Department of Chemical Engineering

The Department of Chemical Engineering continues to be ranked as the world's number-one chemical engineering program by *US News & World Report*, a position it has now for 27 years. The department continues to be a vibrant intellectual community, with many of our faculty receiving major honors and awards.

Sponsored research volume in the department continues to be strong, increasing by 6% this year to $61.1 million. Of this total, $25.7 million was handled directly through the department and the remainder by different cost centers at MIT, including the Koch Institute for Integrative Cancer Research, the MIT Energy Initiative (MITEI), and the Ragon Institute of MGH, MIT and Harvard. The strong engagement with these interdisciplinary centers continues to offer a strong basis for innovation and provides our students with experience solving important and difficult real-world problems.

In addition, several faculty members have led new multi-investigator research initiatives. Richard Braatz led MIT's contribution to a proposal for a smart manufacturing innovation institute that would develop smart technologies and systems for use in advanced manufacturing with $70 million in support from the US Department of Energy and $140 million in public and private investments. President Barack Obama announced in June 2016 that the proposal, which is led by the Smart Manufacturing Leadership Coalition (in which MIT is an academic and research partner), was selected for support. Klavs Jensen and Allan Myerson are leading the Pharmacy on Demand Project, which is funded by the Defense Advanced Research Projects Agency (DARPA). Leveraging continuous manufacturing concepts, they have developed a refrigerator-sized device that can produce hundreds of thousands of doses of medicine a day. In a related effort, Professors Jensen, Braatz, and Myerson have started another DARPA-sponsored project on a computational synthesis design route that aims to integrate retrosynthetic tools, machine learning, and computational chemistry for reaction pathway identification, scoring, and selection. Professor Michael Strano is coordinating the Institute's participation in a proposal to establish the Modular Chemical Process Intensification Institute for Clean Energy Manufacturing, which will be funded by the Department of Energy. Fourteen MIT faculty are working on the effort, which is led by the American Institute of Chemical Engineers to develop the next generation of process intensification strategies (methods to reduce the size and energy consumption of industrial processes by the integration of several existing unit operations into single concerted processes).

In July 2015, Klavs Jensen completed his eighth and final year as department head. The department is thankful for his service and excellent guidance. Professor Paula T. Hammond was appointed department head and has just completed her first year in the position; Patrick Doyle continued as executive officer through July 2016. Richard Braatz continued his service as graduate officer and Barry Johnston as undergraduate officer; Bill Green became the postdoctoral officer. T. Alan Hatton remains the director of the David H. Koch School of Chemical Engineering Practice, which celebrates its 100th anniversary in 2016. Chemical Engineering claims two Institute Professors as primary faculty members—Daniel I.C. Wang and Robert S. Langer. Several Chemical Engineering faculty have important leadership roles on campus: Robert C. Armstrong is the director of the MIT Energy Initiative, Arup K. Chakraborty is the director of the MIT Institute for Medical Engineering and Science (IMES), Dane Wittrup is associate director of the Koch Institute for Integrative Cancer Research, and Karen Gleason is associate provost. Professor Jesse Kroll received tenure and was promoted to associate professor. Tricia Campbell and Catherine Gauthier joined the Administrative Services Organization as financial coordinator and financial officer, respectively; Kristal Kilmain and Sandy DeOliveria were promoted to the rank of financial coordinator, and Marwan Cheguenni was promoted to financial officer. In June 2016, Gerry Hughes joined the department as the new building manager. Building manager Steven Wetzel, one of Chemical Engineering's key staff members, retired after 24 years of service to the department.

