Department of Chemical Engineering

In academic year 2013–2014, MIT's Department of Chemical Engineering continued to be rated the number one chemical engineering program at the undergraduate and graduate levels for the 25th year. Many of the department's faculty received major honors and awards. Although, by these measures, the department has been very stable, it is also undergoing significant rejuvenation. Three new assistant professors joined the Department of Chemical Engineering this year, and Building 66, the department's headquarters for the past 40 years, is in the midst of a major renovation.

Research volume in the department bounced back after a dip last year, increasing by 20% to $53.6 million; $21.8 million of these funds were handled directly through the department and the rest were handled by different cost centers at MIT, including the Koch Institute for Integrative Cancer Research, the MIT Energy Initiative (MITEI), and the Ragon Institute. The department's engagement with these interdisciplinary centers continues to provide a strong basis for innovation, and provides our students with experience solving important and difficult real-world problems.

Professor Klavs Jensen continues as department head and professor William Green as executive officer. Patrick Doyle is the graduate officer, Barry Johnston the undergraduate officer, and Karen Gleason the postdoctoral officer. Chemical Engineering continues to claim two Institute Professors, Daniel I. C. Wang and Robert Langer, as primary faculty members. Several Chemical Engineering faculty members play important leadership roles on campus. Professor Robert Armstrong is director of the MIT Energy Initiative, professor Arup Chakraborty is director of the MIT Institute for Medical Engineering and Science, professor Dane Wittrup is associate director of the Koch Institute for Integrative Cancer Research, and professor Gleason was appointed associate provost. Professor Charles Cooney, who had served as faculty director of the MIT Deshpande Center for several years, retired this spring after 44 years on the MIT faculty.

New Faculty

This year the department welcomed three assistant professors. Kwanghun Chung, an expert on brain imaging, joined the Chemical Engineering faculty with joint appointments in the Institute for Medical Engineering and Science and the Department of Brain and Cognitive Sciences. Heather Kulik, specializing in computational chemistry, and James Swan, who works on complex fluids, also joined the Chemical Engineering faculty this year.

Space Changes and Renovations

Building 66, an iconic building designed by I. M. Pei, is now being heavily renovated. The much-needed renewal is projected to cost $45 million, with MIT providing $25 million toward new infrastructure. The department is working to raise the remaining $20 million, needed to create modern laboratories and offices. The renovations encompass more than half of the building's total footprint, including every floor and all building operations. The improvements will:

- Modernize the laboratories to reflect the experimental and design-oriented range of research conducted by today's faculty and students
- Provide offices for graduate students distinct from the laboratory areas
- Elevate safety standards building-wide through new design and by upgrading infrastructure and equipment
- Redesign all faculty offices for a more efficient use of space
- Create an undergraduate lounge and meeting space to encourage the formal and informal interactions that support a strong learning community
- Tint exterior windows to reduce solar load, which will create a more stable interior climate and provide more consistent working conditions throughout the day
- Fully upgrade building systems, including heating, lighting, and ventilation systems

We are very enthusiastic about this renovation, which will aid the department in retaining its leadership position and help us continue to recruit outstanding faculty and students.

Research and Recognition

Robert Langer received several major awards, including the Kyoto Prize, a number of honorary degrees, and gave several major invited lectures. It was announced that Paula Hammond will receive the Alpha Chi Sigma Award for Chemical Engineering Research, and that Bernhardt Trout will receive the Excellence in Process Development Research Award at the American Institute of Chemical Engineers (AIChE) national meeting in fall 2014. Jesse Kroll received the James B. Macelwane Medal from the American Geophysical Union (AGU). Richard Braatz received the AIChE PD2M Award. William Green received the 2013 Glenn Award from the American Chemical Society (ACS). George Stephanopoulos received the Dhirubhai Ambani Lifetime Achievement Award. Gregory Stephanopoulos received the John Fritz Medal from the American Association of Engineering Societies. William Tisdale received the 3M Non-Tenured Faculty Award.

Two Chemical Engineering faculty members won major Institute awards for undergraduate teaching. Kristala Prather was the first Chemical Engineering faculty member to be selected as a MacVicar Fellow, and Will Tisdale received the Everett Moore Baker Memorial Award.

A more complete account of research conducted by and awards and recognition given to members of the department is given below.

Undergraduate Education

Current Status of the Undergraduate Program

Since 2004, the Department of Chemical Engineering has offered bachelor of science (SB) degrees in both chemical engineering (Course 10) and chemical-biological engineering (Course 10-B). In fall 2011, the department introduced the 10-ENG flexible SB degree in engineering. This year, the Accreditation Board for Engineering and Technology (ABET) renewed accreditation for Course 10 and Course 10-B and accredited Course 10-ENG for the first time as a degree in engineering broadly, reflecting the flexibility inherent in the program.

Undergraduate enrollment has been gradually declining since AY2007. However, Chemical Engineering has one of the highest student-to-faculty ratios in the School of Engineering. The department advises students about career paths in chemical and chemical-biological engineering through active participation in freshman advising seminars, fall- and spring-term open houses, Parent's Weekend, and other activities. Sixty-two SB degrees were conferred in June 2014; 52% of these were awarded to women. Student quality remains high. The distribution of undergraduate students by class over the last 10 years is shown in Table 1.

Table 1. Undergraduate Enrollment over the Last 10 Years

Class Year	04–05	05–06	06–07	07–08	08–09	09–10	10–11	11–12	12–13	13–14
Sophomores	95	100	95	96	87	87	80	72	61	67
Juniors	55	83	75	67	77	68	71	73	63	63
Seniors	55	53	83	77	75	73	75	75	69	58
Total	205	236	253	240	239	228	226	220	196	188

The 10-ENG program was introduced in 2011 in response to students' demand for a curriculum that would allow specialization in particular topics. The program offers some flexibility in that requirements of the department, the Institute, and the profession may be met in some cases by categories of subjects, rather than by particular subjects. The initial specialization tracks are energy, materials, biomedical, and environmental. The enrollment in this newly accredited major is still small (fall 2013 enrollment of 11), but the students who have completed the program report a high degree of satisfaction with it.

The average starting salary for graduates of the Department of Chemical Engineering is $74,333 (2014 senior survey), which is among the highest in the School of Engineering. This attests to the success of the graduates of Course 10 and Course 10-B and to the continued high demand for MIT graduates. The senior survey also indicates that 37% of 2014 graduates are going on to graduate or professional school.

Undergraduates in the Department of Chemical Engineering maintain an active student chapter of the American Institute of Chemical Engineers, with a program of invited speakers, presentations at national meetings, and visits to company sites. The student officers of the AIChE chapter were Michelle Teplensky (president), David Hou (vice president, internal relations), Sam Hagerman (vice president, external relations), Brian Alejandro (vice president, public relations), Whitney Loo (intercollegiate chair), Kali Benavides (recruitment chair), Julia Sun (administrative and financial officer), Allen Leung (webmaster), Anthony Concepcion and Pritee Tembhekar (industrial affairs committee), Chadd Kiggins and Spencer Wenck (national, alumni, and post-grad committee). The roster includes Class of 2014 representatives Josh Zeidman and Eric Safai, Class of 2015 representatives Joel Schneider and Michael Fu, and Class of 2016 representatives Kelsey Jamieson and June Park.

Graduate Education

Current Status of the Graduate Program

The graduate program in the Department of Chemical Engineering offers the master of science (MS) degree in chemical engineering and in chemical engineering practice (MSCEP), the doctor of philosophy (PhD) and doctor of science (ScD) degrees in chemical engineering, and the doctor of philosophy degree in chemical engineering practice (PhDCEP). The PhDCEP track was established in 2000 in collaboration with the Sloan School of Management. The graduate student enrollment is currently 222, with 211 candidates in the doctoral program and 11 candidates in the master's degree programs. In the doctoral program, 202 students are in the PhD/ScD track and nine are in the PhDCEP track. In the master's program, nine are in the MSCEP track. Thirty-five percent of the department's graduate students are women. Four percent are underrepresented minority students. Forty-five of the department's graduate students received outside fellowship awards, including awards from the National Science Foundation (NSF), the National Institutes of Health (NIH), the Department of Defense, and others. The distribution of graduate students by degree for the last 10 years is shown in Table 2.

During the 2013–2014 academic year, 35 doctoral degrees (PhD, ScD, or PhDCEP) were awarded, along with 42 master's degrees (41 MSCEP, one MS) for a total of 77 advanced degrees conferred. Fifty-three students passed the written portion of the doctoral qualifying exams and are one step closer to being promoted to candidacy for the PhD/ScD or PhDCEP degrees. The department received 429 applications for admission to the doctoral program, offered admission to 58 individuals, and received 38 acceptances (66%). There were 111 applications for master's degree programs; the department made 12 offers and received 11 acceptances of offers (92% yield). Of the incoming graduate class for 2014, 21 students are women and five are members of an underrepresented minority. On average, the incoming graduate class held an undergraduate GPA of 4.95 (out of 5.0).

