dots:* Colloidal semiconductor (CdS) nanocrystals are synthesized by arrested precipitation and then used to drive a light-activated reduction of an organic dye molecule. The nanocrystals absorb light, create an excited electron-hole pair, which then drives a redox reaction. Students also measure the absorbance and fluorescence spectra of a standard CdSe nanocrystal sample, revealing the size-dependent shift in optical properties that is characteristic of a quantum dot. This laboratory exposes students to the concept of quantum confinement in a semiconductor and provides a real-world example of how a semiconductor nanocrystal can be used as a photocatalyst to drive a chemical reaction. This basic information is important for many applications of nanomaterials related to energy and environment.

(3) *Acid-doped polyaniline nanofiber sensor for vapor detection:* Polymer nanofibers are synthesized and then used to construct vapor sensor devices on interdigitated array electrodes on plastic substrates. The TA fabricates the electrode structures on plastic at the beginning of the semester. Students test the sensitivity of these chemiresistive sensors. This is a good introduction to the fundamentals of sensing and provides an opportunity for students to proceed through the steps of nanomaterials synthesis, device fabrication, and then property testing.

(4) *Gold nanorod synthesis and optical properties:* Colloidal gold nanorods are synthesized using a "standard" two-step seeded growth approach. The optical properties of the gold nanorods, *i.e.*, the absorbance spectra, are then measured. The absorbance spectra predominantly reflect the surface plasmon resonances within the nanorods, which have peak energies that depend on the dimensions of the nanorods. The experiment gives the students the chance to make some nanomaterials, examine their optical properties, and then begin to understand the origin of the optical properties. The physics is rather complicated and the concept of "plasmon resonances" is difficult for many undergraduate students to understand without doing this kind of hands-on experiment. Students are then called upon to tackle a biosensor design problem using the data that they have acquired.

LOGISTICS: LOCATION AND TUTORIALS

The NANOLAB is housed next to the clean room in modular interdepartmental laboratory space in the newly built Nanoscience and Technology (NST) Building in the Center for Nano- and Molecular Science and Technology (CNM) at UT Austin.[11] The building is centrally located between participating departments and is easily accessible by the undergraduate students. The location is also an exciting one for the undergraduate students because the NST building is primarily designed as modular research and training space for graduate students and it gives the undergraduate students a glimpse of "life after graduation" in a research environment. For many of the students, this is the first time that they will see a clean room, for example. It is an inspiring place for the students to participate in the laboratory.

Considering that students have little background knowledge related to the laboratories, the initial concept was to develop and make available video-based tutorials for each laboratory experiment on DVDs that would be distributed to the students. The video-based tutorials were developed and have turned out to be central to the success of the NANOLAB. They provide a resource for the students to help them come quickly up to speed on new information and ensure that they have the necessary knowledge to complete the NANOLAB in the allotted time. But instead of being offered on DVD, the tutorials have been placed on the Internet as Web-based tutorials. The use of the Internet has saved significant cost—*i.e.*, the time to write the DVDs and their cost—and provided convenient access for the students. Online educational media is also easily accessed by educators from outside UT Austin that are interested in adopting the NANOLAB model and experiments at their own institution.

STARTUP OF THE NANOLAB

There was a significant initial cost to developing the NANOLAB. This cost was offset by a $200,000 seeding grant from the NSF through the Nanoscale Undergraduate Education (NUE) funding program. The NSF funding was matched 3:1 by UT Austin from various sources on campus, with the deans of both the Colleges of Engineering and Natural Sciences and the chairs of the participating departments contributing money for supplies and teaching assistants (TA's) for three years to support NANOLAB.[12] A significant amount of effort was then spent designing and developing the NANOLAB experiments. The three initial NANOLAB experiments were designed and developed over the course of one summer. During the Fall semester when the NANOLAB experiments were first offered, the graduate students who designed them trained the TA's of the laboratory courses and were available for help and troubleshooting as the semester progressed.

One thing to note about the experiments is that they were designed and developed almost exclusively by chemical engineering Ph.D. students. Perhaps it may be better to involve

Ph.D. students and faculty from all of the participating departments in the experiment design, but practical issues and time constraints did not allow this during the initial development of the UT Austin NANOLAB. Other universities looking to develop a similar nanolab may consider the pros and cons of developing the laboratories with a larger team of students and faculty.

The first semester of operation of NANOLAB proved the importance of the online tutorials and the value of the TA. Because of their rigorous academic schedules, the undergraduate students have limited time to prepare for the NANOLAB experiments and need readily accessible teaching resources, of which there are primarily three (Figure 3): (1) an Experimental Manual, (2) a Web-based tutorial, and (3) the TA. The manual provides background information and explains the laboratory procedures that the students must know to perform the experiment. The Web-based tutorial has illustrations and video of the experiments being conducted.[10] These visual "models" provide the students with a snapshot of what they will be doing in the laboratory. The Web-based tutorials have been a particularly effective way to provide undergraduate students with the quick training needed to complete the experiments. At the end of the Web-based tutorial, and after reading the background information in the manual, the students are expected to complete a set of pre-laboratory exercises to ensure they have read and understood the critical issues. The TA is then available for support during the laboratory. Specialized equipment requires a hands-on demonstration, which the TA provides at the beginning of the laboratory. The TA also ensures that the students work safely and is available as questions arise during the laboratory session. It is worth mentioning that safety training is a vital component to preparing the students to work in the laboratory. Because the students are entering NANOLAB from various other undergraduate laboratories, it is necessary to properly provide the students with safety training that is specific to what they will be doing in NANOLAB. Therefore, students must view a safety video and then the TA provides additional safety training immediately upon the students entering the laboratory for the first time. With these resources, students have been able to complete the NANOLAB experiments and learn the intended concepts.

FOR THE FUTURE: CONTINUING CHALLENGES AND IMPROVEMENTS

The NANOLAB is an innovative "integrated-lab" approach to teaching that goes beyond a rigid departmental teaching structure, and although there are other examples of interdisciplinary laboratory courses developed at other universities, the NANOLAB is the only hub-style undergraduate laboratory of which we are aware.[13-17] As such, the NANOLAB is an educational experiment that is still being refined and evaluated. Thus far, student feedback has been very positive. Most students have found the cross-disciplinary and hands-on approach to learning to be a refreshing change from their typical routine. They have also been enthusiastic about learning about nanoscience and nanotechnology and many students have noted that this is their first exposure to NSE concepts. Some students have mentioned that this is an experience that they had been hoping for since entering the university, as there is little offered in the way of nanotechnology-related coursework to undergraduate students. Faculty feedback has also been good. In particular, instructors of the participating laboratory courses have found the new laboratories to be an effective way to update their existing range of laboratory experiments. The biggest challenge expressed by faculty has been the ability to effectively integrate student evaluation within their existing frameworks. For example, in the Department of Biomedical Engineering the undergraduate laboratory is established with groups of four students that work together for the entire semester and their grades are linked. It is difficult to separate the students into the multidisciplinary teams of students for the NANOLAB and still evaluate the students using the same mechanism. In the Department of Mechanical Engineering, students are already expected to complete every laboratory station in their existing course, making their participation in the NANOLAB voluntary for extra credit. Approximately 20% of the students enrolled in the course volunteered to participate in NANOLAB. It is not clear how some of these issues will ultimately be resolved, but there is no question that the students have benefited tremendously from the NANOLAB experience and have expressed very positive feedback.

***Figure 3.** Educational Resources: (Left) Experimental Manual; (Center) TA's from each participating department; (Right) Web Tutorials.[10]*

Because the NANOLAB experiments are newly designed, they are also re-evaluated each semester, with continual improvements of the experiments, the experimental objectives, and the associated teaching media. For example, based on the recent excitement about renewable energy, a new photovoltaics laboratory was designed and implemented in the Spring semester of 2009. Two additional components are also planned for the Web-based tutorials: (1) a pre-recorded lecture to give the students a quick fundamental introduction to the topic of the experiment, and (2) a broader discussion about the health, ethics, and societal impact of the underlying nanoscience and nanotechnology that the students will study in their experiments. A vast array of Web-based educational media has also developed in the recent past which could be incorporated into the tutorials to provide additional background for the students. An example is <nanohub.org>,[18] which provides a plethora of simulations of various nanoscale phenomena that could add a great deal to the content of the tutorials.

The other practical issue is sustainability of the NANOLAB after its "honeymoon" period. The NANOLAB has a financial commitment from the deans of the Colleges of Engineering and Natural Sciences and the chairs of six different academic departments for three years. The NANOLAB will then be evaluated by an independent committee to determine if it will continue. An exit survey and casual feedback of former undergraduate students who participated in the NANOLAB will provide important information for this evaluation (Figure 4).

CONCLUDING REMARKS

NSE concepts cut across departmental boundaries and students benefit from the interdisciplinary approach to instruction of the NANOLAB. The NANOLAB's hub-style approach also provides a practical means of teaching NSE concepts to a large cross-section of undergraduate students at a large public university, providing a hands-on active-learning environment to illustrate concepts unique to the nanoscale, including self-assembly, nanofabrication, and quantum confinement. The new Web-based and written laboratory materials provide the opportunity for easy adoption by other institutions and wide dissemination among peer institutions.

From a chemical engineering perspective, the NANOLAB experiments employ a significant amount of chemistry, but in an engineering context. The experiments require students to think broadly about how nanomaterials and their unique properties might be used to solve a particular technological challenge, and students work with these materials with their hands and experience them directly. The NANOLAB illustrates the concept of product development, in contrast to traditional process development that is the primary focus of the traditional chemical engineering curriculum.[3,19,20] Furthermore, the NANOLAB and its experiments provide undergraduate chemical engineering students with a snapshot of the interdisciplinary environment they will enter after graduation, which will most certainly help prepare them for success. For all of these reasons alone, it has made sense for the Department of Chemical Engineering to play a leading role in the development of the NANOLAB. NANOLAB is not only benefiting the undergraduate science and engineering student body as a whole, but also chemical engineering students specifically. Perhaps this effort will also provide the undergraduate chemical engineering curriculum—rooted in tradition—with more inspiration for change.