Research and Recognition

Many Chemical Engineering faculty members received major awards for their research achievements. Robert Langer received the Benjamin Franklin Medal in Life Science. He also won several other awards, received several honorary degrees, and gave a number of major invited lectures. Karen Gleason won the American Institute of Chemical Engineers (AIChE) Stine Award and was inducted into the National Academy of Engineering (NAE). Allan Myerson won the AIChE Excellence in Process Development Research Award and the Clarence G. Gerhold Award from the AIChE Separations Division. Daniel Blankschtein won the Capers and Marion McDonald Award for Excellence in Mentoring and Advising. Arup Chakraborty was elected to the National Academy of Sciences (NAS). Richard Braatz won the International Society of Automation's 2015 Excellence In Education Award. Pat Doyle was selected as a 2016 Singapore research professor.

Michael Strano was named a Thomson Reuters Highly Cited Researcher for 2015, and Professors Langer and Strano were listed among the World's Most Influential Scientific Minds by Thomson Reuters. Martin Bazant won MIT's 2015 Bose Award for his innovative and unconventional projects and was named the inaugural E.G. Roos (1944) Professor. Langer and Professor Bernhardt L. Trout were named in the 2016 Medicine Maker Top 100 Power List.

Our junior professors continue to receive recognition for their early-career achievements. James Swan won a National Science Foundation (NSF) CAREER Award. William A. Tisdale received a Presidential Early Career Award for Scientists and Engineers and was named a 2016 Alfred P. Sloan Research Fellow in Chemistry. Kwanghun Chung was presented a David and Lucile Packard Fellowship Award.

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

Undergraduate Education

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, we introduced the 10-ENG flexible SB degree in engineering. Department undergraduate enrollment has been gradually declining since AY2007, but Chemical Engineering continues to have 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, Family Weekend, and other activities. Sixty-seven SB degrees were conferred in June 2016, 58% of which 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	06–07	07–08	08–09	09–10	10–11	11–12	12–13	13–14	14–15	15–16
Sophomores	95	96	87	87	80	67	71	67	57	56
Juniors	75	67	77	68	71	70	58	63	66	53
Seniors	83	77	75	73	72	69	69	64	62	65
Total	**253**	**240**	**239**	**228**	**223**	**206**	**198**	**194**	**185**	**174**

The 10-ENG program leading to the engineering bachelor of science degree was introduced in response to demand from our students for a curriculum that would allow specialization in particular topics. The program features 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 particular subjects. We have recently received ABET (Accreditation Board for Engineering and Technology) accreditation for 10-ENG as a degree in engineering. The initial specialization tracks are energy, materials, biomedical, and environmental. Student response has been cautious (with a fall 2015 enrollment of six students).

The average starting salary for graduates of the Department of Chemical Engineering is $77,500 (2016 senior survey), which is among the highest in the School of Engineering. This attests to the success of the graduates of the 10 and 10-B programs and to the continued high demand for our students. The 2016 senior survey indicates that 33% of our students 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 invited speakers, presentations at national meetings, and visits to company sites. The chapter's student officers are Andrea Blankenship '18, Pam Cai '16, Kiara Cui '16, Mary Delaney '16, Natalie Delumpa-Alexander '18, Cody Diaz '16, Jessica Greer '17, Allison Hallock '16, Kelsey Jamieson '16, Barbara Lima '16, Lauren Liou '16, Linh Nguyen '18, Michelle Tai '17, Emma Valentine '17, Jessie Zhao '17, and Brian Zhong '18.

Graduate Education

The graduate program in the Department of Chemical Engineering offers master's of science degrees in chemical engineering (MS) and chemical engineering practice (MSCEP), 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 total graduate student enrollment is currently 233, with 218 in the doctoral program and 15 master's-level degree candidates. In the doctoral program, 208 students are in the PhD/ScD track and 10 in the PhDCEP track. In the master's-level program, 13 students are in the MSCEP track. Thirty-five percent of our graduate students are women, and 5% are members of underrepresented minority groups. Forty-one of our graduate students were recipients of outside fellowship awards, including awards from NSF, the National Institutes of Health, and the Department of Defense.