Table 2. Graduate Enrollment over the Last 10 Years

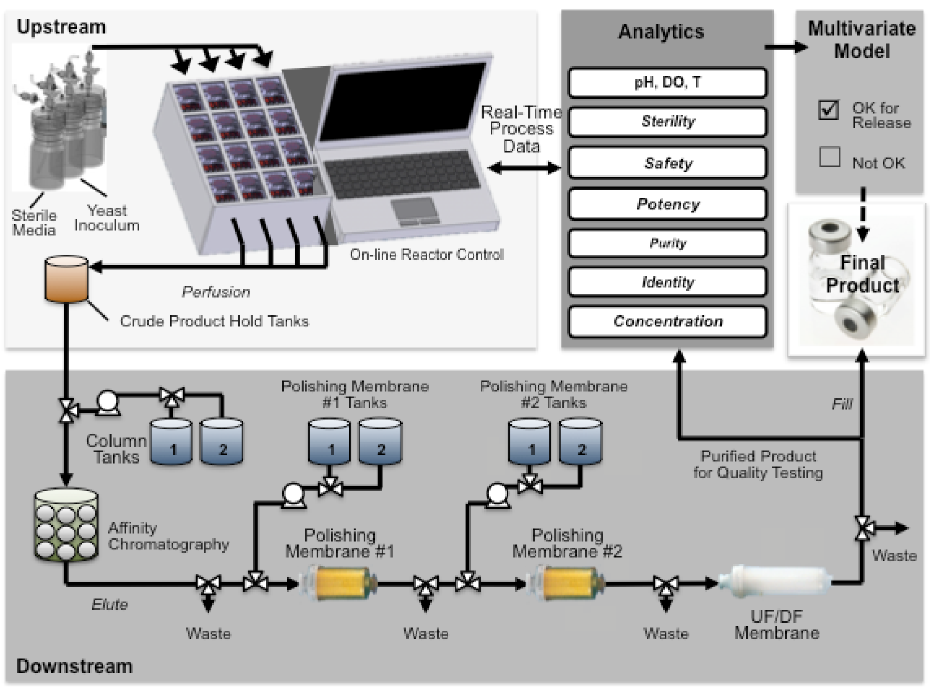
Degree Level	04–05	05–06	06–07	07–08	08–09	09–10	10–11	11–12	12–13	13–14
Master's	19	16	18	26	32	38	28	20	10	11
Doctoral	216	203	217	212	228	203	212	224	212	211
Total	235	219	235	238	260	241	240	244	222	222

Research Centers

The Department of Chemical Engineering is actively involved with, and takes a leadership role in, several Institute-wide education and research programs. A few of these are highlighted here.

Biologically Derived Medicines on Demand

A new Defense Advanced Research Projects Agency (DARPA) program to produce biologically derived medicines on demand was initiated in June 2013 with the vision of developing an end-to-end manufacturing system for making single doses of biologic therapeutics at the point of care within a day. The MIT-led team emphasizes small-scale continual production and purification, incorporating concepts of quality-by-design, process analytics, plant-scale control, and real-time release practices. The ability to make biologic drugs at small scales anywhere opens up new opportunities to improve health care in battlefield medicine, global health, orphan diseases, and ultimately personalized medicine.



Schematic diagram of a prototype integrated, scalable, cyto-technology system for the flexible manufacturing of biologics on demand.

The objectives of this project are ambitious. Today, manufacturing biologics requires weeks to months to produce and release, using many separate operations, often spread physically over a large facility. To envision something akin to a 3-D printer in capability—a manufacturing facility that is fully portable and adaptable to the making of many different products—is to press the limits of what is possible in biomanufacturing for producing high-quality therapeutics for patients.

The interdisciplinary research team consists of seven laboratories spanning MIT's Departments of Chemical Engineering, Electrical Engineering and Computer Science, and Biology, as well as labs from the Barnett Institute at Northeastern University, Rensselaer Polytechnic Institute, and Pall Corporation. Research topics include small-scale perfusion fermentation of a yeast host, synthetic biology approaches to controlling production and providing flexibility in products, novel purification strategies and cutting-edge technologies for affinity capture and polishing of products, nanometer-scale and optical systems for evaluating product quality and potency, and systems control strategies. The integration of technologies is an essential element of the program to realize a small, efficient manufacturing platform that could be portable enough to reach remote locations. Advances in the technologies evaluated and developed in this program will also inform new strategies for integrated and continuous manufacturing of biologics at commercial scales.

As a part of the program, there is an active dialogue between the program team, industry experts, and the Food and Drug Administration (FDA), to understand and define the best strategies for realizing transformational shifts in manufacturing on demand. Led by professor J. Christopher Love, the project is in the first of two phases over four years. Program management is facilitated by Stacy Springs and Anthony Sinskey of the Center for Biomedical Innovation's Biomanufacturing Program and by the Latham BioPharm Group.

Novartis–MIT Center for Continuous Manufacturing

The Center for Continuous Manufacturing is in the middle of the second phase (2012–2017) of a ten-year collaboration between Novartis and MIT. It was formed with the vision of transforming pharmaceutical manufacturing from batch to fully integrated continuous manufacturing. A key milestone in achieving this ambitious vision was realized during the past year when we organized and hosted the International Symposium on Continuous Manufacturing of Pharmaceuticals at MIT. This meeting was the culmination of more than seven years of not only research on the technological hurdles, but also communicating the vision of continuous manufacturing to key stakeholders throughout the pharmaceutical world.

The more than 200 attendees were a hand-selected group of the key decision makers (vice presidents and above) in industry, academia, and regulatory agencies, as well as equipment vendors. The keynote address was given by Janet Woodcock, head of the FDA's Center for Drug Evaluation and Research. Her talk stressed that the FDA's vision of continuous manufacturing is critical to modernizing pharmaceutical manufacturing, not only to decrease manufacturing costs but also to ensure better quality. The rest of the two-day meeting was dedicated to the discussion of eight white papers that covered key aspects of the continuous manufacturing of pharmaceuticals. The ideas and areas of discussion that emerged are being incorporated into the white papers, which will then be published in the Journal of Pharmaceutical Sciences. The group's consensus (not about if to implement continuous manufacturing, but rather how) demonstrated the broad adoption of continuous manufacturing in the pharmaceutical world.

Janet Woodcock, head of FDA's Center for Drug Evaluation and Research, addresses an audience of pharmaceutical executives at MIT in May 2014.

Much of the nonconfidential research conducted over the past year was presented in a poster session at the symposium. This showcased some of the cutting-edge research on continuous manufacturing conducted by many of the 50 to 60 MIT graduate students and post-doctoral fellows associated with the Novartis–MIT Center. The poster topics covered a broad range of research on continuous manufacturing—from new chemical synthesis pathways and processes for drug manufacturing to novel crystallization and tablet-forming processes, as well as modeling of various processes. The work presented displayed some of the advanced research that is moving rapidly from concept, to proof of concept, to process maturation, and subsequent transference to Novartis's continuous manufacturing site in Basel, Switzerland.

In the last year, the center's researchers published 62 publications and presented findings at numerous international and national meetings. The center has filed nine patent applications for breakthrough technologies.

The Novartis–MIT Center is led by Bernhardt Trout, MIT center director, and Markus Krumme, Novartis's head of continuous manufacturing. In addition, the leadership team consists of Keith Jensen, MIT associate director, and Stephanie Bright, MIT program coordinator.

The David H. Koch Institute for Integrative Cancer Research

The research laboratories of five Chemical Engineering faculty members are housed in the David H. Koch Institute for Integrative Cancer Research: Daniel Anderson, Paula Hammond, Robert Langer, Christopher Love, and Dane Wittrup. The Koch Institute brings together scientists and engineers from across MIT to collaborate on research aimed at developing new cancer therapies. Dane Wittrup serves as the associate director of the Koch Institute. A particular strength is cutting-edge research on drug delivery, anchored by the efforts of Anderson, Hammond, and Langer.

Faculty Notes

Professor C. Armstrong serves as director of the MIT Energy Initiative. MITEI continues to grow rapidly in research activities and in its educational, campus, and outreach components. Fifteen companies and public institutions sponsor research as founding and sustaining members of MITEI; altogether, the energy initiative has about 72 industrial and public partners from across four continents. MITEI has helped to bring in approximately $525 million in support over its first six years of operation, with 300 energy graduate fellowships spread over 22 departments. Professor Armstrong serves on the Scientific Commission of the Eni Enrico Mattei Foundation, the EDF Pulse Award Selection Committee, and the External Advisory Board of the National Renewal Energy Laboratory. He serves on the advisory boards of chemical engineering departments at the Georgia Institute of Technology, Northwestern University, and Washington University. He gave numerous lectures on energy around the world during the past year.

Professor Martin Z. Bazant continued research in electrochemistry, transport phenomena, and applied mathematics. His theoretical prediction of a new metastable state of matter, the "quasi-solid solution" in a phase-separating material (lithium iron phosphate, or $LiFePO_4$) that is stabilized by exceeding a critical applied current, first published in 2011, was experimentally confirmed by several groups in 2014 (reported by Ju Li and Yet-Ming Chiang of MIT in Nano Letters and by Clare Gray in Science). In 2010, Professor Bazant founded an experimental laboratory to complement his theoretical work, and the first results were published over the past year in high-impact journals:

- Development of a membraneless hydrogen-bromine flow battery that could dramatically lower the cost of energy storage (with Cullen Buie) (Nature Communications)
- Discovery of the first experimental evidence that electron transfer in a solid electrode (LiFePO4) is rate limiting and obeys Marcus kinetics rather than the empirical Butler-Volmer equation used in electrochemical engineering (Nature Communications)
- Development of a new method of water desalination, "shock electrodialysis," that exploits nonlinear electrokinetics in porous media (Langmuir)

Professor Bazant also published 10 theoretical papers. Over the past year, he delivered 10 invited lectures, including the Stanley Corrsin Memorial Lecture in Fluid Mechanics at Johns Hopkins University. He taught 10.50 Analysis of Transport Phenomena and continued to develop 10.626/426 Electrochemical Energy Systems. One of the undergraduate teams he advised in the Mathematical Contest in Modeling was awarded meritorious standing (meaning the team was in the top 9% of 7,000 teams worldwide).