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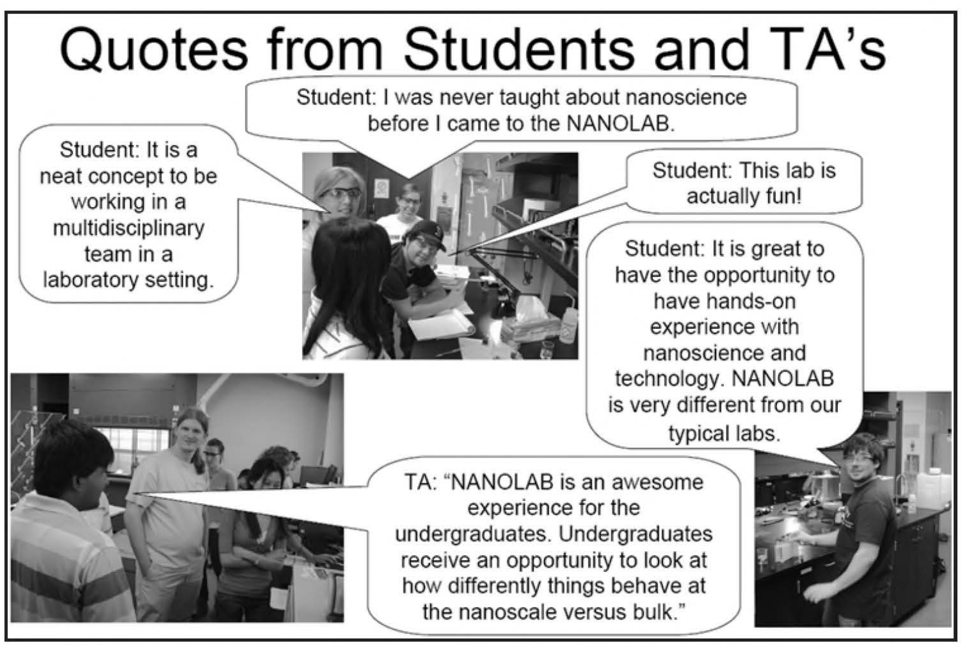

Figure 4. *End of semester feedback from students and TA's about NANOLAB.*

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9. For example, the *UT Austin Final Report* by the Commission of 125—a committee of 125 educational and business leaders assembled to review the educational mission of UT Austin—states, "A narrow education, no matter how deep in its field, will not be sufficient. Future citizens will need to think critically and have a confident grasp of the arts, the humanities, mathematics, science, and technology. The *Final Report* (Sept. 30, 2004) can be accessed on the Internet at <http://www.utexas.edu/com125/final.html>
10. For detailed descriptions of the NANOLAB experiments, visit the online tutorial: <http://www.engr.utexas.edu/nanolab/>
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"STUDENT LAB"-ON-A-CHIP:
Integrating Low-Cost Microfluidics Into Undergraduate Teaching Labs to Study Multiphase Flow Phenomena in Small Vessels

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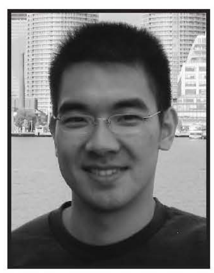
Blood is a complex fluid composed of cells and other biomolecules suspended in plasma. Its main function is to carry oxygen and nutrients to organs and tissues in the body, while also serving as a transport mechanism for elements of the immune system. Because of its composition, blood is a non-Newtonian, shear-thinning fluid that becomes less viscous at higher shear rates, and flows only after overcoming a yield stress that induces rouleaux breakup.[1] Rheological properties of blood are altered under certain pathological conditions, such as sickle cell anemia where abnormalities in red blood cell (RBC) morphology and stiffness result in cell clumping, lower RBC levels, and ultimately higher effective viscosity.[2] Knowledge of blood rheology is therefore fundamental not only to physiologists and biologists, but also to engineers who wish to design biomedical devices, engineer replacement blood vessels, or model blood flow patterns in vivo.

Courses in transport phenomena are core to most chemical engineering programs. Increasingly, interest in biomedical applications of transport and chemical engineering principles has led to the introduction of courses in biotransport and cardiovascular fluid mechanics in chemical and biomedical engineering curricula. At the University of Toronto, topics covered in these courses include blood rheology, steady and unsteady blood flow in large blood vessels, and blood flow in small vessels. The latter topic is interesting because non-intuitive microscale phenomena occur when blood flows in small vessels like arterioles, capillaries, and venules. For blood flowing at a specific shear rate in vessels less than 250 microns in diameter: 1) blood has lower effective viscosity in smaller vessels; and 2) blood hematocrit (*i.e.*, volume fraction of RBCs in the blood) is lower as vessel diameter is reduced.[3, 4] These two phenomena are collectively known as the Fahraeus-Lindqvist (F-L) effect, named after the two scientists who discovered the phenomena in a series of experiments involving the flow of ox blood in fine glass capillaries.[5] This effect can be explained by the concept of the plasma skimming layer, discussed in detail in Ethier and Simmons.[1] Briefly, RBCs concentrate in the core of small blood vessels, away from the walls where RBCs are depleted and where only a thin layer of plasma is present. In smaller vessels, this thin plasma layer occupies a larger fraction of the cross-sectional area compared to the plasma layer in larger vessels, resulting in lower RBC density (*i.e.*, decreased hematocrit) within the vessel and lower viscosity. From this basic explanation, it is clear that the F-L effect is a simple yet useful illustration of the non-Newtonian behavior of blood, and furthermore, is a textbook example of fluid-particle interactions in multiphase flows.

To enhance the students' understanding of the F-L effect and its origin, we developed a low-cost, practical, and feasible laboratory procedure that demonstrates key features of the



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original experiments performed by Fahraeus and Lindqvist. The experiment, which can be performed by the students, uses microchannels fabricated by soft lithography, a popular and widely available technique used for microfluidics research for myriad engineering applications.[6] The use of microfluidics and "lab-on-a-chip" technologies in engineering courses is a growing trend.[7, 8] In this lab, cells in suspension were forced through microchannels of varying widths and heights to mimic blood flow through small vessels. Images taken by light microscopy were used to determine cell density (*i.e.*, equivalent of tube hematocrit in blood) by cell counting, flow rate of the suspension by particle streak velocimetry, and effective viscosity as functions of channel dimensions. Here, we present the methods and results from our F-L experiment, discuss the pedagogical details related to the course and the potential usefulness of the laboratory procedure, and provide recommendations to those who may be interested in developing their own microfluidics laboratory experiment for demonstrating the F-L effect.

MATERIALS

For microchannel fabrication by soft lithography, SU-8-25 negative photoresist and SU-8 developer were acquired from Microchem Corporation (Newton, MA). Sylgard-184 poly(dimethylsiloxane) (PDMS) (Dow-Corning, Midland, MI) was obtained from Paisley Products of Canada, Inc. (Toronto, ON). Glass microscope slides for microchannel device assembly and Intramedic polyethylene tubing (PE60 and PE190) were from VWR International (Mississauga, ON). All slides were cleaned with piranha solution, prepared as a 3:1 (v/v) mixture of sulfuric acid and hydrogen peroxide. Concentrated sulfuric acid and hydrogen peroxide (30%) were from Fisher Scientific Canada (Ottawa, ON). Becton Dickinson Luer-Lok syringes and Precision Glide needles were also purchased from Fisher Scientific Canada. For cell culture, DMEM, penicillin-streptomycin (P/S), and 0.25% trypsin with EDTA were from Sigma-Aldrich Canada (Oakville, ON, Canada). Fetal bovine serum (FBS) was purchased from Hyclone (South Logan, UT, USA). T-75 and T-225 tissue-culture-treated flasks were from Fisher Scientific Canada (Ottawa, ON).

METHODS

Microchannel Fabrication

Microchannels were formed from PDMS and glass using the rapid prototyping technique (Figure 1).[9] Briefly, straight channel patterns were drawn in AutoCAD and printed at high resolution on a transparent photomask. Masters were fabricated by spin-coating SU-8-25 negative photoresist on glass slides that had been cleaned in piranha solution (30 min). After pre-baking, exposure, and post-exposure baking (according to SU-8 manufacturer specifications), the photoresist layer was developed by gentle agitation in SU-8 developer. PDMS in a 10:1 base-to-curing agent ratio was poured over the masters, exposed to vacuum to remove air bubbles, and cured at 70 °C for at least four hours. A piranha-washed glass slide and a PDMS cast of the microchannel pattern were both rinsed in isopropyl alcohol, surface-treated for 90 seconds in a plasma cleaner (Harrick Plasma, Ithaca, NY, USA), and then assembled with polyethylene tubing as inlet and outlet ports. Microchannels fabricated in this manner were either used immediately following inlet and outlet assembly, or stored indefinitely for future use.

Cell Culture

A mouse fibroblast cell line (L929) was obtained from the American Type Culture Collection (ATCC), and used as the model cell type for studying the F-L effect. Cells were seeded at ~20,000 cells/cm^2 in tissue-culture-treated polystyrene flasks, and cultured in DMEM supplemented with 10% FBS and 1% P/S. Media was changed every two days, and cells were passaged every four to five days, depending on confluency. To prepare for the F-L experiment, cells were detached from the flasks with 0.05% trypsin with 40 μg/mL EDTA, centrifuged at 284 × g for 7 min, resuspended in supplemented media at 20 million cells/mL, and kept on ice for the duration of the experiment.

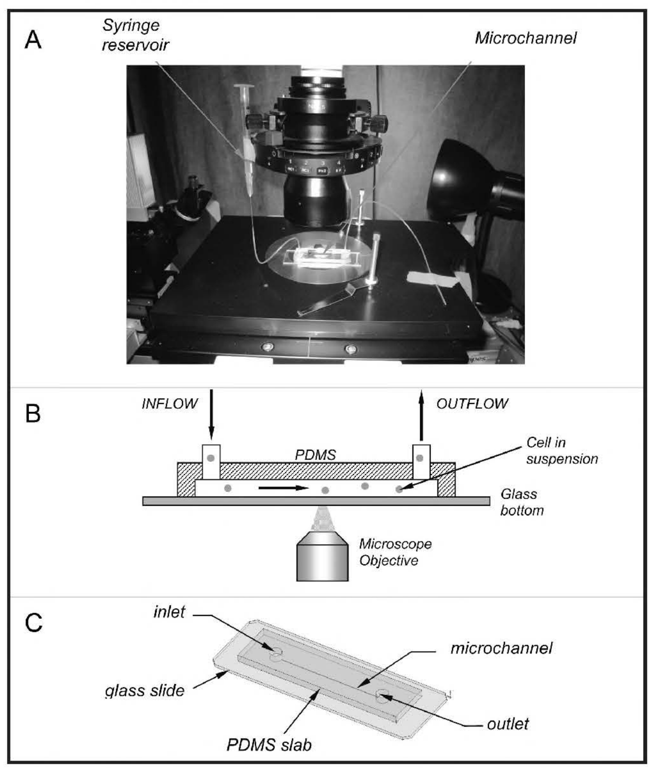

Figure 1. *Microfluidic experimental setup. (A) Gravity-driven flow is generated in the microchannel by securing the syringe containing the cell suspension to the microscope. (B) Side view of cell suspension flowing through microchannel and detected by objective of inverted microscope. (C) Construction of microchannel slide used in the laboratory session.*

Experimental Setup

To observe the F-L effect, an optical microscopy-based method was used (Figure 1). Microchannel slides were mounted on the microscope stage of an optical phase contrast microscope (Olympus IX-71), and connected via polyethylene tubing to an open syringe-needle assembly. The syringe-needle assembly was secured to the microscope at a height of ~10-15 cm above the microchannel. Cells suspended in media at 20 million cells/mL were dispensed into the syringe barrel and allowed to flow into the microchannel by gravity. Phase contrast images of the flowing cell suspension were captured with a CCD camera (QImaging Retiga, Surrey, BC) connected to the microscope, and analyzed using ImageJ software (NIH).