The distribution of graduate students by degree level over the last 10 years is shown in Table 2. During AY2016, 76 advanced degrees were conferred, 30 at the doctoral level (PhD, ScD, PhDCEP) and 46 at the master's level (MSCEP, MS). Thirty-nine students passed the written portion of the doctoral qualifying exams and are thus one step closer to being promoted to candidacy for the PhD/ScD or PhDCEP. The department received 411 applications for admission to the doctoral program and offered admission to 55 individuals; 40 students accepted the offer (an acceptance rate of 73%). There were 105 applications for master's-level programs; the department made nine offers, six of which were accepted (a yield of 67%). Among the incoming graduate class, 11 students are women and one is a member of an underrepresented minority group. The average GPA of the incoming graduate class was 4.95 (out of 5.0).

Table 2. Graduate Enrollment over the Last 10 Years

Degree Level	06–07	07–08	08–09	09–10	10–11	11–12	12–13	13–14	14–15	15–16
Master's	18	26	32	38	28	20	10	11	15	15
Doctoral	217	212	228	203	212	224	212	211	222	218
Total	**235**	**238**	**260**	**241**	**240**	**244**	**222**	**222**	**237**	**233**

Research Centers

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

Biologically Derived Medicines on Demand

This DARPA-sponsored program successfully entered into its third year of research and has begun developing plans for translational development. The program aims to establish an end-to-end manufacturing system for making small numbers of doses of biologic therapeutics at the point of care in about 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. In the past year, the team has extended its prototype designs for a system capable of producing tens to thousands of doses of different biologic drugs and has worked to test the range of medicines that would be compatible with manufacturing in the system. 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.

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

The interdisciplinary research team comprises labs in Chemical Engineering, Electrical Engineering, and Biological Engineering at MIT (Professors Richard Braatz, Michael Strano, Jongyoon Han, J. Christopher Love, Tim Lu, and Rajeev Ram) as well as labs from the Barnett Institute at Northeastern University, the Rensselear Polytechnic Institute, and the Pall Corporation. Research topics include small-scale perfusion fermentation of a yeast host, 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. Integration of technologies is an essential element of the program to realize an efficient and small manufacturing platform that can be portable and reach remote locations. Advances in the technologies evaluated and developed in this program will inform new strategies for integrated and continuous manufacturing of biologics at commercial scales. As part of the program, an active dialogue among the program team, industry experts, and the Food and Drug Administration (FDA) continues with the aim of understanding and defining best strategies toward realizing such transformational shifts in manufacturing on demand. The project is led by Professor Love.

Novartis-MIT Center for Continuous Manufacturing

May 2016 marked the end of the ninth year of the initial 10-year collaboration with Novartis on continuous manufacturing of pharmaceuticals. We have continued to work on a large set of projects to overcome technical problems related to the transition from batch manufacturing to the more efficient continuous mode. This work has been conducted in 12 research groups spread across three departments (Chemical Engineering, Chemistry, and Mechanical Engineering).

Although MIT is working closely with Novartis on the projects, the advances and findings have been published in a wide variety of journals and new intellectual property has been captured in patents. In the last year alone, project researchers published 30 papers and the center filed four patent applications for breakthrough technologies.

We not only have made great strides in solving the technical problems related to continuous manufacturing of complex and high-value drug molecules but have engaged the global pharmaceutical industry, academics, and regulators to attack regulatory and mind-set challenges to adoption. To continue this work, we are jointly organizing the second International Symposium on Continuous Manufacturing of Pharmaceuticals, which will be held in September. Janet Woodcock, head of the FDA's Center for Drug Evaluation and Research, will again present the keynote address. The meeting will bring together global leaders in the pharmaceutical world to report on the advances made in the past two years and to discuss the challenges ahead. One of the major outputs of the symposium will be a regulatory white paper on continuous manufacturing of pharmaceuticals. The paper will incorporate all of the learning and commentary from the meetings and post-meeting discussions.