Professor Daniel Blankschtein's research group conducts fundamental theoretical and experimental research in the area of colloid and surfactant science, with emphasis on industrial and biomedical applications. Recent research advances include molecular-thermodynamic modeling and simulation of the interfacial behavior of surfactant systems, molecular dynamics simulation of surfactant/polymer-induced stabilization of carbon nanotubes and graphene sheets in aqueous media, molecular modeling of the wetting behavior of water on graphene, oral drug delivery using an ingestible ultrasound-emitting pill (uPill) and an ingestible microneedle pill (mPill), and ultrasound-assisted transdermal vaccination. Professor Blankschtein's group interacts closely with several companies that make use of software developed by his group to facilitate surfactant formulation design. His teaching responsibilities included 10.55 Colloid and Surfactant Science (Program in Polymer Science and Technology) in fall 2013 and the interdisciplinary 10.56 Advanced Topics in Surfactant Science in spring 2014. Professor Blankschtein and his students delivered both invited and regular talks, and presented posters, at the 2013 American Institute of Chemical Engineers annual meeting, the 2013 Materials Research Society fall meeting, the Biophysical Society's 58th annual meeting, the Controlled Release Society's annual conference, the 240th national meeting of the American Chemical Society, and the 10th Annual Protein Engineering Summit. Professor Blankschtein continues to serve on the editorial board of Marcel Dekker's "Surfactant Science Series" of books.

Professor Richard D. Braatz received the International Society of Automation's Excellence in Technical Innovation Award and the AIChE PD2M Award for Outstanding Contribution to quality-by-design for drug substance for research in pharmaceutical manufacturing. As the graduate admissions officer for Chemical Engineering, he led a successful recruiting year. He gave numerous invited talks, included many addresses to plenary sessions and keynote addresses. He led systems engineering research in many large campus projects. He served on numerous award committees and advisory and editorial boards, and also served as editor-in-chief of *IEEE Control Systems Magazine.* Three postdoctoral associates from his research group accepted faculty positions, including a position at the University of California Berkeley.

Fikile R. Brushett entered his first full year in the Department of Chemical Engineering, where he is currently the Raymond A. & Helen E. St. Laurent career development chair assistant professor. His research group continued to advance the science and engineering of electrochemical systems, with an overarching goal of enabling sustainable energy technologies. This work has attracted sponsorship from the US Department of Energy (DOE), MITEI, the MIT–Kuwait Center for Natural Resources and the Environment, ENI S.p.A., and the National Aeronautics and Space Administration. In May, his group moved into newly renovated laboratory space onhh the fourth floor of Building 66. Brushett served as an instructor for 10.492 Integrated Chemical Engineering in fall 2013 and as a co-instructor for 10.301 Fluid Mechanics in spring 2014. He received the Michael Mohr Outstanding Faculty Award in the spring, which "recognizes excellence in teaching in undergraduate subjects."

Kwanghun Chung started his position in October 2013 in the Department of Chemical Engineering and the Institute for Medical Engineering and Science as Hemholtz career development assistant professor. He is also a principal investigator at the Picower Institute for Learning and Memory. His lab has continued to improve CLARITY, a technology Professor Chung developed as a postdoctoral associate at Stanford to replace lipid molecules with a clear gel, hence unlocking the capacity to study large-scale biological systems comprehensively. Chung was named a 2014 Searle Scholar and was also one of *Cell'*s 40 Under 40. CLARITY was a runner-up for Science's Breakthroughs of the Year. The laboratory has hosted several CLARITY workshops since July, which are open to anyone who is interested in learning the technique.

Professor Robert E. Cohen spent the second half of 2013 on sabbatical leave in Paris, at l'École Supérieure de Physique et de Chimie Industrielles (ESPCI), in the research group of internationally acclaimed surface scientist professor David Quere. Based on a successful proposal submitted to the Marion and Jasper Whiting Foundation, Cohen organized and hosted a one-day workshop at ESPCI in September 2013, "Harvesting Water from the Atmosphere." Researchers from England, Wales, France, and the United States made presentations about their research activities aimed at economical and scalable processes for capturing meaningful amounts of potable water from dew and fog in selected regions of the world. The workshop has led to subsequent successful and collaborative efforts. Cohen has produced two research papers in collaboration with workshop participants in the first six months of 2014: "Dew Harvesting Efficiency of Four Species of Cacti from Different Environments" and "Quantification of Feather Structure, Wettability and Resistance to Liquid Penetration." The latter topic was featured on the MIT Home Page.

Professor Clark K. Colton has pioneered the development of implantable devices containing encapsulated insulin-secreting islets of Langerhans to cure diabetes, beginning his work with a collaboration initiated in 1970 with Dr. William Chick at Harvard Medical School. Oxygen supply to the transplanted tissues was a major hurdle and in 1999 Colton developed an approach to supply additional exogenous oxygen to the tissue. In 2013, he coauthored several papers with an Israeli company, Beta-O2 Technologies, and a group of German researchers. The papers describe the use of such a device in rats with rat islets, the successful cure of diabetes in pigs with xenogeneic rat islets without immunosuppression, and the first successful implantation with a subclinical dose of human islets in a diabetic human for 10 months, during which time the device continued to function and to reduce the subject's insulin requirements. This work is leading to further trials of xenogeneic experiments in primates and human clinical experiments.

Professor Charles L. Cooney, Robert T. Haslam (1911) professor of chemical and biochemical engineering, retired on June 30, 2014, and became professor without tenure. He will continue to teach in the department and remain involved with selected MIT activities. On April 30, 2014, he stepped down as the founding faculty director of the Deshpande Center for Technological Innovation to become faculty director emeritus, and on June 30 he stepped down as faculty lead for the entrepreneurship and innovation activities associated with the MIT/Skolkovo Institute of Science and Technology Initiative (MIT Skoltech Initiative) to become a special advisor. In addition, he served on the MIT–NIH Engagement Committee, the MIT–Sanofi Joint Scientific Steering Committee, the executive committee of the Masdar Institute of Science and Technology (Abu Dhabi), the Center of Biomedical Innovation steering committee, the steering committee of the bioengineering section of the MIT Portugal Program, the steering committee of the Novartis–MIT Center for Continuous Manufacturing, the executive committee of the Legatum Center for Development and Entrepreneurship, and the advisory committee to the Singapore–MIT Alliance for Research and Technology (SMART) Innovation Center. He is co-chair of the MIT India Strategy Group and the faculty director of the summer course on downstream processing held at MIT's Professional Institute. Professor Cooney is also an overseer of the Boston Symphony Orchestra and a trustee emeritus of Boston Ballet.

Professor Patrick S. Doyle continued to advance his work on DNA polymer physics and microfluidic synthesis of functional microparticles using stop-flow lithography. An important advance in his research was the development of a new barcoded particle motif for use in material tracking and anti-counterfeiting (*Nature Materials* 2014). He is in the process of commercializing these ideas. Doyle is actively involved in the SMART program, which was renewed for another five years. For the second year in a row, he received the Michael Mohr Outstanding Faculty Award, which "recognizes excellence in teaching in undergraduate subjects." He delivered several invited and keynote lectures, including the Institute of Advanced Studies Distinguished Lectureship at Hong Kong University of Science and Technology. Professor Doyle serves as head of the scientific advisory board at Firefly Bioworks, a life sciences company he co-founded to commercialize inventions from his laboratory. He continues to serve as the graduate officer for the Department of Chemical Engineering.

Professor Karen K. Gleason was promoted to associate provost. In this role, she provides oversight of space planning, allocation, and renovations across the Institute. She is also responsible for the oversight of MIT's industry-facing offices. Professor Gleason was elected as a fellow of AIChE. She presented a "'moonshot"' talk on durable surface modification for improving the efficiency of steam power cycles at "Solve for X," a conference sponsored by Google X. She was a keynote speaker at the Sixth International Symposium on Flexible Organic Electronics, held in Thessaloniki, Greece, and gave invited presentations at the Harvard Science Symposium on "Smart Clothes," at the Japanese Society of Applied Physics in Kyoto, and at the Korea Advanced Institute of Science and Technology. Professor Gleason became a member of the editorial advisory board of the new Wiley Online Library journal *Advanced Materials Interfaces*.

Professor William H. Green continues as executive officer of the Chemical Engineering Department. He plays several roles in MITEI, in both research and education. Research highlights include direct measurement of the rates of reactions of Criegee intermediates, analysis of the environmental and economic impact of proposed changes in the gasoline octane number system in the US, and new methods for discovering new chemical reactions on the computer and computing reaction rates from first principles. His work on new methods for fuel desulfurization earned him the ACS' Glenn Award in fall 2013.

Professor Paula Hammond completed her year's sabbatical at the end of 2013. She was at Nanyang Technological University in Singapore and at THE Dana-Farber Cancer Institute in Boston, where she was hosted by Dr. David Livingston. Professor Hammond was selected to receive the 2014 Alpha Chi Sigma Award for Chemical Engineering Research, which is an Institute Award from the American Institute of Chemical Engineers that recognizes an individual's outstanding accomplishments in fundamental or applied chemical engineering research. She continues to serve as an associate editor of the American Chemical Society journal *ACS Nano*, and is in the second year of her term as a member of the board of directors for AIChE. Hammond was honored to be the Joe M. Smith Lecturer at the University of California, Davis in May 2014; she also delivered an invited lecture at the High Polymer Research Group at Shrigley Potts in Cheshire, UK, and at the Biannual Wageningen Symposium on Organic Chemistry in the Netherlands in 2014. She is serving as the vice chair of the Gordon Conference on Drug Carriers in August 2014. Professor Hammond is a co-founder of a new company involved in using her technologies for controlled release from surfaces.