Particle Streak Velocimetry

Phase contrast images of the flowing cell suspension were used to determine the flow rate within the microchannels by particle streak velocimetry.[10] Suspended particles traveling at a steady velocity U generate a streakline in flow of length l over time t. Measuring lengths of streaklines for an image taken with a given exposure time yields velocity $U = l/t$. Particles residing on different streamlines of flow produce streaklines with varying lengths depending on the particles' location. The longest streaklines are found on the horizontal midplane, near the center of the microchannel, and correspond to maximum velocity in the microchannel.

Thus, the mean velocity, flow rate, and ultimately the effective viscosity can be calculated from measurements of the longest streakline in each image and formulae for the theoretical velocity profile in a rectangular microchannel. Figure 2A shows a typical particle streakline image obtained using fluorescent microbeads seeded into a rectangular microchannel, while Figures 2B and 2C are similar images from flowing cells.

Flow in Rectangular Microchannels

The theoretical background presented here was included in the laboratory manual presented to the students (see handout available at <www.introductorybiomechanics.com>). In the original experiments by Fahraeus and Lindqvist,[5] and in subsequent tests by Barbee and Cokelet,[4] fine glass capillaries with circular cross sections were used, and effective viscosity, μ_{eff}, was determined using Poiseuille's law:

$$Q = \frac{\pi R^4}{8\mu_{eff}} \frac{\Delta P}{L} \tag{1}$$

$$u_m = \frac{Q}{A} \frac{2D^2}{64\mu_{eff}} \frac{\Delta P}{L} \tag{2}$$

In Eqs. (1) and (2), Q is the flow rate, ΔP is the pressure drop across the capillary, L is the capillary length, R is the capillary radius, D is the capillary diameter, A is cross-sectional area, and $u_m = Q/A$ is the mean velocity in the channel. The constant $\beta = 64$ is the friction constant, equal to the product of the Reynolds number Re and the friction factor f:

$$\beta = f \cdot Re \tag{3}$$

In the current study, Poiseuille's law was modified for flow in rectangular microchannels.

Eq. (2) thus becomes:

$$u_m = \frac{2}{\beta} \frac{D_h^2}{\mu_{eff}} \frac{\Delta P}{L} \tag{4}$$

where capillary diameter D is replaced by the hydraulic diameter $D_h = 4A/P_w$, and P_w is the wetted perimeter, $P_w = 2(w + h)$. β for rectangular cross sections is governed by an empirical relationship[11] for channel aspect ratio $\alpha = h/w$:

$$\beta = f \cdot Re = 96\left[1 - 1.3553\alpha + 1.9467\alpha^2 - 1.7012\alpha^3 + 0.9564\alpha^4 - 0.2537\alpha^5\right] \tag{5}$$

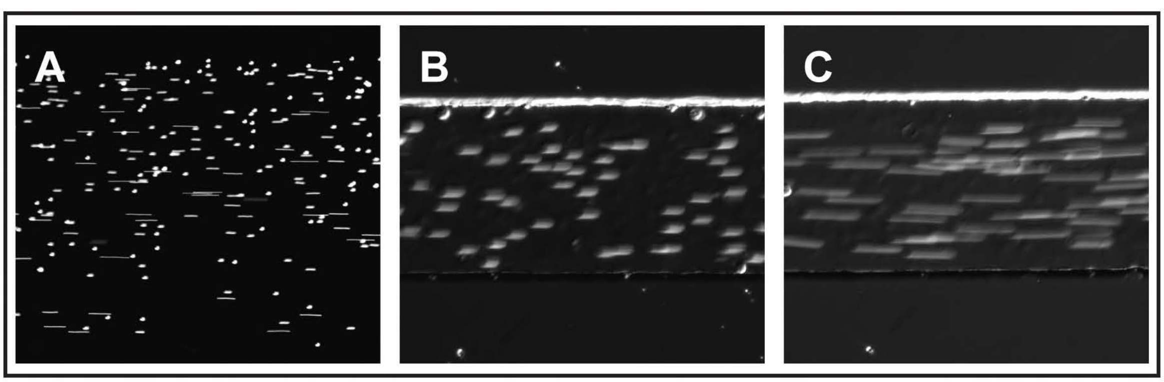

Figure 2. *Particle streak velocimetry using fluorescence microbeads or phase contrast imaging of cells. (A) Fluorescent 1-µm microbeads inside a 500-mm microchannel, using 200 ms exposure time to produce streaklines. (B and C) L929 mouse fibroblasts suspended in media at 20 million cells/mL in a 200-µm wide microchannel, using (B) 3 ms exposure time, and (C) 10 ms exposure time. The short streaklines in (B) were suitable for determining cell density within the microchannel, while the longer streaklines in (C) were suitable for determining velocity.*

For gravity-driven flow, the pressure drop across the channel is $\Delta P = \rho g H$, where H is the height difference from inlet to outlet reservoir. Thus, measurement of the mean velocity in the microchannel provides a solution to the effective viscosity using Eq. (4).

For laminar flow in rectangular channels, an approximation for the fully developed velocity profile was proposed by Purday.[11] For a microchannel of half-width a = w/2, and half-height b = h/2, the laminar velocity profile is:

$$\frac{u}{u_m} = \left(\frac{m+1}{m}\right)\left(\frac{n+1}{n}\right)\left[1-\left(\frac{y}{b}\right)^n\right]\left[1-\left(\frac{z}{a}\right)^m\right] \tag{6}$$

or

$$\frac{u_{max}}{u_m} = \left(\frac{m+1}{m}\right)\left(\frac{n+1}{n}\right) \tag{7}$$

where y is the channel height direction, z is the channel width direction, u and u_{max} are the local axial and maximum velocities, respectively, and m and n are empirical parameters found to be:

$$m = 1.7 + 0.5\alpha^{-1.4} \tag{8}$$

$$n = \begin{cases} 2 & \alpha \le 1/3 \\ 2 + 0.3(\alpha - 1/3) & \alpha > 1/3 \end{cases} \tag{9}$$

Figure 3 illustrates the velocity profile of Eq. (6). The profile is parabolic in the y-direction. The maximum velocity occurs at the midplane at y = 0. This maximum velocity is fairly constant throughout the midplane, except near the side walls where the no-slip condition reduces the velocity to zero.

Normalized Cell Density

To determine volume cell density within each of the four microchannels, short-exposure-time images were captured, and the number of cells in each image was counted. The total cell volume in the image was equal to the product of the number of cells and the volume of one cell, estimated by assuming that each cell was spherical with average diameter 16.5 μm (determined using the Vi-CELL Analyzer (Beckman Coulter, Mississauga, ON)). Dividing the total cell volume by the volume of the channel section in the viewfield yielded the volume cell density. Finally, the volume cell density was normalized by dividing it by the known suspension cell density in the reservoir. This normalized value was equivalent to the relative tube hematocrit reported in the classical F-L experiments.

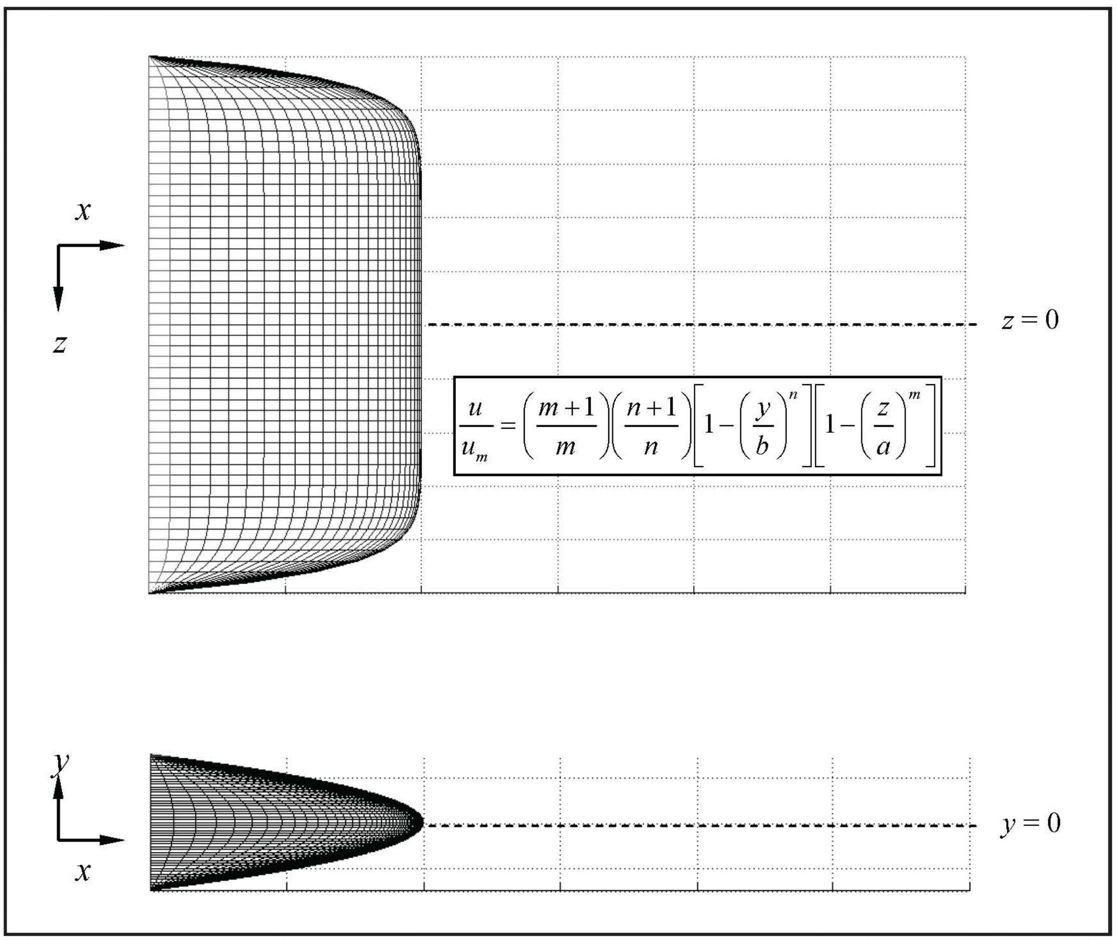

***Figure 3.** Laminar velocity profile in microchannel of rectangular cross-section. The profile in the vertical x-y plane is parabolic for most of the channel width, except near the side walls where the velocity decreases to zero because of the no-slip condition.*

RESULTS OF THE EXPERIMENTS

Experimental trials of the above methods were tested for four microchannels of varying cross-sectional dimensions to demonstrate changes in effective viscosity (Table 1). For each microchannel, the column height of the cell suspension above the microchannel was measured, and 10 images each of short and long exposure time (Figure 2B and 2C) were captured. Short-exposure-time (3 milliseconds in our case) images were used to determine cell density in the microchannels, and long-exposure-time (10 milliseconds in our case) images were used to determine flow rates by particle streak velocimetry.