The Novartis-MIT Center is led by Bernhardt L. Trout, director, and Markus Krumme, Novartis head of continuous manufacturing. The team also includes the associate director, Keith D. Jensen, and the program coordinator, Faika E. Weche.

David H. Koch Institute for Integrative Cancer Research

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

Faculty Notes

Robert C. Armstrong serves as director of the MIT Energy Initiative. MITEI continues to grow rapidly in its research, educational, and outreach components. Twelve companies sponsor research as founding and sustaining members of MITEI; all together the energy initiative has more than 80 industrial and public partners across four continents. MITEI has helped to bring in well over $600 million in support during its first nine years of operation, along with 350 energy graduate fellowships spread over 25 departments. During the past year, MITEI has begun creating eight low carbon energy centers (in the technology areas of solar energy; energy storage; carbon capture, utilization, and storage; materials for energy and extreme environments; advanced nuclear engineering science; energy bioscience; electric power systems; and fusion), which are a key component of MIT's Climate Action Plan. Professor Armstrong serves on the Scientific Commission of the Eni Enrico Matteo Foundation, the PULSE Award selection committee for EDF (Électricité de France), and the external advisory board of the National Renewal Energy Laboratory. Also, he serves on the advisory boards of the chemical engineering departments at Northwestern University, Washington University, and the Energy Institute at Texas A&M University. He gave numerous lectures on energy around the world during the past year.

Martin Z. Bazant continued research in electrochemistry, transport phenomena, and applied mathematics and began serving as executive officer. His lab developed the first prototype for shock electrodialysis, a water desalination method he predicted theoretically in 2009 and patented. On sabbatical at Stanford as the Global Climate and Energy Project Chair, he published 15 papers, conducted independent mathematical research, and began writing a textbook on electrochemical physics. He delivered the IMA Lighthill Lecture at Oxford and was the youngest recipient of the International Society of Electrochemistry's Alexander Kuznetsov Prize in Theoretical Electrochemistry.

Daniel Blankschtein's group conducts fundamental theoretical and experimental research in the area of colloid and interface science, with an emphasis on industrial and biomedical applications. Recent research advances include molecular dynamics simulation and kinetic modeling of the exfoliation, dispersion, and stabilization of 2D materials such as phosphorene, MoS2, and hBN in various solvents; molecular modeling of the wetting behavior of water on MoS2 and hBN; interfacial modeling of reconfigurable multiple emulsions; molecular-thermodynamic modeling of the surface tension of aqueous surfactant solutions; experimental studies of emulsions stabilized with particles and surfactants; modeling of water desalination using carbon nanotubes and 2D porous membranes; and ultrasound-assisted transdermal vaccination. Professor Blankschtein's group interacts closely with several companies that make use of software developed by the group to facilitate surfactant formulation design. His teaching responsibilities included the core graduate course 10.55 Colloid and Surfactant Science (fall 2015) and the interdisciplinary graduate course 10.56 Advanced Topics in Surfactant Science (spring 2016).

Professor Blankschtein received the Capers and Marlon McDonald Award for Excellence in Mentoring and Advising in July 2015. He and his students delivered talks and presented posters at the 250th and 251st American Chemical Society (ACS) national meetings in Boston and San Diego, respectively; the 10th Annual Immunotherapy and Vaccine Summit in Boston; the 2015 American Institute of Chemical Engineers annual meeting in Salt Lake City; the 2015 Materials Research Society (MRS) fall meeting in Boston; and the International mRNA Health Conference in Berlin. Professor Blankschtein continues to serve on the editorial board of Marcel Dekker's Surfactant Science Series.

Richard D. Braatz received the Excellence in Education Award from the International Society of Automation. As the department's graduate officer, he coordinated graduate administrative activities and oversaw graduate affairs. He gave numerous invited talks, including plenaries at major international conferences, and continued to lead systems engineering research in pharmaceutical and biopharmaceutical manufacturing projects on campus. He served on numerous advisory and editorial boards, including as senior editor of *IEEE Life Sciences Letters*.