Professor T. Alan Hatton continued to serve as the director of the David H. Koch School of Chemical Engineering Practice, where he has maintained the international flavor of the program by placing student teams at host companies in Switzerland and the UK, in addition to in the US. He has advised the Masdar Institute and the Skoltech Initiative on the potential establishment of programs like those at the David H. Koch School of Chemical Engineering Practice in Abu Dhabi and Russia. He is an active participant in the Singapore–MIT Alliance program of chemical and pharmaceutical engineering and is a member of the scientific advisory boards of the Particulate Fluids Processing Center at the University of Melbourne and of the GSK–Singapore Partnership for Green and Sustainable Manufacturing in Singapore. He is on the editorial advisory board of *Colloid and Interface Science Communications* and is an advisory board member of Engineering Conferences International in New York. In addition to a number of presentations at companies in the United States and abroad, he gave invited talks at ACS and AIChE meetings, and at the third NanoToday Conference, the Singapore–MIT Alliance Symposium, and the Green and Sustainable Manufacturing Symposium in Singapore. He presented the Eastman Lecture at Akron University, the MERIT Scholar Lecture at the University of Melbourne, Australia (where he spent the spring semester on sabbatical), and a plenary talk at the fourth International Conference on Colloid and Interface Science in Madrid, Spain.

In addition to his responsibilities as department head, Professor Klavs F. Jensen continued his research on functional micro- and nano-structured materials and devices for chemical and biological applications. He has explored a wide range of flow systems for chemical applications with particular emphasis on systems for which continuous processing provides unique performance advantages. These systems also form the basis for continuous flow synthesis and separation developments as part of the Novartis–MIT Center for Continuous Manufacturing and the DARPA-sponsored Pharmacy on Demand (PoD) program. Both programs reached major milestones this year. The Novartis program published the first publication demonstrating end-to-end (i.e., from chemicals to tablets) continuous manufacturing of a pharmaceutical and received the Collaboration Award from the Council for Chemical Research. The PoD effort demonstrated the continuous synthesis of four common pharmaceuticals in a small, integrated, reconfigurable, and transportable system. The ability of small systems to operate at high pressure and temperature conditions was used in the synthesis of nanoparticles for optical applications. Professor Jensen also participated in catalysis studies for biomass conversion and carbon dioxide reduction through MITEI-sponsored projects. Biological applications, specifically devices to facilitate the transport of macromolecules across cell membranes, were pursued in collaboration with Koch Institute researchers. During the past academic year, he gave plenary lectures on micro-reaction technology at international conferences and at universities. He served on advisory boards to chemical engineering departments, including departments at the University of California Berkeley, Princeton University, and the University of Wisconsin. Professor Jensen also was on the governing board of the Technical University of Denmark and the scientific advisory board for the Singapore Agency for Science, Technology, and Research (A*STAR) Institute for Nano and Biotechnology.

Jesse H. Kroll was promoted to associate professor (without tenure) and continued his research on the chemistry and fate of organic compounds in the Earth's atmosphere.

Experimental efforts in his group included studies of chemical transformations of organic species (at MIT and at Lawrence Berkeley National Laboratory), measurements of atmospheric emissions (at California's Air Resources Board engine laboratory), and characterization of ambient levels of organic carbon (as part of the Southern Oxidant and Aerosol Study campaign). He gave a number of invited talks, including at the fall meeting of the American Geophysical Union and the Goldschmidt Conference. In addition to teaching his graduate-level class in atmospheric chemistry, he co-instructed a new capstone class in civil and environmental engineering, in which students designed, constructed, and deployed a state-of-the-art air quality monitoring network across MIT's campus. In December 2013 Kroll received the James B. Macelwane Medal, AGU's "young scientist" award, and became an AGU Fellow.

Heather J. Kulik began her position in the Department of Chemical Engineering in November 2013, where she is currently the Joseph R. Mares ('24) career development chair assistant professor. Kulik's' research focuses on employing large-scale accelerated density functional theory calculations to understand catalysis and materials science. She has presented some of this research in an invited GTC Express webinar to approximately 100 attendees. The group has been awarded funding from MITEI and the Research Support Corporation. The Kulik group consists of one postdoctoral associate, two graduate students, one freshman participant in the Undergraduate Research Opportunities Program, and one research assistant.

In 2013 and 2014, Robert Langer received honorary degrees from Ben Gurion University, Tel Aviv University, Boston University, the University of Western Ontario, and Drexel University. He was elected a fellow of the American Association for the Advancement of Science, a foreign corresponding member of the Austrian Academy of Science, and an honorary fellow of the American College of Clinical Pharmacology. Langer received the Breakthrough Prize in Life Science, the Kyoto Prize, the Chemical Heritage Foundation's Biotechnology Heritage Award, the American Institute of Chemists' Chemical Pioneer Award, the ETH Zurich Chemical Engineering Medal, the Mack Memorial Award, the RUSNANOPRIZE International Prize in Nanotechnology, the American College of Clinical Pharmacology's Distinguished Investigator Award, the Julio Palmaz Award for Innovation in Healthcare and the Biosciences, the Industrial Research Institute Medal, the IEEE Medal for Innovations in Healthcare Technology, the Society of Biomaterials' Founders Award, and the Medical Design Excellence Awards Lifetime Achievement Award.. He presented the 52nd Robbins Lecture Series (Pomona College), the George S. Hammond Lecture (Bates College), the Edward Mack Memorial Award Lecture (Ohio State University), the Axalta Lecture (University of Pennsylvania), the Inaugural Thomas H. Chilton Lecture (DuPont Central Research and Development), the BC^2 Annual Lecture (Wellesley College), the Warren L. McCabe Lecture (North Carolina State University), the Lucas Lecture (Colorado School of Mines), the Reed Izatt and James Christensen Lecture (Brigham Young University), and the Professor Dame Julia Polak Inaugural Lecture (Imperial College).

Professor J. Christopher Love continued his research in applying new bioanalytical processes to profile immune responses in chronic diseases, including HIV/AIDS, multiple sclerosis, Type 1 diabetes, cancer, and food allergies. His laboratory also worked to advance biomanufacturing research to lower the costs of producing protein therapeutics to promote global access. He led a team of investigators from MIT, Rensselaer Polytechnic Institute, Pall Corporation, and Northeastern University on a new contract under DARPA's Biologics Manufacturing on Demand program for end-to-end manufacturing of biologic drugs at the point of care in approximately 24 hours. With a team involving scientists, engineers, and computational biologists from the Koch Institute, the Broad Institute, and the Dana Farber Cancer Institute, the Love lab also established a framework for precisely sequencing the genomes of tumor cells isolated from blood, opening opportunities to develop precision medicine for metastatic cancer. Professor Love also served on the scientific advisory board for the Singapore A*STAR Bioprocessing Technology Institute. In May 2014, Professor Love received tenure at MIT.

Professor Allan S. Myerson continued his research on fundamental and applied problems in crystallization and pharmaceutical manufacturing. He continued his work as a principal investigator in the Novartis–MIT Center in Continuous Manufacturing and the DARPA PoD project, "which involves the development of a tabletop pharmaceutical manufacturing device. Professor Myerson serves as an associate editor of the ACS journal "*Crystal Growth and Design*" and as a scientific advisor to the Pharmaceutical Solid State Cluster in Ireland. He serves on the scientific advisory boards of Gensyn Technologies, a company devoted to particle engineering applications in pharmaceuticals, and of BlueSpark, a company that develops novel flexible batteries. He is also a member of the Genentech science advisory board for small-molecule pharmaceuticals.

Bradley D. Olsen is the Cook career development assistant professor. His research group continued its work in the areas of bio-inspired and bio-functional block copolymers, polymer gels, and protein-based materials for applications in defense, sustainability, and human health. This research is supported by the Air Force Office of Scientific Research, the Institute for Soldier Nanotechnologies, the Department of Energy Office of Basic Energy Science, the National Science Foundation, DARPA, and the Defense Threat Reduction Agency. During AY2014, Olsen published 17 peer-reviewed papers and presented 16 invited lectures, including a plenary lecture at the American Institute of Chemical Engineers annual meeting's bio-nanotechnology plenary session and a lecture at the MIT–Japan Industrial Liaison Program conference. His group also submitted a patent on injectable hemostats and a provisional patent on nuclear pore-mimetic protein gels. Olsen was awarded a 2014 Sloan Research Fellowship and the Department of Chemical Engineering Graduate Student Teaching award. He served as an instructor for subjects 10.40 Introduction to Chemical Engineering Thermodynamics and 10.10 Introduction to Chemical Engineering.