Figure 4 shows results for effective viscosity and normalized cell density from one representative trial. Effective viscosity was calculated using Eqs. (6) and (7) to determine mean microchannel velocity from measured streaklines, and then using Eq. (4) to solve for μ_{eff}. Effective viscosity decreased monotonically as the hydraulic diameter of the microchannel was reduced. Normalized cell density also decreased with decreasing hydraulic diameter, although the results for the 116- and 176-μm-wide microchannels deviated substantially from the general trend. The results for effective viscosity, and the general trend for normalized cell density, were consistent with the classical observations by Fahraeus and Lindqvist.

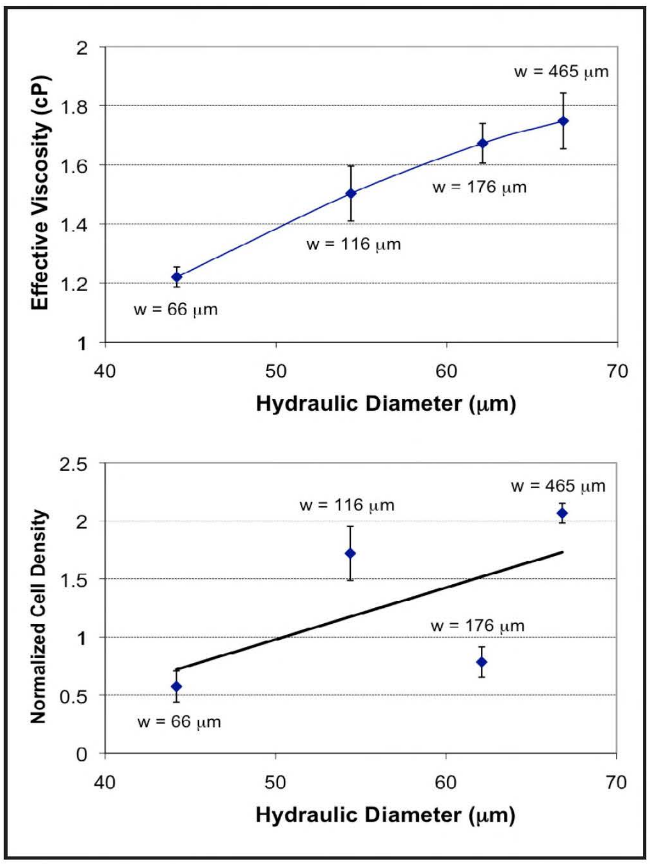

Figure 4. (A) Effective viscosity vs. hydraulic diameter. Effective viscosity decreases monotonically with decreasing hydraulic diameter, as expected from the Fahraeus-Lindqvist effect. (B) Normalized cell density vs. hydraulic diameter. The general trend of decreasing normalized cell density with decreasing hydraulic diameter is apparent.

DISCUSSION OF EXPERIMENTAL RESULTS

Fahraeus and Lindqvist observed that the effective viscosity and relative tube hematocrit of flowing blood in glass capillaries less than 250 μm in diameter both decreased as tube diameter decreased.[5] These phenomena were confirmed by Barbee and Cokelet,[3, 4] and are now frequently cited as textbook examples of the non-Newtonian behavior of blood. To enhance student understanding of this concept, we designed a laboratory session to allow students to observe the F-L effect firsthand. Four microchannels with hydraulic diameters ranging from ~ 40 to 70 μm were fabricated by soft lithography. Gravity-driven flow through the channels demonstrated that the effective viscosity and tube hematocrit decreased for smaller channels, consistent with the F-L effect reported in the literature.

Development of this laboratory session was made possible by the advances in microfluidics technology, and the continuing trend for less expensive and more accessible fabrication techniques. Microfabrication facilities and resources for producing chips by soft lithography are available at many universities, and increasingly so. If these facilities or materials for the production of SU-8 masters are not available or are too costly, alternative fabrication methods may be used, including recently reported techniques that employ Shrinky-Dink thermoplastics,[12] or rapid felt-tip marker masking.[13] While these techniques generally result in microchannels with dimensions that are difficult to characterize accurately due to greater surface roughness and less uniformity along the channel length, they are attractive because of their extremely low cost, and would likely be adequate for demonstration of the F-L phenomenon.

The laboratory procedure involved flowing a concentrated suspension of cells (20 million cells/mL of mouse L929 fibroblasts) through the microfluidic channels. This cell suspension is considerably different from a normal blood sample since there are typically ~5×10^9 RBCs/mL in blood, and RBCs (~ 8 μm) are biconcave disks that are much smaller than the spherical fibroblasts in suspension (~ 16 μm diameter). Using a non-blood sample has several advantages, however. First, the cell concentration can be tailored to produce images that have appropriate lengths of streaklines for easier analysis. A blood sample was used during preliminary lab testing, but the high density of RBCs generated overlapping streaklines, and thus was not well-suited for velocimetry. Secondly, from a biosafety standpoint, the mouse fibroblasts are an established cell line that requires facilities to be biosafety-certified to Containment Level 1 standards.[14] In contrast, human blood samples require Containment Level 2 safety. Since the L929 cells demonstrated the F-L effect in an effective manner, these two advantages made the cell line an attractive alternative to blood. We note that commercial microparticles can be used as an alternative to cells if cell culture facilities are not available, but we suggest that they be avoided if possible since they lack important cellular properties, such as deformability and the propensity for aggregation, that provide students with a more useful learning experience.

The use of the cells themselves as tracer particles was convenient, but the relatively large cell size compared to typical tracer particles meant that the cells likely interacted hydrodynamically with the surrounding fluid, and did not accurately represent the true channel velocity, as when 1-μm particles are used to generate streaklines (Figure 2A). This discrepancy is likely more important for wider microchannels where the cell density is greater, and particle-fluid interactions are therefore greater than in narrower microchannels. For the purposes of this lab, however, it was found that the use of cells did not adversely affect the ultimate outcome and that the F-L effect is clearly noticeable under the proposed experimental conditions.

Results for normalized cell density in the microchannels followed the expected trend as predicted by the F-L effect. There were inconsistencies with some of the results, however. First, the normalized cell densities for the 116- and 465-μm-wide microchannels were larger than unity when normalized cell densities were expected to be always less than unity for conduits having hydraulic diameters less than 250 μm. Second, the 176-μm microchannel had a considerably lower cell density compared to the 116-μm microchannel. These two anomalies may be attributable to two important differences between the experimental setup described here vs. those of the classical experiments: 1) the microchannel cross-section is rectangular, which likely impacts the effective surface area available for a plasma skimming layer to form; and 2) the syringe-needle assembly and microchannel reservoir geometry likely concentrated the cell suspension prior to its entrance into the microchannel, leading to cell densities higher than the density predicted for the reservoir cell suspension. This latter issue may be avoided by re-designing the microchannel geometry at the inlet port to reduce the amount of cell accumulation.

COURSE BACKGROUND, LABORATORY IMPLEMENTATION, PEDAGOGY, AND FEEDBACK

Course background

The lab has been conducted the past two years as part of MIE439-Biomechanics, a one-semester senior-level course offered by the Department of Mechanical & Industrial Engineering at the University of Toronto. The course serves as a capstone elective primarily for students in the bioengineering streams of mechanical and chemical engineering, and those in the biomedical engineering program of the Division of Engineering Science. This course provides a broad survey of topics within biomechanics, ranging from cell biomechanics to human locomotion, with emphasis on solving physiological problems using basic engineering principles. The course is popular, with typical enrollment of approximately 40-60 senior engineering students each semester. The course consists of three one-hour lectures per week, biweekly tutorial sessions, three laboratories per semester, and a semester-long group project. Evaluation is based on mid-term and final examinations, laboratory reports, homework assignments, and final class presentation and written technical report of the group project. There are no formal prerequisites, but the nature of the curricula ensures that all students have basic understanding of elementary dynamics, application of the Navier-Stokes equations, the concept of viscosity, and the difference between Newtonian and non-Newtonian fluids; these concepts are also reviewed during lecture. Indeed, it is the application of these principles and the synthesis of fundamental concepts from lower-level courses to solve complex biological problems that make this course unique from other electives.

Laboratory Logistics and Personnel

The laboratory was held in the undergraduate teaching laboratory of the Institute for Biomaterials and Biomedical Engineering (IBBME) at the University of Toronto. The IBBME teaching facility has biosafety level 1 (BSL-1) designation and has basic equipment for sterile cell culture work, as well as six phase contrast microscopes equipped with video cameras and basic imaging software.

Due to practical issues of course scheduling and the limited capacity of the teaching lab, the lab has been run in three one-hour sessions the past two years. In each section, students were further divided into groups of three to four students, with each group stationed at one microscope with one set of microchannels to obtain a shared set of data between all team members. Because of these logistics, the lab assignment was designed for completion within 50-60 minutes and preparations were made to attempt smooth transition between the three sections of students, such that as one section completed their work and the next was ready to begin.

TABLE 1
Measured Microchannel Dimensions

Channel	Height (μm)	Width (μm)	Cross Sectional Area (10^3 sq. μm)	Hydraulic Diameter (μm)
1	33.2	66	2.2	44.2
2	35.5	116	4.1	54.4
3	37.7	176	6.6	62.1
4	36	465	16.7	66.8

One week prior to the laboratory session, the students were divided into their groups and informed of the logistics. In the week leading up to the lab, various preparations were made. A laboratory manual was posted on the course Web site for students to download (available at <www.introductorybiomechanics.com>). The relevant theoretical concepts were presented in the regular lectures prior to the lab so that the lab served as reinforcement of the lecture material. Also during the week before the lab, cells were maintained and expanded in the teaching facility by a teaching assistant and lab technician to obtain sufficient quantities for running the lab. On lab day, the instructor, teaching assistant, and lab technician were present for the entire three-hour session to provide basic background materials, assist the students in setup, monitor their progress during the assignment, and provide formative feedback. Because dedicated hands-on training could not be provided due to limited resources, student groups relied on help from the staff and, in some cases, team members who had cell-handling and lab-bench experience from other bioengineering courses. Students were also given detailed instructions in the lab handout on how to operate the microscope and use the software package, and they were expected to come to the lab having read the material.

After completion of the lab, students were asked to analyze the data and complete three post-lab questions listed in the laboratory manual. The questions provided students with the opportunity to re-examine the experimental design, and discuss possible sources of error in the experiment. Since the post-lab questions were given to the students before the start of the lab, students were prepared to make observations about the procedure, and discuss possible improvements for the lab.

In terms of material costs and other resources, the teaching facility provided the space and access to equipment. Device fabrication and cell maintenance and expansion totaled approximately \$200 CAD. Approximately 30 hours of time from the teaching assistant were devoted to design, development, and validation of the lab procedure prior to the pilot study. An additional 10 hours subsequent to development were devoted to preparations for operation of the actual lab, including microdevice fabrication, cell maintenance and expansion, student interaction on the day of the lab, and post-lab feedback.