Fikile Brushett, the Raymond A. (1921) and Helen E. St. Laurent Career Development Assistant Professor, continued his research on the science and engineering of electrochemical energy systems. He and his group are currently focusing on redox flow batteries for grid storage and the electrochemical valorization of carbon dioxide and biomass. Professor Brushett published 12 papers and gave 11 invited lectures. His research is supported by, among other sources, the Joint Center for Energy Storage Research, Shell, Bosch, Eni SpA., and the MIT Center for Materials Science and Engineering. Brushett served as an instructor for 10.301 Fluid Mechanics.

Arup Chakraborty is continuing efforts to understand the mechanistic bases of specific and systemic immune responses to pathogens and how aberrant regulation leads to disease. Research aimed at understanding how this knowledge can be harnessed for the rational design of vaccines and therapies is also important. Chakraborty serves as the director of IMES and taught a core chemical engineering graduate subject. He was elected to the NAS this year, making him in all likelihood the first person to be elected to the NAS and the NAE for completely different bodies of work recognized by completely different communities of researchers. He continues to serve as a member of the US Defense Science Board and as a senior editor of *eLife* (one of the premier journals in biology).

Kwanghun Chung, the Samuel A. Goldblith Career Development Assistant Professor, is a faculty member in the Department of Chemical Engineering and the Institute for Medical Engineering and Science. He is also a principal investigator at the Picower Institute for Learning and Memory. His interdisciplinary research team is devoted to developing and applying novel technologies for integrative and comprehensive understanding of the brain. The group has continued to develop enabling technologies to accelerate the pace of scientific discovery of therapeutic strategies in a broad range of biomedical research. Recent research advances by Chung and his team include tissue-processing technologies that are up to 50 fold-faster than conventional methods, proteomic imaging of human brain tissues, and superresolution and scalable proteomic imaging of large samples. Chung was a 2015 Packard Fellowships for Science and Engineering awardee and a 2016 McKnight Technological Innovations in Neuroscience awardee. Since July 2015, Professor Chung has traveled extensively to speak about his new technologies, including at the Weizmann Institute and Temple University. During the past year, he taught HST.562 Imaging and Sample Processing and 10.032 Transport Phenomena. He also served on the IMES Committee for Academic Programs.

In May 2016, Robert E. Cohen was honored for his 43 years of teaching, research, and service to MIT during a weekend symposium organized by his former students and current colleagues in the Department of Chemical Engineering. Cohen's research highlights in the past year included a new MITEI-funded project with Exxon-Mobil on fundamental wetting phenomena and a *Proceedings of the National Academy of Sciences* publication on a novel method for generating wettability patterns using spontaneous creasing instabilities in suitably stressed thin coatings. A new research collaboration with the Masdar Institute of Science and Technology in Abu Dhabi is organized around the need for multifunctional protective coatings for desert-deployed solar cells. In June 2016, Cohen and his research group traveled to Princeton University to participate in the 23rd rendition of a two-day MIT-Princeton microsymposium on polymers.

Charles L. Cooney, Robert T. Haslam (1911) Professor of Chemical and Biochemical Engineering (emeritus), teaches the 10.491 Integrated Chemical Engineering capstone subject, which introduces all chemical engineering seniors to batch process design and pharmaceutical manufacturing. In addition, he continues as an advisor to the Singapore-MIT Alliance for Research and Technology Innovation Center in Singapore, as a member of the executive committee of the MIT-Masdar Institute Cooperative Program, and as a member of the steering committee for the Deshpande Center for Technological Innovation. He is the faculty director of the Downstream Processing summer course, organized through MIT's Professional Institute, and co–faculty lead on a custom Sloan executive education program for Takeda Pharmaceuticals. Professor Cooney is also an overseer of the Boston Symphony Orchestra and a trustee emeritus of the Boston Ballet.