Professor Kristala L. J. Prather continued her research activities primarily in the areas of metabolic engineering and synthetic biology as the Theodore T. Miller career development associate professor. She was appointed co-director of the Microbiology Graduate Program, a joint degree program of the School of Science and the School of Engineering, on July 1, 2013. In addition to several conference presentations, Professor Prather delivered 16 invited lectures, including keynote lectures at the Jülich Biotech Day (Jülich, Germany) and the ACS annual meeting in Dallas, TX. Prather's service to the academic and scientific community included positions on the editorial boards of three biotechnology journals and guest-editing the 2013 issue on chemical biotechnology of the journal *Current Opinion in Biotechnology*. She also served as chair for Division 15C of AIChE and as program chair for the 2014 Society for Industrial Microbiology and Biotechnology Annual Meeting. Prather is currently serving as co-chair of the DOE Office of Biological Environmental Research Workshop on Bioenergy and as a member of the National Academies/National Research Council Study Committee on the Industrialization of Biology. In May, Prather was recognized as a MacVicar Faculty Fellow, the highest honor awarded for undergraduate teaching at MIT. She is the first chemical engineering faculty member to be honored as a MacVicar Fellow.

Professor Yuriy Roman continued his work on heterogeneous catalysis and materials design for the conversion of alternative feedstock, such as lignocellulosic biomass, natural gas, and carbon dioxide. His work is sponsored by federal and industrial sources, including NSF, DOE, British Petroleum, and Saudi Aramco. His group recently published papers on a novel catalyst design strategy to synthesize transition metal carbide nanoparticles (in *Angewandte Chemie)* and on nuclear magnetic resonance (NMR) methods based on hyperpolarization techniques for the characterization of inorganic solids (in the *Journal of the American Chemical Society*). Professor Roman delivered 17 invited lectures, including a keynote lecture at the Canadian Society of Catalysis and a plenary lecture at the Barcelona Energy Challenges Symposium. He received the Young Investigator Award from the Society of Hispanic Professional Engineers. Professor Roman continued his role as vice president of the New England Catalysis Society and became program coordinator for the AIChE Catalysis and Reaction Engineering Division. Together with his wife, Professor Roman continued serving as associate housemaster in Ashdown House.

Gregory C. Rutledge is the Lammot du Pont professor of chemical engineering. Professor Rutledge's research involves the molecular engineering of polymers and soft condensed matter. The Rutledge group develops process–structure–property relationships for advanced plastics by molecular simulation. Currently, efforts in the group are focused on the molecular description of nucleation and growth of polymer crystals and on the mechanical behavior of semicrystalline materials and other complex, multiphasic forms of polymers such as segmented polyurethanes. In the lab, they are pioneering the technology of "electrospinning" for the fabrication of novel nanofibers and membranes for a variety of applications, ranging from sensors to water purification. Over the past year, Professor Rutledge delivered several invited lectures at domestic and international venues, including the Third International Discussion Meeting on Polymer Crystallization in Kyoto (Japan), the Natta Symposium at the Politecnico di Milano (Italy), the Workshop on Electrospinning for High Performance Sensing in Rome (Italy), the Centre Européen de Calcul Atomique et Moléculaire Workshop on Molecular Level Understanding of Nucleation in Lausanne (Switzerland), and the Electrospinning Symposium at the ACS annual meeting in Dallas, TX. He was a delegate to the NSF Workshop on Opportunities in Theoretical and Computational Polymeric Materials and Soft Matter in Santa Barbara, CA. He currently serves as editor of the *Journal of Engineering Fibers and Fabrics* and for the *Journal of Materials Science*, as well as on the editorial boards for the journals *Macromolecules* and *Polymer*. At MIT this year, he coordinated the renewal of accreditation by ABET of the undergraduate programs in the

Department of Chemical Engineering, which was the only department in the School of Engineering to receive full accreditation. After five years of service, Professor Rutledge stepped down this year as the chairman of the Doctoral Qualifying Examination in the Department of Chemical Engineering. He continues as co-chair of the Committee on Research Computing, answering to the vice president for research.

Professor Hadley D. Sikes and her research group continued their work in the area of molecular technology development with the overarching goal of improving human health. One set of projects focuses on the low-cost, user-friendly diagnosis of disease using samples of bodily fluids. Targeted diseases include several cancers, malaria, and tuberculosis. Other efforts within the group focus on developing molecules and methodologies for quantitative measurement and modulation of redox states in living human cells. The goal of this work is defining and exploiting therapeutic windows for treating cancers using redox-based approaches. Several graduate-level lab members gave talks and posters at conferences this year. Professor Hadley spoke at the MIT Center for Environmental Health Science's Friday Forum, at the University of Connecticut, and at the Koch Institute's Chemists in Cancer Research Mini-Symposium. Hadley served her research communities as conference chair of the AIChE' Sensors Topical Conference and as a session chair for a protein engineering techniques session at the annual fall meeting. She also continued to serve in an NIH study section.

Professor George Stephanopoulos continued his research in the area of nanoscale process systems engineering with particular focus on optimal control for the assembly of nanoparticles to structures with desired geometries and conceptual reformulation of intracellular transformations into four interacting networks of molecular interactions. In collaboration with his colleagues—Professors Prather, Olsen, and Roman—he embarked on an integrated study for the identification of high-value chemicals and specialty commercial polymers from biomass and the biochemical and catalytic paths for their manufacturing. In November 2013 he received the Dhirubhai Ambani Lifetime Achievement Award, presented by alumni of the Mumbai University Institute of Chemical Technology and the Ambani Corporation. He was invited to present a keynote lecture, "Systems Engineering at the Nanoscale: Toward Molecular Factories, Synthetic Cells, and Adaptive Devices," at the Ninth World Congress of Chemical Engineering in Seoul, Korea, and at a plenary session of the Frontiers in Multi-Scale Systems Engineering Workshop in Kaist, Korea. With his colleague, professor Nancy Leveson of the Department of Aeronautics and Astronautics, Stephanopoulos prepared an article on process safety that was published in the *AIChE Journal* (January 2014). Finally, his paper on a brief history and assessment of process control theory and practice in the early 1970s will appear in *Computers & Chemical Engineering* as an invited contribution to the Festschrift issue honoring the contributions of professor Manfred Morari.

Professor Gregory Stephanopoulos is the Willard Henry Dow professor of biotechnology and chemical engineering and director of the Metabolic Engineering Laboratory. In the latter capacity, he supervises the efforts of 25 researchers to engineer microbes in such a way as to convert them into little chemical factories for the production of fuels and chemicals. Notable successes in this area, aiming at the development of technologies for a bio-based economy, are the engineering of oleaginous microbes for lipid and biodiesel production as well as the production of ethylene glycol from renewable resources. In parallel, Stephanopoulos continued his investigation of the metabolic aspects of cancer with a particular focus on the identification of therapeutic metabolic targets. Professor Stephanopoulos continued his service on the advisory boards of four academic institutions and as chair of the managing board of the Society for Biological Engineering (SBE), which promotes the integration of biology and engineering to provide enabling technologies for industrial and medical applications. He delivered the 2013 Lacey Lectures at the California Institute of Technology and the Inaugural Giulio Natta Lecture at Politecnico di Milano, along with Distinguished Lectures at the University of Western Ontario and the Luojia Lecture at Wuhan University, China. He also continues to serve as editor-in-chief of the journals *Metabolic Engineering* and *Current Opinion in Biotechnology*, and on the editorial boards of eight other scientific journals. Besides numerous research presentations at professional societies' meetings (AIChE, ACS, American Society for Microbiology), he also delivered plenary and keynote lectures at the Seventh Conference of Plants Research of the European Plant Science Organization (Porto Heli, Greece), at the 14th International Conference of Systems Biology (Copenhagen, Denmark), and at an international conference on the environment organized by Eni S.p.A. and Legambiente (Bologna, Italy). During this year, Stephanopoulos won the John Fritz Medal from the American Association of Engineering Societies. He was also elected a fellow of the American Academy of Microbiology.

Professor Michael S. Strano has continued his research focusing on the chemical engineering of low-dimensional systems. He was selected as one of 10 finalists for the Blavatnik National Award for Young Scientists and was also nominated to, and serves on, the Defense Science Study Group. His work on plant nanobionics was published in *Nature Materials* earlier this year and was featured in several major media outlets, including *Popular Science*, the *Los Angeles Times*, *The Economist*, and the BBC. The Strano lab developed a new method for producing nanoparticles that recognize specific molecules called corona phase molecular recognition; the work was published in *Nature Nanotechnology*. Professor Strano also continues his work on in vivo sensing tattoos for glucose monitoring; he published another study in *Nature Nanotechnology* demonstrating the viability of such sensors for more than 400 days. Work on label-free protein detection in the Strano lab was spun off by graduate Nigel Reuel in a company called Volvox Biologic Inc., later acquired by Malvern Instruments, which is now commercializing the technology. Strano was a guest speaker at Stanford's Center for Cancer Nanotechnology Excellence Seminar Series, the University of Michigan's Department of Chemical Engineering's seminar series, the physical chemistry seminar series at the University of Pittsburgh, and the Princeton Institute for the Science and Technology of Materials and the Princeton Center for Complex Materials at Princeton University. He was also an invited speaker at the Gordon Conference on Free Radicals in Biology and at the International Winterschool on Electronic Properties of Novel Materials: Molecular Nanostructures, in Kirchberg, Austria. Strano presented a plenary lecture at the International Conference on Nanoscience and Nanotechnology and the 23rd Australian Conference on Microscopy and Microanalysis in Adelaide, Australia. He also served on the organizing committee for the 2014 Brazil–US Frontiers of Science and Engineering Symposium in Rio de Janeiro, Brazil, giving a lecture focusing on nanoengineering and nanomaterials. Strano was recently selected as a Thomson Reuters highly cited researcher for 2014.