Laboratory Pedagogy

The laboratory exercise served mainly to reinforce the concept of the F-L effect taught in lecture. An additional benefit of the lab, however, was that it acted as a hands-on exercise in cell handling, microscopy, and flow visualization, as well as a tool to reinforce other aspects of the bioengineering curriculum. Blood rheology and hemodynamics comprise a significant portion (approximately 25%) of the lecture material in MIE439, yet prior to this lab, the material was presented only during lectures and not through an active-learning experience. Engineering students have many different learning styles,[15] and lab exercises such as the one described here

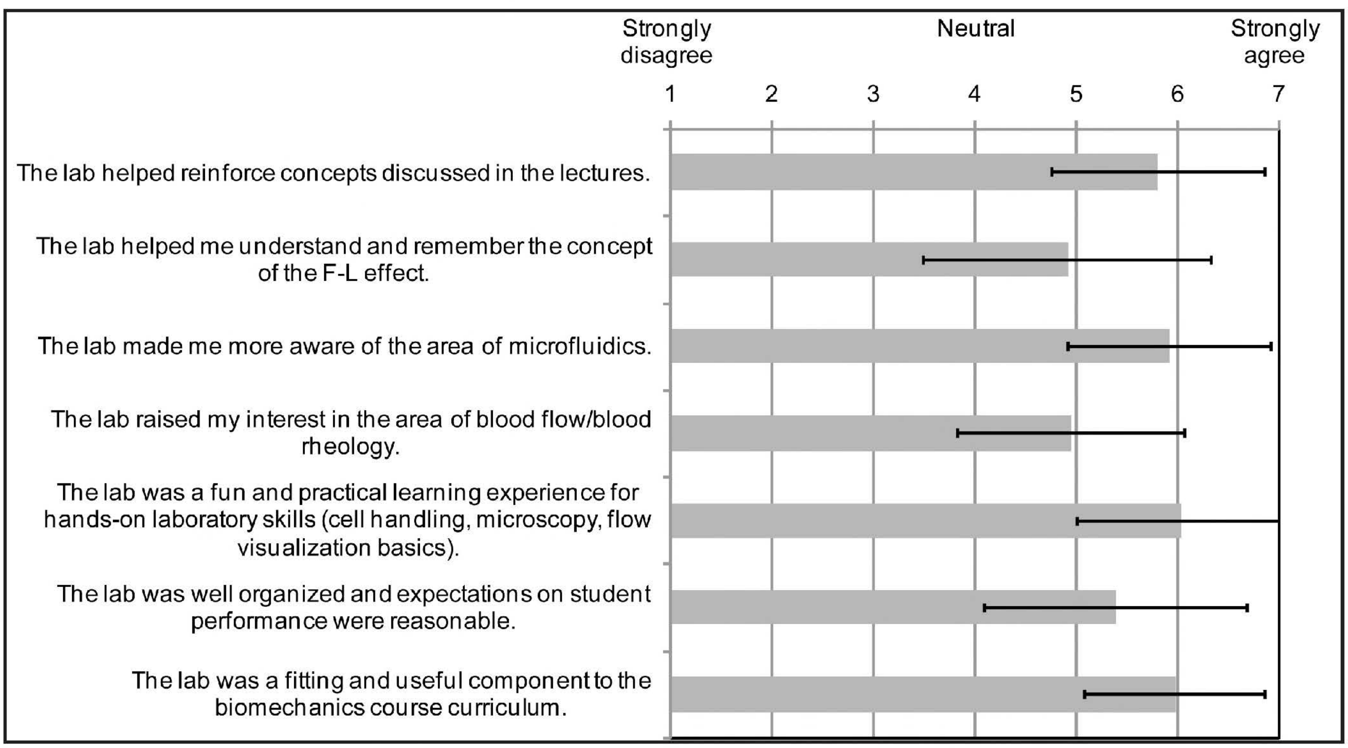

Figure 5. *Summary of student feedback from a voluntary online survey. Bars represent mean ± standard deviation for 34 to 36 responses per question.*

complement the lecture material, provide a visual representation to abstract concepts, and cater to the visual and sensory learners of the class.[16]

Other than the content described in the lab handout, students were not responsible for additional material related to microfabrication or microfluidics since these were not main topics within the course. Nonetheless, the exposure to microfluidics allows the students to learn basic aspects about this emerging field, its impact on biological and biomedical research activities, and its associations with other relevant courses in their chemical, mechanical, or biomedical engineering programs. Thus, the microfluidics aspect of the current lab assignment provides students with a clear example of the integrative nature of bioengineering as well as the importance of making connections between different science and engineering disciplines, an issue that remains an ongoing challenge in the development of core bioengineering curricula at many universities.[17]

The post-lab activities were limited to student contemplation of the questions posed in the lab handout. A formal laboratory report was not required, so as to relieve the "burden" of another report[18, 19] and to allow the students to focus on learning the concepts. To ensure the material was reviewed and the questions answered, the students were informed before the lab that a question on the final exam would be based directly on the lab exercise. As such, answers to the post-lab questions were not provided to the students. Though some may argue that a mandatory write-up of the exercise would have further improved chances of students retaining the material,[20] our guarantee of a final exam question in fact resulted in more student-staff interaction, and created a new opportunity for formative feedback because students came forward to discuss their interpretations of the post-lab questions with the teaching staff in preparation for the exam.

Logistics and resource limitations prevented the students from receiving hands-on training on the equipment prior to the lab. Therefore, to successfully complete the lab, teams had to rely on the laboratory manual and laboratory staff for assistance, but more often on their colleagues' experience and the team's ability to solve problems. Thus, an unintended benefit of the lab exercise was that it provided an opportunity for students to engage in face-to-face promotive interaction and to develop collaborative skills for future team-based projects.[21]

Student Feedback

Students in the Fall 2008 course were asked to provide feedback by completing a voluntary online survey; approximately 60% of the students responded. Feedback was generally very positive (Figure 5). The majority of students moderately or strongly agreed that the lab reinforced concepts from lecture and helped them understand and remember the F-L effect—the main objectives of the lab exercise. Many students appreciated the "hands-on experience" that was closely aligned with

An additional benefit of the lab was that it acted as a hands-on exercise in cell handling, microscopy, and flow visualization, as well as a tool to reinforce other aspects of the bioengineering curriculum.

lecture material, such that the lab enabled them to "visualize the F-L effect," making it "very educational" and "useful for understanding the theory" from lecture. As summarized by one student: "Anyone can draw diagrams of fluid flow in capillaries and provide the equations, but it didn't really mean anything to me until I saw it happen—and this lab enabled that." Similarly, the vast majority of students moderately or strongly agreed that the lab was a fun and practical learning experience for hands-on laboratory skills that had the added benefit of making them more aware of microfluidics. The opportunity to work with "cutting-edge," "high-tech" equipment that was "simple," involved "something other than computer simulations," and allowed them to see "real cells" was mentioned frequently by the students. In total, 94% of the students agreed that the lab exercise was a useful component of the course curriculum.

Most students generally "appreciated being able to use the (laboratory) time to learn the concepts without the pressure or burden of having an ugly follow-up report." In contrast, a minority felt that a formal lab report would further reinforce concepts by forcing the students to answer the questions fully. Interestingly, only 56% of students agreed that the lab helped their performance on the final exam. Qualitatively, students did very well on the exam question related to the lab, but because a similar question was not asked in years prior to implementing the lab, it is not known to what extent the lab exercise was responsible for the students' performance. The majority of students reported that they were more interested in blood rheology as a result of the lab.

Criticisms and suggestions for improvement were primarily related to the logistics of the lab. Many students commented that they would have preferred more than one hour to complete the lab because they had felt rushed, and several felt that the groups should be limited to two students so that there would be more opportunity for everyone to get hands-on experience and the laboratory room would be less crowded. Laboratory and course staff had the same opinion, and these issues will be addressed in the future by having several 1.5 hour sessions over multiple days. Other criticisms were related to equipment issues (*e.g.*, a malfunctioning camera, software problems, leaky connections in some chips), and problems with cells clogging in the channels, which delayed data collection. Clogs were readily cleared by application of positive pressure with the syringe, and—as suggested by one student—may be minimized by using other cell lines, such as nonadherent Jurkat cells (an immortalized line of T-cells).

CONCLUSIONS

Microfluidics was successfully implemented into an undergraduate teaching laboratory session to demonstrate the Fahraeus-Lindqvist effect visually through optical imaging. Effective viscosity and normalized cell density within the microchannels was calculated and compared qualitatively to expected results. Overall, the experiment produced results that were consistent with the observations made originally by Fahraeus and Lindqvist. The experimental setup was easy, affordable (assuming soft lithography equipment and biosafety-certified laboratory facilities are available), and reasonable to manage. Students learned to apply particle streak velocimetry as a technique for determining flow rate within microchannels, and were able to observe flow phenomena firsthand in a practical laboratory setting. The implementation of this lab session therefore appealed to visual and sensory learners, and generated interest in the topic on hemodynamics and blood rheology.

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Random Thoughts . . .

PRIORITIES IN HARD TIMES

Richard M. Felder
North Carolina State University

It's been one annoying budget cut after another around here lately, and when I read the memo limiting faculty members to one box of paper clips a year I went straight to Kreplach, my guru on administrative policy. (I almost went to him when the toilet paper memo came out but got distracted.) I found him in his office, staring at his computer.

Me: Good morning, Kreplach—got a few minutes?

Kreplach: Certainly, certainly—I was just reading the Chancellor's invitation to the reception for the new Deputy Associate Vice Chancellor for Parking Permits.

M: I hadn't heard about that position—seems pretty specialized.

K: Maybe, but it's essential. Ever since the motor pool was cut to three cars and a pair of roller blades, the Associate Vice Chancellor for Vehicular Affairs has been spending so much time on backed-up requests that it's been cutting into his midday power walk.

M: I can see why he'd be distressed.

K: Who wouldn't be? Anyway, what can I do for you, my boy?

M: I was just told that we're limited to a box of paper clips a year, and it seemed to me that...

K: Ah yes—you have me to thank for that.

M: You?

K: Absolutely! The Provost's original plan was to have faculty requisition one clip at a time from Central Stores, and I talked him out of it.

M: Well done, Kreplach—what a waste of faculty time that would have been!

K: Faculty time? . . . Oh, I suppose there's that too, but the real issue was the added load it would have put on Central Stores, especially since they just cut the service staff in half. We would have had to add a new assistant provost just to coordinate paper clip dispensation.

M: Point taken—but really, isn't rationing paper clips a little over the top?

K: Not at all. You know we've been mandated by the legislature to cut our expenses by 15%, which means we all have to make sacrifices.

M: True enough, but I still think the administration is overdoing the penny-pinching, and the faculty is taking the biggest hits.

K: It may look that way to you, but only because as usual you're missing the big picture. We're all assuming our fair share of the burden, with the administration leading the way.

M: That's reassuring to know.