Patrick S. Doyle, the Robert T. Haslam (1911) Professor of Chemical Engineering, continued to serve as the department's executive officer and worked on revitalizing the undergraduate curriculum. His research focuses on fundamental studies of DNA polymer physics and microfluidic synthesis of functional microparticles using stop flow lithography. A developing area of emphasis for his group is fundamental studies and applications of nano-emulsions. Professor Doyle co-founded Motif Micro, a start-up that is advancing developments in his lab on up-converting barcoded particles for anti-counterfeiting applications. He delivered several invited lectures, including a plenary lecture at the European Colloid and Interface Society and a keynote lecture at the PittCon conference. Professor Doyle serves on the scientific advisory boards of Lariat Biosciences, Achira Labs, and Motif Micro.

William H. Green is the faculty chair of MIT's Mobility of the Future study, part of MIT's Climate Action Plan, and plays a leading role in several MITEI projects. Research highlights include the release of a new version of the Reaction Mechanism Generator software package, which automatically constructs chemical kinetic models for thermal reactions of organic molecules, and the development of a new method for conversion of natural gas into liquids that can be of economic value at small scales. Professor Green gave invited plenary talks at the International Conference on Chemical Kinetics and at a Department of Energy workshop on the role of high-performance computing in engine and fuel co-optimization.

Paula Hammond began her first year as department head and launched new initiatives with the support and participation of Chemical Engineering faculty, including an undergraduate curriculum revitalization process and a long-range planning exercise. She gave several named lectures across the country, including the 2016 Cary Lecture at the Georgia Institute of Technology, the 2016 Habermann Lecture at Marquette University, the 2016 Distinguished Su Lecture at the University of Rochester, and the 2016 Mason Lecture at Stanford University. She attended the World Economic Forum in Davos, Switzerland, in January 2016, where she presented a MIT IdeasLab talk on personalized medicine. While in Davos, Professor Hammond was one of the panelists on Vice President Joe Biden's roundtable launch of the Cancer Moonshot effort. In November 2015, she gave a live TED talk on the use of layered nanoparticles for targeted delivery of combination cancer drugs that aired on PBS in April 2016.

Professor Hammond continues to serve as an associate editor of the American Chemical Society journal *ACS Nano*. This January, she co-chaired the Society of Biological Engineering's International Conference on Biological Engineering. She serves as a member of the Secretary of Energy Advisory Board (SEAB) and is part of the SEAB Task Force on Biomedical Sciences. Her research continues to expand in the area of targeted cancer nano-therapies, with additional key publications this academic year on the release of siRNA and proteins to heal soft tissue wounds (e.g., diabetic ulcers and burn wounds). Professor Hammond was also the chair of the Gordon Research Conference on Drug Carriers, which took place in summer 2016.

T. Alan Hatton continued to serve as director of the David H. Koch School of Chemical Engineering Practice, where he has placed student teams at host companies in the United States, Ireland, Dubai, Canada, and Australia. He has advised the Masdar Institute on the establishment of a Practice School–like program in Abu Dhabi. He is a co-director of the MITEI Low-Carbon Energy Center for Carbon Capture, Utilization, and Storage, and in this role he has participated in many MITEI workshops and meetings. Hatton is a member of the scientific advisory board of the Particulate Fluids

Processing Center at the University of Melbourne, a member of the editorial advisory board of *Colloid and Interface Science Communications*, and an advisory board member of Engineering Conferences International in New York. He presented invited and keynote lectures at the University of Melbourne, the CDI (capacitive deionization) conference in Saarbrücken, and at the meetings of AIChE and ACS. Also, he gave a plenary talk at the PARTEC conference in Nuremburg. He is currently involved with preparations for the centennial celebration of the Practice School program in fall 2016.