James W. Swan, who joined the department in September 2013, is currently the Texaco-Mangelsdorf career development professor. His research focuses on the computation and modeling of colloidal scale self-assembly and is intended to advance scalable manufacturing of ordered materials with applications to sustainable energy and biomedical technologies. His publications were featured on the covers of *Soft Matter* and the *Journal of Rheology* in February 2014. The Swan Research Group consists of four graduate students and one postdoctoral associate. In spring 2014, the group was awarded funding from the MIT Portugal Program and the MIT Research Support Committee.

William A. Tisdale entered his second full year in the department, where he is currently the Charles and Hilda Roddey career development assistant professor. Tisdale's research interests lie in understanding and controlling the movement of energy in nanostructured materials, with particular emphasis in advanced optical spectroscopy and imaging techniques. In a publication in *Nano Letters*, Tisdale and his team used time-resolved optical microscopy to study the dynamics of exciton transport in nanocrystal solids, revealing the central role of energetic disorder. In April, Tisdale was recognized for his research in luminescent quantum dots with a 3M Non-Tenured Faculty Award. For his teaching in 10.302 Transport Processes, a junior-level core Chemical Engineering subject, Tisdale received MIT's student-nominated 2014 Everett Moore Baker Memorial Award for Excellence in Undergraduate Teaching. Tisdale also serves as a co-instructor for 10.27 Energy Engineering Projects Laboratory, where he launched two new projects this year: "Engineering Quantum Dot Materials for Energy Efficient Lighting and Displays," and "Heat Transport in Nanostructured Materials used in Solar Cells."

Professor Bernhardt L. Trout continues to serve as director of the Novartis–MIT Center for Continuous Manufacturing—an $85 million partnership—and as director of the Benjamin Franklin Project for the Advancement of the Arts and Sciences. His role as co-chair of the Singapore–MIT Alliance program on chemical and pharmaceutical engineering wound down over the year; the program ended at the end of June 2014. In addition, he runs a laboratory with 20 graduate students, postdoctoral associates, and staff focusing on pharmaceutical small molecule manufacturing and biopharmaceutical formulation and stabilization. Other recent scientific accomplishments in the Trout group include elucidation of the molecular mechanisms of heterogeneous nucleation of small molecular organics via both computational and experimental methods and the development of methods to predict viscosity and protein-protein binding of biotherapeutics. These methods and specific algorithms are used by large and medium-sized pharmaceutical companies around the world. He gave more than 10 invited talks, including several keynote and plenary talks, and published or submitted more than 20 research papers and five patents. He is on the scientific advisory boards of three companies. The Benjamin Franklin Project aims at broadening the education of MIT undergraduates in the realms of ethics, the foundations of economics and leadership, and the origins of modern science. Professor Trout has extended this program beyond chemical engineering to all of the engineering departments in the MIT School of Engineering and has cross-listed courses as electives in Mechanical Engineering and Civil and Environmental Engineering. He and his team from the FDA, Novartis, and MIT won the 2014 Council for Chemical Research Collaboration Award.

Professor Daniel I. C. Wang continues his involvement with the Singapore–MIT Alliance (SMA). He advises two PhD candidates at the National University of Singapore, both of whom spent the spring term at MIT. He is continuing his SMA research on high throughput systems for mammalian cells. Professor Wang also continues his research with Saudi Aramco on microbial desulfurization of crude oil. He was invited by the Bioprocessing Technology Institute of A*STAR (Singapore) to serve as the chairman of the institute's scientific advisory board. The journal *Biotechnology and Bioengineering* has established the Daniel I. C. Wang Award for Research Excellence for investigators under the age of 35. His former students have endowed the D.I.C. Wang Award for Excellence in Biochemical Engineering—an award that is sponsored by three professional organizations: ACS, AIChE, and SBE. Most recently, two of his former students have endowed a Daniel I. C. Wang professorship in the Department of Biological Engineering. The formal announcement was made on June 5, 2014.

Research Highlights

Design and Engineering of Microbial Systems for Biochemical Production (Kristala L. J. Prather)

The past decade has witnessed increasing interest in and activities around the use of biomass—more precisely, the sugars derived from biomass—as feedstocks for the production of chemical compounds. Such compounds may be used as substitutes for petroleum-derived transportation fuels or as bio-based chemicals. These bio-based compounds should exhibit the same functional properties of their fossil-based relatives and be cost competitive, and they can be created using chemical or biological catalysts. Research activities in the Prather lab are focused on the biological conversion of sugars into a variety of molecules, using microorganisms as the catalyst of choice. Although the Prather group and others have continued to explore efficient routes for microbial synthesis of fuels, production of higher-value chemicals has begun to receive more attention from both industrial and academic labs. We are inspired by the complexity of chemistry in natural biological systems and the diversity of reactions mediated by enzymes, the catalytic group of proteins. This complexity and diversity allows us to envision—and subsequently realize—novel routes toward biological synthesis of target molecules. We design and assemble these metabolic routes either as alternatives to naturally occurring but unwieldy routes or to facilitate biological synthesis of molecules without known biological origin.

As one example, the Prather group has explored a class of compounds known as 3-hydroxyacids, characterized by the presence of a hydroxyl group at the C-3 position and a carboxylic acid at C-1. Naturally occurring variants of these molecules can be found in many organisms, mostly notably as components of the polyhydroxyalkanoate (PHA) class of biopolymers. We adopted an existing pathway for PHA production and engineered it to yield the free monomers of the most common constituents, 3-hydroxybutyrate and 3-hydroxyvalerate, without the need for polymer production (Tseng 2009; Tseng 2010). Specificity for each monomer could be controlled based on exogenous supply of precursor substrates. Simultaneously, we were working toward the production of 3-hydroxy-g-butyrolactone (3-HBL), a compound with widespread use as a chiral building block for pharmaceuticals. Although 3-HBL synthesis has not been previously identified in any biological system, its hydrolyzed form, 3,4-dihydroxybutyric acid (3,4-DHBA), is also a 3-hydroxyacid. Using the same pathway previously adopted from nature, we hypothesized that supplying the appropriate precursor, glycolate, could yield the target molecule. Indeed, we were able to produce 3,4-DHBA, concomitant with a small amount of the 3-HBL lactone, in titers of approximately 1 g/L. Surprisingly, we discovered that this pathway could also produce an alternative isomer, 2,3-DHBA, in roughly equimolar amounts. 2,3-DHBA has potential as a monomer for highly functionalized materials; thus, continuing efforts are focused on increased production of both isomers. Finally, we demonstrated extension of this pathway to produce longer (6-carbon) aliphatic monomers. Our results with this platform pathway were published last year in Nature Communications (Martin 2013), and two patents have recently been issued that cover this novel technology for the production of DHBA and 3-HBL.

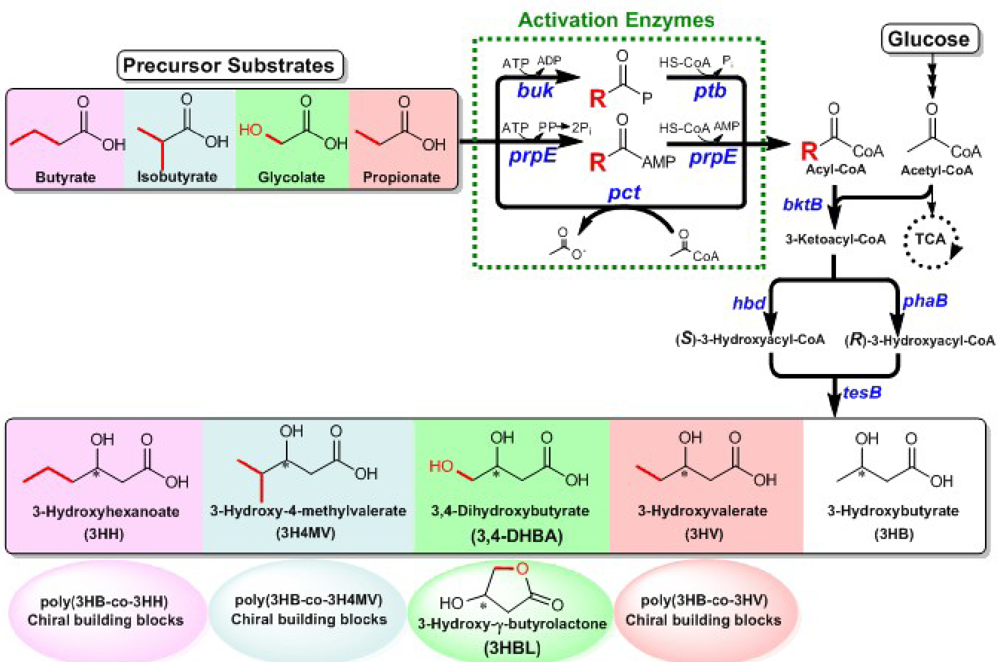


Figure 3. A novel platform pathway yields multiple products from a single combination of enzymes expressed in recombinant microbial cells. End products are determined by the choice of precursor substrate provided to the system. One product of particular interest is 3-hydroxy-γ-butyrolactone, a key building block for a variety of pharmaceutical compounds.