K: Yes, and everything that can be cut is on the table except critical functions the university simply couldn't manage without . . . . excuse me, that's the Chancellor calling, let me just . . . Hello, sir . . . right . . . Flight 207 to Honolulu . . . business class . . . meet you in the departure lounge . . . great, see you then . . . Ciao.

M: Sounds like a big trip coming up.

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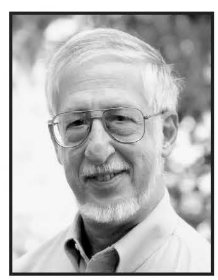

K: Yeah, it's a high-level conference on maintaining administrators' salaries in the face of budget cuts . . . now where were we?

M: Everyone is sharing the burden and only indispensable functions aren't being cut.

K: Right.

M: But see here, Kreplach—a conference trip to discuss salaries doesn't seem like an indispensable function, especially since faculty travel has been completely suspended.

K: Except for emergencies—and if the potential impact of these cuts on the Chancellor's salary doesn't count as an emergency, I don't know what does.

M: That makes sense . . . but Hawaii in business class?

K: Look, if we want to keep our top administrative talent we have to treat them right. If we tell the Chancellor he can't go to this conference or the one in Paris next month on modern developments in dry-erase marker technology, or that he has to fly economy class, his CV will be on its way to Stanford in the next FedEx pickup.

M: We certainly can't risk that.

K: No indeed . . . and it might interest you to know that he insisted on flying business class to Paris instead of first class—that's just the kind of team player he is.

M: Unbelievable—the man is a saint! So, any other budget cuts coming down the pike?

K: Well, yes, but I need you to keep this one under your hat until it's official. Last week yours truly came up with an idea that will save the university tens of millions every year and it got the Chancellor's approval yesterday. I even impressed myself with this one.

M: I'm all ears.

K: Okay, first we make the minimum class size in freshman courses 250, which means we can get rid of three-quarters of the English and Math faculties. That already saves millions. Next we eliminate PE, which lets us convert all those open gym spaces to auditoriums big enough for the new freshman classes, and—here's the beauty part—we no longer have to heat the gym! Someone in mechanical engineering figured out that the body heat from all those students should be enough to keep the building comfy even in the dead of winter.

M: Kreplach, that's the most brilliant plan I've ever . . .

K: Wait, I'm not done yet! Those vacant rooms where the freshman classes used to meet? We rent them out to small businesses!

M: Fast food places, I suppose?

K: Nope—plenty of those across the street. I was trying to think of something students spend lots of money on but can't get easy local access to . . . and then it hit me. Composition facilitation!

M: Say what?

K: You know—a student has a paper or project report to write and turns to a skilled professional for help with the background research and the paper composition, and then . . .

M: Wait a minute, Kreplach—are you talking about those outfits that write students' papers?

K: Certainly not—that would be unethical. This service would just produce first drafts and the students would then do their own supplementary research and rewriting, with a reasonable percentage of the fee—say, 60%—going into the Provost's discretionary fund.

M: But what would keep the students from just turning in the papers as their own work?

K: Aha—I anticipated that some cynical faculty members would raise that unlikely scenario, so I make the students pledge that everything in the paper is either their words or exactly what they would have written.

M: Fiendishly clever—that should satisfy even the most jaded among us! Kreplach, I've got to hand it to you—you've thought of everything.

K: Coincidentally, that's just what the Chancellor said. He was so excited about all those savings that he switched himself back into first class on the Paris flight, and then he . . . oh my goodness, look at the time! I've enjoyed this little chat but I need to run to a meeting with the Search Committee for the Deputy Vice Provost for Emergency Relief Revenues.

M: Boy, that sounds really important! I imagine a serious salary goes with it.

K: You got that right, but it's crucial if you want to get someone with the right qualifications for a sensitive job like this one—all hell could break loose if you put an amateur in charge of converting all the rest rooms on campus to pay toilets. Oh, by the way—would you happen to have an extra paper clip on you? ❐

All of the *Random Thoughts* columns are now available on the World Wide Web at
http://www.ncsu.edu/effective_teaching and at http://che.ufl.edu/~cee/

The object of this column is to enhance our readers' collections of interesting and novel problems in chemical engineering. We request problems that can be used to motivate student learning by presenting a particular principle in a new light, can be assigned as novel home problems, are suited for a collaborative learning environment, or demonstrate a cutting-edge application or principle. Manuscripts should not exceed 14 double-spaced pages and should be accompanied by the originals of any figures or photographs. Please submit them to Dr. Daina Briedis (e-mail: briedis@egr.msu.edu), Department of Chemical Engineering and Materials Science, Michigan State University, East Lansing, MI 48824-1226.

BIOKINETIC MODELING OF IMPERFECT MIXING IN A CHEMOSTAT

an Example of Multiscale Modeling

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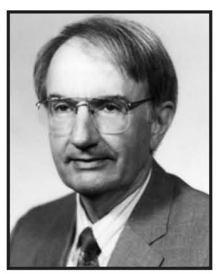
Mathematical software packages such as Excel®, MAPLE™, MATHCAD®, MATLAB®, Mathematica®, and POLYMATH™ are currently used routinely for numerical problem solving in engineering education.[1, 2] From the numerical solution perspective, it is convenient to characterize the various problems as Single Model-Single Algorithm (SMSA) problems and complex problems with some combination of Multiple Models and Multiple Algorithms (MMMA). A typical example of an SMSA problem is the solution of a system of ordinary differential equations coupled with explicit algebraic equations where one numerical integration algorithm (such as the 4th order Runge-Kutta) can be used to solve the problem (*e.g.*, steady-state operation of a tubular reactor).

The application of mathematical software packages for solving SMSA problems has essentially replaced all other solution techniques, as can be seen in many recent textbooks (see, for example, Fogler[3]). For complex and/or multi-scale problems, however, the solution process is often more involved.

The types of models included in the "complex" category are:

1. *Multiple Model-Single Algorithm (MMSA) Problem.* *A typical example is the cyclic operation of a semi-batch bioreactor.[4] The three modes of operation of the*



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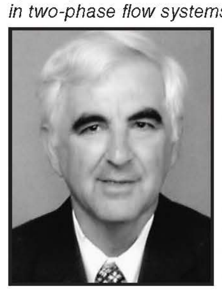

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bioreactor (initialization, processing, and harvesting) are represented by different models comprising ordinary differential equations and explicit algebraic equations. All models can be solved by one numerical integration algorithm (such as the 4th order Runge-Kutta).

2. Single Model-Multiple Algorithm (SMMA) Problem. *Typical examples are the solution of two-point boundary value problems, where the integration of the model is carried out in the inside loop and a nonlinear equation solver algorithm adjusts the boundary values in an outer loop, or the solution of differential-algebraic systems of equations where the same algorithms are used but in an opposite hierarchy.*
3. Multiple Model-Multiple Algorithm (MMMA) Problem. *A typical example is the modeling of an exothermic batch reactor, where the two stages of operation (heating and cooling) require different models and different integration algorithms (stiff and non-stiff).*

The solution of such complex problems can be rather cumbersome and time consuming even if mathematical software packages are used, as manual transfer of data from one model/problem to another and consecutive manual reruns are often required. Combining the use of several software packages of various levels of complexity, flexibility and user friendliness, however, can considerably reduce the time and effort required for solving complex models.

Following this premise, the models representing the various stages of the problems can be coded and tested using a software package (for example, POLYMATH[5]) that requires very little technical coding effort. After testing each of the modules separately, they are combined into one program using a programming language, or a mathematical software package that supports programming (say, MATLAB[6]). To minimize the probability of introducing errors into the model equations, the POLYMATH input for the various modules can be automatically converted within POLYMATH to MATLAB code. This allows MATLAB functions to be created that enable the consecutive and repetitive calls to the various models, apply the appropriate solution algorithms, and assign the hierarchy of the computations during the solution.

A homework assignment that demonstrates this suggested approach is the following problem of biokinetic modeling of a chemostat with imperfect mixing. This problem is a modified version of a problem presented by Cutlip and Shacham.[7] The solution algorithm presented for this problem includes the use of various computing tools in the different stages of the problem solution (the solution of an SMSA problem, parametric runs of an SMSA problem, and the solution of an SMMA problem).

PROBLEM BACKGROUND

Biokinetic Modeling of Imperfect Mixing in a Chemostat

A chemostat is usually considered to be a completely mixed reactor; however, this is not always the case. Consider the situation where the chemostat may be considered to be modeled as a reactor with a completely-mixed volume V_1 (dm^3) that interacts with another completely-mixed volume V_2 (dm^3) as shown in Figure 1. Volume V_2 with an exchange flow rate F_2 (dm^3/hr) may be considered to model the poorly mixed regions within a production fermenter. The microbial

TABLE 1
POLYMATH Model for the Chemostat with Imperfect Mixing

No.	Equation # Comment
1	f(S1) = F1*S0+F2*S2-(1/Yxs)*(mum*S1/(Ks+S1))*X1*V1-F1*S1-F2*S1 # Substrate balance on volume V1
2	f(S2) = F2*S1-(1/Yxs)*(mum*S2/(Ks+S2))*X2*V2-F2*S2 # Substrate balance on volume V2
3	f(X1) = F2*X2+(mum*S1/(Ks+S1)-kd)*X1*V1-F1*X1-F2*X1 # Cell balance on volume V1
4	f(X2) = F2*X1+(mum*S2/(Ks+S2)-kd)*X2*V2-F2*X2 # Cell balance on volume V2
5	F1 = 0.17 # Feed flow rate to volume V1 (dm^3/hr)
6	F2 = 0.2*F1 # Feed flow rate to volume V2 (dm^3/hr)
7	P1 = Yps*(S0-S1) # Production (g/dm^3)
8	D = F1/(V1+V2) # Dilution rate (1/hr)
9	S0 = 0.6 # Feed substrate concentration (g/dm^3)
10	kd = 0.002
11	Yxs = 0.4 # Yield coefficient (g cells/g substrate)
12	Yps = 0.2 # Yield coefficient (g product/g substrate)
13	Ks = 0.2 # Saturation constant (g substrate/dm^3)
14	mum = 0.2 # Maximal specific growth rate (1/hr)
15	V1 = 1.7 # Volume V1 (dm^3)
16	V2 = 0.3 # Volume V2 (dm^3)
17	PR_DX1 = D*X1 # Cell production rate (g/hr)
18	PR_DP1 = D*P1 # Product production rate (g/hr)
19	S1(0) = 0 # Substrate concentration in volume V1 (g/dm^3)
20	S2(0) = 0 # Substrate concentration in volume V2 (g/dm^3)
21	X1(0) = 0.025 # Cell concentration in volume V1 (g/dm^3)
22	X2(0) = 0.025 # Cell concentration in volume V2 (g/dm^3)

system to be modeled involves substrate S (g/dm^3) going to product P (g/dm^3) only under the action of cells X (g/dm^3). The following separate balances on the substrate, cells, and product in each reactor volume use Monod kinetics and a cell death rate constant given by k_d (hr^{-1}).