Klavs F. Jensen spent the spring semester on sabbatical at ETH (Eidgenössische Technische Hochschule Zürich) in Zurich and continued his research on functional micro- and nano-structured materials and devices for chemical and biological applications. He explored a wide range of flow systems for chemical applications, with a particular emphasis on systems for which continuous processing provides unique performance advantages. These systems also formed 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 program. The Pharmacy on Demand effort expanded beyond the initial demonstration of continuous synthesis of four common pharmaceuticals in a small integrated, reconfigurable, and transportable system. With colleagues in chemical engineering, chemistry, and computer science, Jensen initiated a new DARPA-sponsored program focusing on systems for knowledge-based continuous organic synthesis. With Professors Moungi Bawendi and Heather Kulik, he examined growth mechanisms underlying the formation of indium phosphide quantum dots. Also, in collaboration with Professor Langer, he explored microfluidic devices enabling the transport of macromolecules across cell membranes through cell squeezing and electroporation. During the past academic year, Professor Jensen gave plenary lectures on microreaction technology at international conferences and at universities. He served on advisory boards to chemical engineering departments, participated in the governing boards of the Technical University of Denmark and SQZ Biotech, and was a member of the scientific advisory board of the Singapore A*STAR Institute for Bioengineering and Nanotechnology.

Jesse H. Kroll and his research group continued their work on the organic chemistry of the atmosphere and the formation of atmospheric particulate matter. Although most of the group's research centered on laboratory studies, a new research direction involved characterization and use of low-cost sensors for monitoring air quality in a range of environments. He again led TREX (Traveling Research Environmental eXperience), an Independent Activities Period (IAP) spring class focused on environmental fieldwork in which students traveled to Hawaii to measure pollution in the air (from the Kilauea volcano) and in the soil (from historical use of arsenic-based herbicides). Professor Kroll gave several invited lectures and seminars, including talks at the American Geophysical Union fall meeting and the American Association of Aerosol Research annual meeting. He was awarded tenure effective July 2016.

Heather J. Kulik, the Joseph R. Mares ('24) Career Development Chair Assistant Professor, focuses on developing and employing large-scale accelerated density functional theory calculations to further the understanding of catalysis and materials science. This work, which has been featured in eight peer review publications in the past year (including in *Advanced Functional Materials* and the *Proceedings of the National Academy of Sciences*), is supported by NSF, the Burroughs-Wellcome Fund, and MITEI. New software and algorithms developed by Professor Kulik and her group have enabled high-throughput screening and materials design with applications ranging from quantum dot synthesis to separations and catalysis. The Kulik group consists of one postdoc, seven graduate students, one Undergraduate Research Opportunities Program student, and one research assistant.

Robert Langer was presented honorary degrees from the Karolinska Institutet, Carnegie Mellon University, the University of Maryland, Hanyang University, and the University of New South Wales. He received the Queen Elizabeth Prize for Engineering, the Sackler Award for Sustained National Leadership, the Benjamin Franklin Medal in Life Science, the Hoover Medal, the Scheele Award, and the Royan Institute's Kazemi Award for Research Excellence in Biomedicine. Also, he was named the Cornell Entrepreneur of the Year. He presented numerous named lectures, including the Robert E. Gross Lecture, the Baker Symposium Lecture (Cornell University), and the Irving Shain Lecture (University of Wisconsin).

J. Christopher Love continued his research applying new bioanalytical processes to profile immune responses in chronic diseases, including multiple sclerosis, type 1 diabetes, cancer, and food allergies. His lab also worked on advancing biomanufacturing research to lower the costs of producing protein therapeutics to promote global access. He continued to lead a team of investigators from MIT, Rensselaer, the Pall Corporation, and Northeastern University under DARPA's Biologics Manufacturing on Demand program for end-to-end manufacturing of biologic drugs at the point of care in approximately 24 to 48 hours. An edX course on biomanufacturing (10.03r) was offered twice in collaboration with the Center for Biomedical Innovation and the Department of Biology. Professor Love also took time on sabbatical leave as a distinguished engineer in residence at Biogen in Cambridge, and he served as a scientific advisor to several groups in biomanufacturing and immunotherapies.