The group's pathway design work facilitates the biological synthesis of compounds through novel routes, yet the integration with the natural microbial metabolism creates a competition for shared resources. For example, the acetyl-coenzyme A (acetyl-CoA) that serves as an essential precursor for production of 3-hydroxyacids (Figure 3) is also essential for microbial growth. As a consequence of this dual essentiality, the traditional metabolic engineering approach of deleting enzymes that compete for intermediates in the engineered pathway cannot be employed. Our solution to this challenge is the creation of "metabolite valves" that can dynamically control metabolic flux. When the valve is "open," the system facilitates microbial growth and catalyst formation at the expense of high-yield product formation. When the valve is "closed," the system favors product formation at the expense of microbial growth and endogenous metabolism. To demonstrate this concept, we designed a genetic device to control glucose flux into primary metabolism in *E. coli*. First, we constructed an E. coli strain with modified glucose transport such that endogenous metabolism (i.e., cell growth) required flow through a single enzyme, glucokinase (Glk). Next, expression of the glk gene encoding Glk was modulated by controlled expression of a repressor protein (Figure 4 inset). Thus, the initial state was open and addition of a chemical inducer triggered valve closure. Use of this "glucose valve" for production of gluconate, a model compound, improved product yield by up to 20% and reduced metabolic waste from endogenous metabolism (acetate) by up to 70% (Figure 4). The magnitude of these changes was a function of timing of induction, demonstrating the benefit of dynamic control. We are currently working to extend this concept to other metabolites and other organisms.

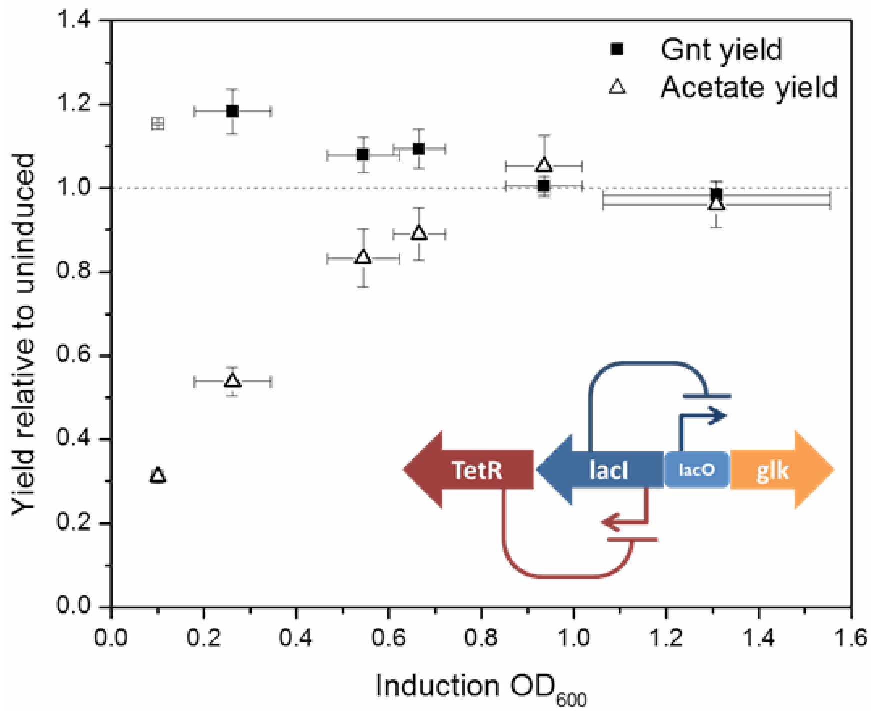


Figure 4. The integration of engineered pathways with natural pathways creates competition for natural resources. Our design for a "glucose valve" consists of a glucokinase gene (glk) under the expression of a repressible promoter (inset). The addition of an inducer represses glk expression, reducing flux toward endogenous metabolism and increasing heterologous product yield. Simultaneously, acetate waste is substantially reduced.

As industry and consumers continue to look for "green" and renewable alternatives to many commercial products, the ability to engineer biology will be increasingly useful for the development of microbial chemical factories. The Prather group's approaches for the de novo design of biosynthetic pathways should facilitate this increased use of microbial synthesis of chemicals. Additionally, the development of generally useful approaches to regulate metabolic flux should be applicable to engineer many systems and improve productivity.

Engineering Microporous Catalysts to Curb Hydrogen Use in Bio-Refining (Yuriy Roman)

The development of more carbon-efficient and economically viable lignocellulosic biomass conversion technologies is critical for the sustainable production of liquid transportation fuels and chemicals. Thermocatalytic routes offer an attractive complement to biological routes to diversify the number of biomass-derived products, including specialty and commodity chemicals, as well as long-chain hydrocarbons. Due to the high oxygen content of biomass feeds, reductive pathways are necessary to complete the vast majority of catalytic upgrading processes. Accordingly, reactions are typically performed under high pressures of hydrogen gas and in the presence of expensive Group VIII metal catalysts. To increase the viability of these catalytic processes, it is imperative to develop new catalytic schemes that use earth-abundant materials, consume minimum quantities of hydrogen, and minimize the number of unit operations in the biorefinery. Such catalysis research is now at a critical juncture: the effective conversion of alternative feedstock calls for new, highly active, robust, and inexpensive catalysts, but doing so requires conceptually new materials since traditional catalysts are poorly suited to operate under the conditions required to transform these new carbon sources.

The Roman group has recently developed a new set of microporous materials featuring water-tolerant Lewis acid centers. Indeed, Lewis acids are exceptional at promoting transfer hydrogenation (TH) reactions, whereby a hydrogen donor can be used to reduce a carbonyl functional group by way of a Meerwein-Ponndorf-Verley reaction mechanism. Although Lewis acids are easily deactivated in the presence of water, properly engineering zeolites with the appropriate hydrophobicity and electron-accepting framework heteroatoms (e.g., zirconium or tin), allows TH reactions to be promoted even in the presence of water. The versatility of these materials was demonstrated in the production of gamma-valerolactone (GVL) from biomass-derived feeds. GVL, a valuable bio-derived chemical intermediate, is commonly synthesized in a two-step process using supported precious metal (e.g., ruthenium/carbon and palladium/silicon dioxide) catalysts and H_2 pressures exceeding 30 bar. By exploiting the TH properties of the Lewis acid zeolites, a reaction cascade was developed for the production of GVL from xylose using primary or secondary alcohols as hydrogen donors (see Figure 5). Under optimal conditions, a GVL yield of 78 mol% was obtained, which is amongst the highest reported to date from C5 sugars. Effectively, this catalytic system offers an attractive streamlined strategy for the production of GVL from lignocellulosic biomass without the use of precious metals or high pressures of molecular H_2.

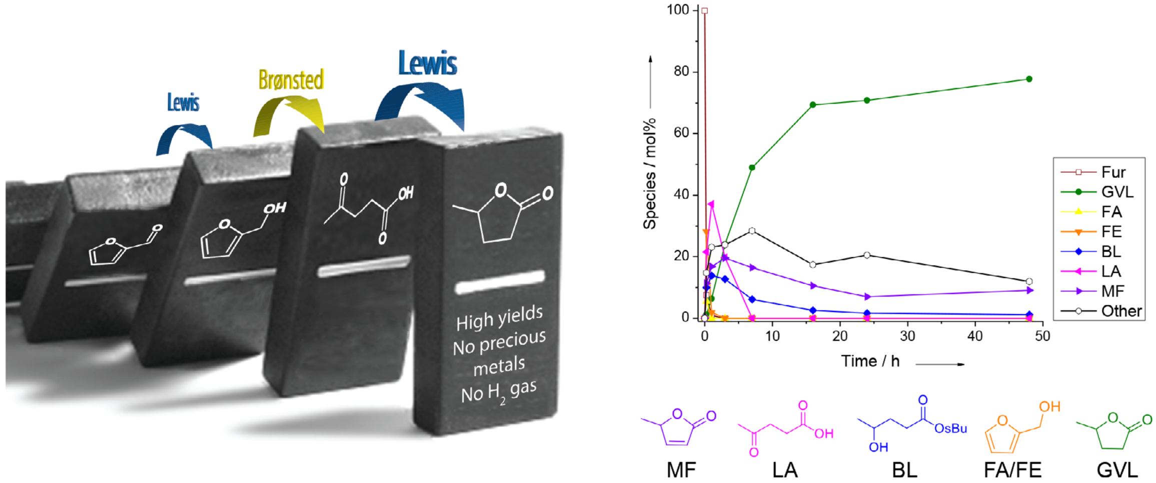


Figure 5. GVL production via transfer hydrogenation chemistry promoted by microporous Lewis acid catalysts.

The catalytic activity of Lewis acid zeolites, such as Sn-Beta, is critically dependent on the successful incorporation of the tin (Sn) metal center into the zeolite framework. However, synchrotron-based techniques or solid-state nuclear magnetic resonance (ssNMR) are the only reliable methods to verify framework incorporation. Although framework tin incorporation can be quantitatively verified with ^{119}Sn (I = 1/2, natural abundance = 8.6%) NMR, the coupled effects of low natural abundance of the ^{119}Sn isotope, low intrinsic NMR sensitivity, and low Sn loadings in the sample make NMR analysis impractical without ^{119}Sn isotopic enrichment. Unfortunately, the high cost of isotopic enrichment drastically hinders high throughput screening, routine analysis, or analysis of low-yield syntheses with NMR. The Roman group recently showed a new analysis method based on dynamic nuclear polarization (DNP) for boosting ssNMR sensitivity, thus enabling the characterization of zeolites made with natural abundance Sn precursors.