Steady-State Substrate Balance on Volume V_1

$$F_1S_0 + F_2S_2 + \frac{1}{Y_{X/S}}\left(\frac{\mu_m S_1}{K_S + S_1}\right)X_1V_1 = F_1S_1 + F_2S_1 \qquad (1)$$

where F is flow rate (dm^3/hr), $Y_{X/S}$ is yield coefficient (g cells/g substrate), μ_m is the maximal specific growth rate (hr^{-1}), and K_S is the saturation constant (g substrate/dm^3). The indexes 0, 1, and 2 are used as shown in Figure 1.

Steady-State Substrate Balance on Volume V_2

$$F_2S_1 + \frac{1}{Y_{X/S}}\left(\frac{\mu_m S_2}{K_S + S_2}\right)X_2V_2 = F_2S_2 \qquad (2)$$

Steady-State Cell Balance on Volume V_1

$$F_2X_2 + \left(\frac{\mu_m S_1}{K_S + S_1} - k_d\right)X_1V_1 = F_1X_1 + F_2X_1 \qquad (3)$$

Steady-State Cell Balance on Volume V_2

$$F_2X_1 + \left(\frac{\mu_m S_2}{K_S + S_2} - k_d\right)X_2V_2 = F_2X_2 \qquad (4)$$

Overall Steady-State Material Balance for the Product

$$P_1 = Y_{P/S}\left(S_0 - S_1\right) \qquad (5)$$

where $Y_{P/S}$ is the yield coefficient (g product/g substrate).

PROBLEM STATEMENT

Microbial growth has been studied in a continuous culture, and the following parameters were obtained: $\mu_m = 0.2\ h^{-1}$, $K_S = 0.2\ g/dm^3$, $k_d = 0.002\ hr^{-1}$, $Y_{X/S} = 0.4$ g cells/g substrate, and $Y_{P/S} = 0.2$ g product/g substrate. Tracer studies have indicated that the incomplete mixing can be described by a well-mixed volume $V_1 = 1.7\ dm^3$ and a volume of $V_2 = 0.3\ dm^3$ with an exchange flow rate F_2. The flow rate relationship with the overall flow rate to chemostat, F_1, is given by $F_2 = 0.2\ F_1$ in dm^3/hr. Chemostat operation is such that $F_1 = 0.17\ dm^3/hr$, $X_0 = 0$ and $S_0 = 0.6\ g/dm^3$, and the endogenous metabolism can be neglected.

(a) *Create a single graph of S_1, X_1, and P_1 vs. the dilution rate defined by $D = F_1/V_1$.*

(b) *Plot the cell production rate, the product DX_1, and the product production rate, the product of DP_1, as functions of the dilution rate between 0.05 and 0.130 hr^{-1}.*

(c) *Estimate the dilution rate that will maximize the production rate, DX_1, for the cells and the dilution rate that will maximize the production rate, DP_1, for the product.*

PROBLEM SOLUTION

Modeling the Chemostat and Solving the Single Model-Single Algorithm (SMSA) Problem

The mathematical model of the chemostat can be formulated as a system of nonlinear algebraic equations (NLEs) that can be solved by a single algorithm. This simple, uncomplicated model can be easily solved with POLYMATH version 6.1 to obtain the solution of this SMSA problem.

The complete POLYMATH code for the chemostat model is given in Table 1. The model includes four implicit nonlinear algebraic equations that are obtained from the material balances. The POLYMATH model (including the "comments," which start with the # sign) provides complete documentation of the equations, the values of the constants, and the initial estimates used for the four unknowns: S_1, S_2, X_1, and X_2. Statements 1 through 4 present the implicit equations for obtaining the substrate concentration in the well-mixed volumes (S_1, S_2, respectively), and the cell concentration in the well-mixed volumes (X_1, X_2, respectively). Explicit variables and constants are described in statements 5-18. Initial estimates for the unknowns in the nonlinear equations are provided in lines 19 to 22.

The results for the case where $F_1 = 0.17\ dm^3/hr$ and the initial estimates $S_{1,0} = S_{2,0} = 0$, $X_{1,0} = 0.025$, and $X_{2,0} = 0.025$ are given in Table 2. For this case with the dilution rate D =

TABLE 2
Chemostat Results From POLYMATH For $F_1 = 0.17\ dm^3/hr$

Variable	Value	f(x)	Initial Guess
S_1 (g/dm^3)	0.1821	4.20E-11	0
S_2 (g/dm^3)	0.03589	3.91E-11	0
X_1 (g/dm^3)	0.1631	-1.68E-11	0.025
X_2 (g/dm^3)	0.2178	-1.56E-11	0.025
D (1/hr)	0.085		
F_1 (dm^3/hr)	0.17		
F_2 (dm^3/hr)	0.034		
PR_DP1 (g/hr)	0.00711		
PR_DX1 (g/hr)	0.01387		

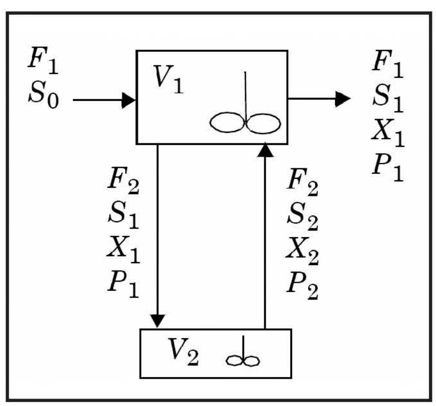

Figure 1. Chemostat model.

TABLE 3
MATLAB Function (Model) for the Chemostat with Imperfect Mixing

No.	Equation % Comment
1	function fx = MNLEfun(x, F1);
2	S1 = x(1); %Substrate concentration in volume V1 (g/dm^3)
3	S2 = x(2); %Substrate concentration in volume V2 (g/dm^3)
4	X1 = x(3); %Cell concentration in volume V1 (g/dm^3)
5	X2 = x(4); %Cell concentration in volume V2 (g/dm^3)
6	F1 = 0.17; %Feed flow rate to volume V1 (dm^3/hr)
7	F2 = 0.2 * F1; %Feed flow rate to volume V2 (dm^3/hr)
8	Yps = 0.2; %Yield coefficient (g product/g substrate)
9	V2 = 0.3; %Volume V2 (dm^3)
10	S0 = 0.6; %Feed substrate concentration (g/dm^3)
11	kd = 0.002; %Cell death rate (1/hr)
12	Yxs = 0.4; %Yield coefficient (g cells/g substrate)
13	P1 = Yps * (S0 - S1); %Production (g/dm^3)
14	Ks = 0.2; %Saturation constant (g substrate/dm^3)
15	mum = 0.2; %Maximal specific growth rate (1/hr)
16	V1 = 1.7; %Volume V1 (dm^3)
17	D = F1 / (V1 + V2); %Dilution rate (1/hr)
18	PR_DX1 = D * X1; %Cell production rate (g/hr)
19	PR_DP1 = D * P1; %Product production rate (g/hr)
20	fx(1,1) = F1 * S0 + F2 * S2 - (1 / Yxs * mum * S1 / (Ks + S1) * X1 * V1) - (F1 * S1) - (F2 * S1); %Substrate balance on volume V1
21	fx(2,1) = F2 * S1 - (1 / Yxs * mum * S2 / (Ks + S2) * X2 * V2) - (F2 * S2); %Substrate balance on volume V2
22	fx(3,1) = F2 * X2 + (mum * S1 / (Ks + S1) - kd) * X1 * V1 - (F1 * X1) - (F2 * X1); %Cell balance on volume V1
23	fx(4,1) = F2 * X1 + (mum * S2 / (Ks + S2) - kd) * X2 * V2 - (F2 * X2); %Cell balance on volume V2

TABLE 4
Part of the MATLAB “Main Program” for Parametric Studies with the Chemostat

No.	Equation % Comment
1	options = optimset(‘Diagnostics’,[‘off’],’TolFun’,[1e-9],’TolX’,[1e-9]);
2	Yps = 0.2; S0 = 0.6; kd = 0.002; Yxs = 0.4; Ks = 0.2;
3	mum = 0.2; V1 = 1.7; V2 = 0.3;
4	F1=0.1; %Initial feed flow rate to volume V1 (dm^3/hr)
5	xguess = [0 0 0.025 0.25]; % initial guess vector
6	for k=1:16
7	xsolv=fsolve(@MNLEfun,xguess,options,F1);
8	S1(k)=xsolv(1); S2(k)=xsolv(2); X1(k)=xsolv(3); X2(k)=xsolv(4);
9	F1list(k)=F1; D(k) = F1 / (V1 + V2); P1(k)= Yps * (S0 - S1(k));
10	PR_DX1(k) = D(k) * X1(k); PR_DP1(k) = D(k) * P1(k);
11	F1=F1+0.01; %Incrementing feed flow rate to volume V1 (dm^3/hr)
12	end

0.085 hr^{-1}, the cell production rate $DX_1 = 0.0139$ g/hr and the product production rate $DP_1 = 0.00711$ g/hr. Lower initial values of $X_{1,0} = X_{2,0}$ that are less than 0.0247 g/dm^3 result in negligible steady-state reaction corresponding to cell washout operation. Thus the simulated chemostat has a critical value of initial cell concentration that leads to a sustained steady-state biochemical reaction. The production rates associated with the operation where washout of the cells is avoided will be studied in more detail.

Parametric Studies on the Chemostat

Parametric runs, requested in the second part of the assignment, can be carried out with POLYMATH by manually changing the parameter values. This approach, however, is inefficient and cumbersome—particularly for problems where there are many parameters and a wide range of parameter values to be considered. In such cases, programming is desirable for repetitive solution of the problem with the various parameter values. One option is to carry out the parametric runs efficiently using MATLAB. The MATLAB function representing the operation of the chemostat can be automatically and efficiently generated by POLYMATH (Table 3). Note that MATLAB requires input of the variable values into the function in a single array (**x**, in this case), and return of the function values in a single array (**fx**, lines 20-23 in Table 3). The variable values are put back into variables with the same names as used in the POLYMATH model (lines 2-5) to make the MATLAB code more meaningful. POLYMATH orders the basic model equations sequentially as required by MATLAB and converts any needed intrinsic functions and logical expressions.

Convenient parametric runs can be made for various values of the feed flow rate (F_1), and this variable can be added as an input parameter to the MNLEfun function (Table 3). A main program can be prepared that changes the value of F_1, solves the system of nonlinear equations, collects the pertinent data, and plots the results of the parametric runs. Part of this main program is shown in Table 4. The value of F_1 is changed starting at $F_1 = 0.1$ up to $F_1 = 0.25$ with steps of 0.01. The MATLAB library function *fsolve* is used to solve the system of algebraic equations as shown in line 7 of Table 4. The variable values needed for preparing the various plots are calculated and stored in lines 8 through 10.

