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

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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.

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

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.

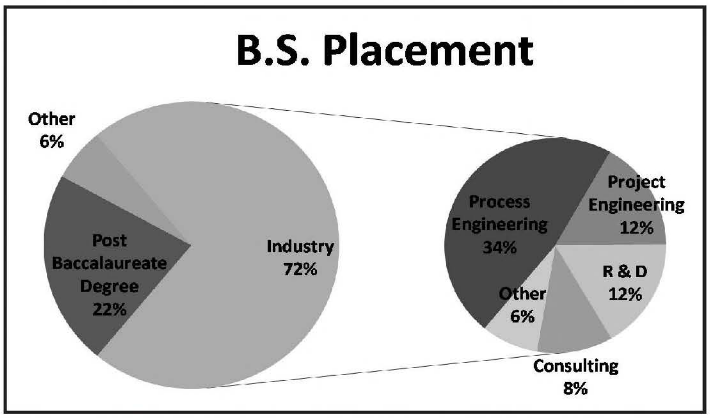


Figure 1. *Placement statistics for Illinois ChBE graduates by job function averaged over the past decade.*

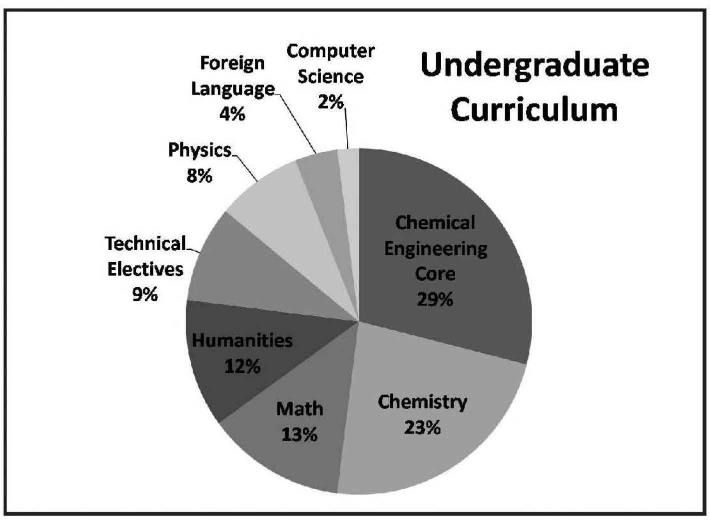


Figure 2. *Distribution of subject material in the Illinois undergraduate curriculum. Chemistry, mathematics, and other sciences are represented particularly strongly.*

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 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.

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.

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.

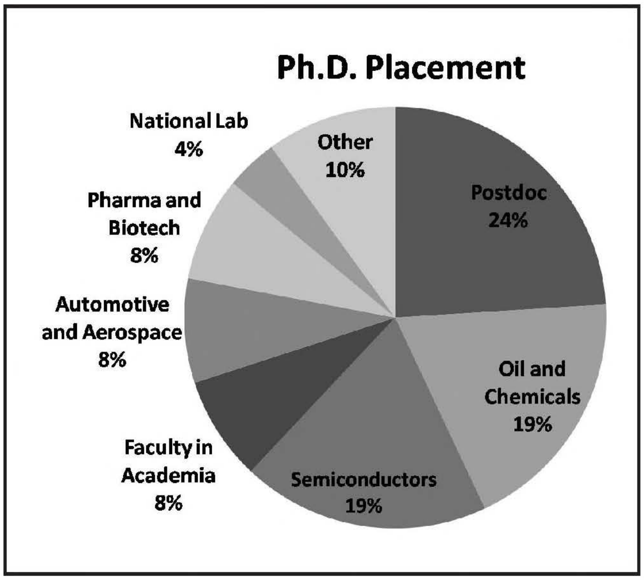


Figure 3. *Placement of Illinois Ph.D. students by sector.*

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.

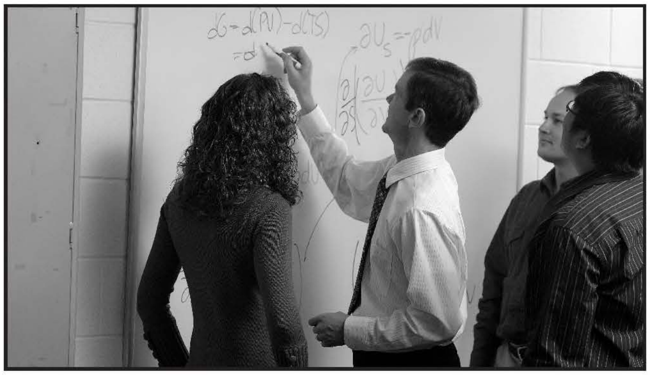
efficient production of novel biofuels such as ethanol, butanol, and alkanes from nonfood crops. Related protein engineering and metabolic engineering efforts are also being used for the green synthesis of fine chemicals via biocatalysis.

• ***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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