Dynamic nuclear polarization ssNMR addresses low-sensitivity challenges by transferring the larger polarization of electron spins, such as those found in stable exogenous radical compounds, to nuclear spins. The target nuclei then become dynamically polarized and their NMR signals are enhanced by orders of magnitude. In the first step of this process, high-power microwaves irradiate the sample treated with an exogenous biradical and a glassing agent (i.e., 1,1,2,2-tetrachloroethane). Next, the electron polarization is transferred from the radical to the protons in the solvent through electron–nuclear dipolar couplings. Freezing the sample at cryogenic temperatures (100° K) allows for ^{1}H–^{1}H spin diffusion to occur efficiently and enables the relay of polarization to the solvent molecules present inside the zeolite pores. Lastly, by using appropriate contact times (ranging from 1 ms to 8 ms), ^{1}H polarization can be effectively transferred to the Sn sites using a cross-polarization step. Using this strategy, we demonstrated that DNP NMR allows the characterization zeolites containing ~2 wt % of natural abundance Sn without the need for ^{119}Sn isotopic enrichment. Using the bCTbK stable radical led to an enhancement (ε) of 75, allowing the characterization of natural-abundance ^{119}Sn-Beta with excellent signal-to-noise ratios in less than 24 hours. Without DNP, no ^{119}Sn resonances were detected after 10 days of continuous analysis. Figure 6 shows ssNMR spectra obtained of hydrated and dehydrated natural abundance Sn-Beta, indicating the presence of tetrahedrally coordinated framework tin sites. This technique reduces acquisition times more than approximately two orders of magnitude, allowing for a previously unattainable analysis to be completed in a matter of hours.

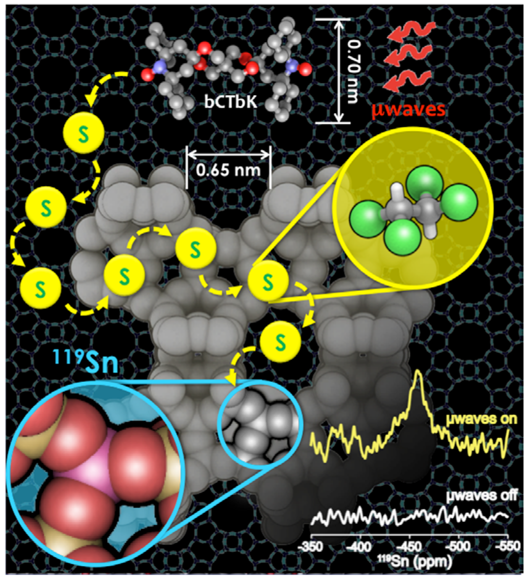


Figure 6. Analysis of tin-containing zeolites prepared with natural abundance precursors using dynamic nuclear polarization NMR.

Annual Lectures and Seminars

During AY2013–2014, the Chemical Engineering Department hosted a distinguished group of academic and industry leaders, speaking on topics that highlighted cutting-edge research addressing today's energy and health-related challenges. Webcasts for all major lectures can be accessed at *http://web.mit.edu/cheme/news/webcast.html*.

28th Hoyt C. Hottel Lecture (December 4, 2013): "How Quantum Mechanics Can Help Solve the World's Energy Problems." Professor Emily A. Carter, Gerhard R. Andlinger professor in energy and the environment and professor of mechanical and aerospace engineering and applied and computational mathematics at Princeton University, discussed the future of alternative energy. Professor Carter is the founding director of the Andlinger Center for Energy and the Environment. Her current research is focused entirely on developing and applying quantum mechanics methods to enable design of molecules and materials for sustainable energy, including converting sunlight to electricity and fuels, providing clean electricity from solid oxide fuel cells, clean and efficient biofuel combustion, optimizing lightweight metal alloys for fuel-efficient vehicles, and characterizing hydrogen isotope incorporation into plasma facing components of fusion reactors.

20th Alan S. Michaels Lecture (May 2, 2014): "What's in Your Blood? Molecular Deconvolution of the Human Serum Antibody Repertoire in Health and Disease." George Georgiou, from the University of Texas at Austin's departments of Chemical Engineering, Biomedical Engineering, and Molecular Genetics and Biology, discussed his current research. His laboratory has developed a suite of proteomic, microfluidic, protein engineering, and informatics technologies that have enabled the deconvolution of the identities and relative amounts of antibodies in biological fluids and the delineation of the relationships between antibody production and the relevant B cell immunological mechanisms. He has used this approach to elucidate a number of key questions in medicine and human health, including the repertoire and functionality of antibodies elicited in humans following vaccination and how many different antibodies in toto are typically present in the blood. These technologies enable the development of potent therapeutic antibodies to infectious diseases, discovered by mining the protective antibody responses in convalescent patients who have overcome infection and more efficient metrics for new vaccines.

36rd Warren K. Lewis Lecture (April 30, 2014): "Fighting Cancer with Nanoparticle Medicines: The Nanoscale Matters!" Professor Mark E. Davis of the California Institute of Technology discussed how nanoscale research is changing how we fight cancer. The Lewis Lecture includes a residency and technical lecture, which Professor Davis gave on Monday, April 28, titled "New Heterogeneous Catalysts for Converting Sugars in Aqueous Media." Professor Davis is the Warren and Katharine Schlinger professor of chemical engineering at the California Institute of Technology and a member of the Experimental Therapeutics Program of the Comprehensive Cancer Center at the City of Hope and the Jonsson Comprehensive Cancer Center at UCLA. He is the recipient of numerous awards, including the Colburn and Professional Progress Awards from the AIChE and the Somorjai, Ipatieff, Langmuir, Murphree, and Gaden Prizes from the ACS. Professor Davis's research efforts involve materials synthesis in two general areas: zeolites and other solids that can be used for molecular recognition and catalysis, and polymers meant for the delivery of a broad range of therapeutics. He is the founder of Insert Therapeutics Inc., Calando Pharmaceuticals, Inc. (a company that created the first RNA interference therapeutic to reach the clinic for treating cancer), and Avidity Nanomedicines. Professor Davis has achieved All-American status for Masters track and field in the 400, 200, and 100 meter dashes. In 2011, he won the 400 meter dash for men of aged 55–59 at the Masters World Championship.

Departmental Awards

The department awards ceremony took place on May 12, 2014, in the Gilliland Auditorium of the Ralph Landau Building. This year's recipients of the Outstanding Faculty awards were professor Bradley Olsen (the graduate students' choice) and professor Fikile Brushett and professor Patrick Doyle (the undergraduate students' choices).

The Edward W. Merrill Outstanding Teaching Assistant Award was presented to PhD student Alexander Bourque for his work in 10.213 Chemical and Biological Engineering Thermodynamics. The Outstanding Graduate Teaching Assistant Award was presented to PhD student Ray Smith for his service to the students of 10.50 Analysis of Transport Phenomena. All third-year graduate students are required to present a seminar on the progress of their research; the two recipients of the Award for Outstanding Seminar were Ben Renner and Eric Zhu.

Chemical Engineering Special Service Awards were conferred on the members of the Graduate Student Council: Abel Cortinas, David Emerson, Jose Gomez, Kevin Kauffman, Monique Kauke, Kathryn Maxwell, Nicholas Mozdzierz, Karthick Murugappan, Justin Nelson, Issac Roes, Sue Zanne Tan, and Harry Watson. Members of the Graduate Student Advisory Board were also recognized: Ankur Gupta, Jose Gomez, Lionel Lam, Katie Maass, Kaja Kaastrup, Sayalee Mahajan, Brandon Reizman, Siddarth Srinivasan, and Andrew Silverman. In addition, Brandon Reizman was awarded the Chemical Engineering Rock Award for his contributions to athletics within the department. The following undergraduate students were also recognized for their service to the student chapter of the AIChE: Michelle Teplensky, David Hou, Samantha Hagerman, Brian Alejandro, Whitney Loo, Kali Benevides, Julia Sun, Allen Leung, Anthony Concepcion, Pritee Tembhekar, Chadd Kiggins, Spencer Wenck, Eric Safei, Joshua Zeidman, Michael Fu, Joel Schneider, Kelsey Jamieson, and June Park.

The department's undergraduates also earned numerous accolades over the course of the year. The Xi Chapter of Phi Beta Kappa voted to invite five members of the department's Class of 2014 to membership in recognition of their excellent academic records and commitment to the objectives of a liberal education: William Baysinger '14, Samantha Hagerman '14, Benjamin Niswonger '14, Akshar Wunnava '14, and Devin Zhang '14. Michelle Teplensky '14 was recognized as a Gates Cambridge Scholar. The Robert T. Haslam Cup, which recognizes outstanding professional promise in chemical engineering, went to Akshar Wunnava. The department's oldest prize, the Roger de Friez Hunneman Prize, is awarded to the undergraduate who has demonstrated outstanding achievement in both scholarship and research; this year it went to Samantha Hagerman. The Wing S. Fong Prize is awarded, in honor of Wing S. Fong, to a chemical engineering senior of Chinese descent with the highest cumulative GPA, for his or her hard work and dedication to his or her adopted home, university, and country. This year's prize was awarded to Kevin Wu. The BP award for outstanding academic achievement by sophomore women chemical engineers went to Pamela Cai, Kiara Cui, and Kelsey Jamieson. Sarah Mayner won the BP award for outstanding academic achievement for a junior woman chemical engineer. The BP award for outstanding performance in the Projects Laboratory course by a junior woman chemical engineer went to Xingyi Shi. And Catherine Liou earned the BP award for outstanding performance in research by a junior woman chemical engineer.

The department is pleased to recognize Gwen Wilcox as the ' Outstanding Employee of the Year for her dedication and exceptional service to faculty, staff, and students.

The Department of Chemical Engineering at MIT has had a very fruitful and rewarding year and is poised for equal success in the coming year.

Klavs F. Jensen
Department Head
Warren K. Lewis Professor of Chemical Engineering

William H. Green
Executive Officer
Hoyt C. Hottel Professor of Chemical Engineering