Excel[8] can also be used for carrying out the parametric runs efficiently. The model can be automatically exported from POLYMATH to Excel with a single key press. Part of the Excel worksheet as generated by POLYMATH is shown in Table 5, where the variable cell calculations are indicated. The variable names are translated to cell addresses, a new equation that calculates the sum of squares of the function values is added, and the equations are rearranged in a form that is appropriate for solving the equation using the *solver* add-in available within Excel. The complete worksheet with the solution obtained using solver is shown in Table 6 (next page). The numerical results are identical to those obtained by POLYMATH. The variable names in column B, the POLYMATH equations in column D, and the variable descriptions in column E provide complete documentation for the Excel formulas in column C.

Solution of the system of equations using *solver* for various values of F_1 requires the creation of a macro or a VBA (Visual Basic for Applications[8]) program. A plot of S_1, X_1, and P_1 as functions of the dilution rate is shown in Figure 2, and the cell and product production rates are plotted in Figure 3. Maximum points for the two production rates in the vicinity of $D = 0.1$ hr^{-1} can be observed in this figure. A more precise determination of the maximum is discussed in the next section.

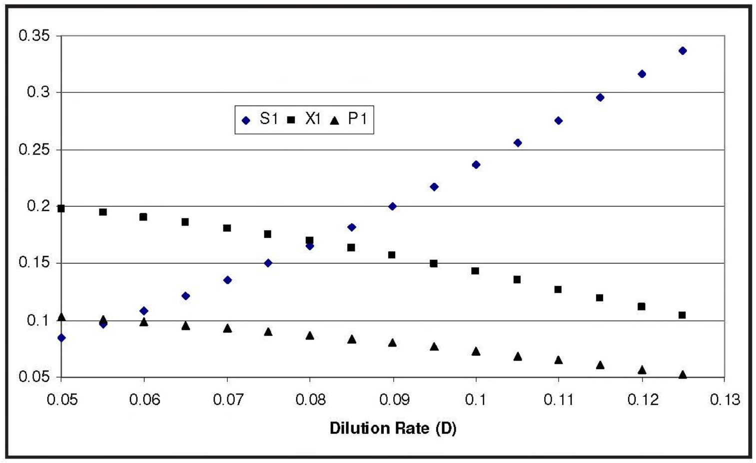

Figure 2. *Plot of S_1, X_1, and P_1 as functions of dilution rate.*

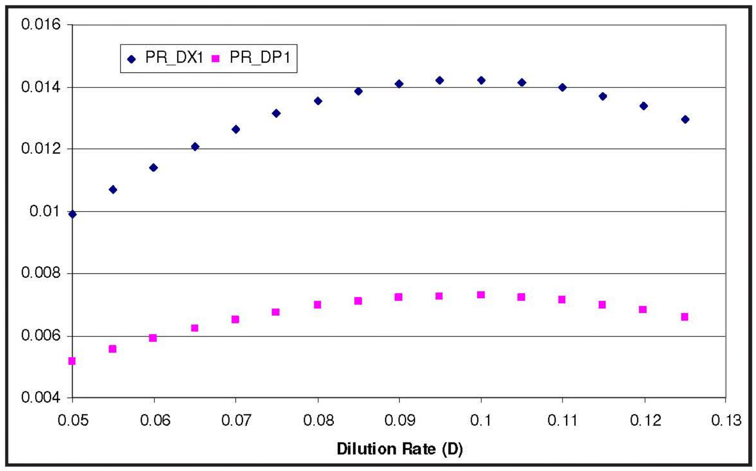

Figure 3. *Cell production rate (PR_DX1) and product production Rate (PR_DP1) as functions of dilution rate.*

Maximization of the Production Rates by Solving an SMMA Problem

The two optimization problems can be posed as the following minimization problems:

$$\min_{F_1} - DX_1 \text{ and } \min_{F_1} - DP_1 \text{ where } D = F_1 / V_1 \qquad (6)$$

(The minus signs in front of DX_1 and DP_1 are used to convert the maximization problems into minimization problems).

The calculation of D, X_1, and P_1 associated with a particular value of F_1 involves the solution of a system of NLEs, while a minimization algorithm is required in order to find the values of F_1 that satisfy Eq. (1). This is a single model (the chemostat) and multiple algorithms (one for solution of NLEs and one for minimization) problem.

TABLE 5

POLYMATH Model of the Chemostat Exported to Excel with Display Formulas Option.

	A	B	C
1			**POLYMATH NLE Migration Document**
2		**Variable**	**Value**
3	Explicit Eqs	F1	=0.17
4		F2	=(0.2 * C3)
5		P1	=(C10 * (C7 - C17))
6		D	=(C3 / (C13 + C14))
7		S0	=0.6
8		kd	=0.002
9		Yxs	=0.4
10		Yps	=0.2
11		Ks	=0.2
12		mum	=0.2
13		V1	=1.7
14		V2	=0.3
15		PR_DX1	=(C6 * C19)
16		PR_DP1	=(C6 * C5)
17	Implicit Vars	S1	0
18		S2	0
19		X1	0.025
20		X2	0.025
21	Implicit Eqs	f(S1)	=((((C3 * C7) + (C4 * C18)) - ((((1 / C9) * ((C12 * C17) / (C11 + C17))) * C19) * C13)) - (C3 * C17)) - (C4 * C17))
22		f(S2)	=(((C4 * C17) - ((((1 / C9) * ((C12 * C18) / (C11 + C18))) * C20) * C14)) - (C4 * C18))
23		f(X1)	=((((C4 * C20) + (((((C12 * C17) / (C11 + C17)) - C8) * C19) * C13)) - (C3 * C19)) - (C4 * C19))
24		f(X2)	=(((C4 * C19) + (((((C12 * C18) / (C11 + C18)) - C8) * C20) * C14)) - (C4 * C20))
25	**Sum of Squares:**		**=((((C21 ^ 2) + (C22 ^ 2)) + (C23 ^ 2)) + (C24 ^ 2))**

The MATLAB library function *fminbnd* for single-value minimization can be used for finding the minimum of the functions in Eq. (1). In order to carry out the minimization, two new functions should be prepared. The first one (shown in Table 7) obtains F_1 as input, uses the *fsolve* library function to solve the chemostat model, and returns $-DX_1$ to the calling function. The second function does the same except that it returns the value of $-DP_1$. Two calls to the library function *fminbnd* identify the highest production rate for cells $DX_1 = 0.0142$ g/hr at a dilution rate of $D = 0.0986$ hr^{-1} and the highest production rate for product $DP_1 = 0.00727$ g/hr at a dilution rate of $D = 0.0979$ hr^{-1}.

CONCLUSIONS

The example presented here provides an opportunity to practice several aspects of modeling and computation:

- *Modeling of a bio-reactor and imperfect mixing.*
- *Categorizing problems according to the number of models and number of algorithms involved.*
- *Solving SMSA problems with a software package.*
- *Using Excel (VBA) or MATLAB programming for parametric runs of SMSA problems.*
- *Using MATLAB programming for solving SMMA problems.*

We suggest that a combination of three popular packages— POLYMATH, Excel, and MATLAB—enables the solution of problems of increasing complexity in the educational setting. The example presented is suitable for courses in chemical reaction engineering, biochemical engineering, numerical methods, and optimization.

The POLYMATH and MATLAB programs used in this study are available at the site <ftp://ftp.bgu.ac.il/shacham/chemostat/>.

TABLE 6
Excel Worksheet with Numerical Results and Documentation for the Chemostat Problem.

	A	B	C	D	E	F
1	**POLYMATH NLE Migration Document**					
2		**Variable**	**Value**		***Polymath Equation***	***Comments***
3	Explicit Eqs	F1	0.17		*F1=0.17*	*Feed flow rate to volume V1 (dm^3/hr)*
4		F2	0.034		*F2=0.2*F1*	*Feed flow rate to volume V2 (dm^3/hr)*
5		P1	0.083588165		*P1=Yps*(S0-S1)*	*Production (g/dm^3)*
6		D	0.085		*D=F1/(V1+V2)*	*Dilution rate (1/hr)*
7		S0	0.6		*S0=0.6*	*Feed substrate concentration (g/dm^3)*
8		kd	0.002		*kd=0.002*	*Cell death rate (1/hr)*
9		Yxs	0.4		*Yxs=0.4*	*Yield coefficient (g cells/g substrate)*
10		Yps	0.2		*Yps=0.2*	*Yield coefficient (g product/g substrate)*
11		Ks	0.2		*Ks=0.2*	*Monod constant (g substrate/dm^3)*
12		mum	0.2		*mum=0.2*	*Maximal specific growth rate (1/hr)*
13		V1	1.7		*V1=1.7*	*Volume V1 (dm^3)*
14		V2	0.3		*V2=0.3*	*Volume V2 (dm^3)*
15		PR_DX1	0.013867371		*PR_DX1=D*X1*	*Dilution rate (1/hr)*
16		PR_DP1	0.007104994		*PR_DP1=D*P1*	*Cell production rate (g/hr)*
17	Implicit Vars	S1	0.182059175		*S1(0)=0*	*Substrate concentration in volume V1 (g/dm^3)*
18		S2	0.035888744		*S2(0)=0*	*Substrate concentration in volume V2 (g/dm^3)*
19		X1	0.163145542		*X1(0)=0.025*	*Cell concentration in volume V1 (g/dm^3)*
20		X2	0.217791093		*X2(0)=0.025*	*Cell concentration in volume V2 (g/dm^3)*
21	Implicit Eqs	f(S1)	-7.7311E-07		*f(S1)=F1*S0+F2*S2-(1/Yxs)*(mum*S1/(Ks+S1))*X1*V1-F1*S1-F2*S1*	
22		f(S2)	-5.0319E-07		*f(S2)=F2*S1-(1/Yxs)*(mum*S2/(Ks+S2))*X2*V2-F2*S2*	
23		f(X1)	8.79323E-07		*f(X1)=F2*X2+(mum*S1/(Ks+S1)-kd)*X1*V1-F1*X1-F2*X1*	
24		f(X2)	-5.0428E-07		*f(X2)=F2*X1+(mum*S2/(Ks+S2)-kd)*X2*V2-F2*X2*	
25	**Sum of Squares:**		**1.8784E-12**		*F = f(S1)^2+f(S2)^2+f(X1)^2+f(X2)^2*	

TABLE 7
A Function for Calculating the Cell Production Rate for a Single Value of F_1

No.	Equation % Comment
1	function PR_DX=ProdRateCell(F1) %Cell production rate (g/hr)
2	V1 = 1.7; %Volume V1 (dm^3)
3	V2 = 0.3; %Volume V2 (dm^3)
4	xguess = [0 0 0.025 0.025]; %initial guess vector
5	options = optimset('Diagnostics',['off'],'TolFun',[1e-9],'TolX',[1e-9]);
6	xsolv=fsolve(@MNLEfun,xguess,options,F1);
7	X1=xsolv(3); %Cell concentration in volume V1 (g/dm^3)
8	D = F1 / (V1 + V2); %Dilution rate (1/hr)
9	PR_DX = -D* X1; %Cell production rate (g/hr)

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