Allan S. Myerson continued his research on fundamental and applied problems in crystallization and pharmaceutical manufacturing. Also, he continued his work as a principal investigator in the Novartis-MIT Center for Continuous Manufacturing and on the DARPA Pharmacy on Demand project. Professor Myerson serves as an associate editor of the ACS journal *Crystal Growth and Design*. He serves on the scientific advisory boards of Gensyn Technologies, a company devoted to particle engineering applications in pharmaceuticals; BlueSpark, a company that develops novel flexible batteries; and CONTINUUS Pharmaceuticals. Professor Myerson was the recipient of the 2015 Clarence G. Gerhold Award from the AIChE Separations Division and the 2015 Excellence in Process Development Award from the AIChE Process Development Division.

Bradley D. Olsen, the Cook Career Development Associate Professor, and his research group continued their work in the areas of bioinspired and biofunctional block copolymers, polymer gels, and protein-based materials for applications in defense, sustainability, and human health. Major accomplishments included reporting on a new method to self-assemble antibodies into biosensors with transformatively high protein density, developing enzyme-based formulations for the decontamination of toxic organic chemicals, and developing a new theory that can quantitatively predict the modulus of polymer gels without adjustable parameters. This research is supported by the Air Force Office of Scientific Research, the Institute for Soldier Nanotechnologies, the Department of Energy's Office of Basic Energy Science, NSF, and the Defense Threat Reduction Agency. During the year, Professor Olsen published 14 peer-reviewed papers and presented 23 invited lectures. His group also submitted a patent for bioconjugate brush polymers. Olsen won the 2015 American Institute of Chemical Engineers Colburn Award and was named a fellow of the Polymer Division of the American Chemical Society. He served as an instructor for 10.10 Introduction to Chemical Engineering and 10.40 H-Level Chemical Engineering Thermodynamics. In addition, he developed and taught for the first time 10.00 Molecule Builders, a new maker-space course.

Kristala L.J. Prather returned from sabbatical as a fellow of the Radcliffe Institute for Advanced Study at Harvard University. Her research lab continues to work at the forefront of metabolic engineering and synthetic biology. Over the past year Prather delivered several invited lectures, including the inaugural Martin H. Freeman Lecture at Middlebury College (Middlebury, VT), and was selected to provide her thoughts on the frontiers of biotechnology in the journal *Nature Biotechnology* as one of the "voices of biotech." She currently serves on the scientific advisory board of the Novo Nordisk Center for Biosustainability (Copenhagen, Denmark), and the external advisory board of the Center for Sustainable Polymers, and she is an associate editor of *Metabolic Engineering Communications*. Prather spoke at the "Beyond 2016: MIT's Frontiers of the Future" symposium (part of the campus centennial celebrations) and at the MIT-hosted regional meeting of the National Academy of Engineering. She continues to serve as co-director of the long-running Fermentation Technology course (founded by Professor Daniel I.C. Wang and offered through the MIT Professional Education program); as co-director of the Microbiology Graduate Program, an interdisciplinary program with faculty from the Schools of Engineering and Science; and as bioengineering systems program lead for the MIT Portugal Program. AY2016 marked her first year of service on the Committee for Academic Performance. Prather was honored with her second C. Michael Mohr Outstanding Faculty Award for Undergraduate Teaching.

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 group published 12 peer-reviewed papers and filed two provisional patent applications. His work included the synthesis of novel core-shell nanoparticles to reduce the use of precious metals (published in *Science*) and the development of a zeolite-based catalyst to selectively oxidize methane into methanol at low temperatures (published in *ACS Central Science*). He delivered 16 invited lectures at international conferences, universities, and research institutes. Professor Roman continued his role as president of the New England Catalysis Society, finished his last year as the program coordinator for the AIChE Catalysis and Reaction Engineering Division, and joined the international advisory board of the journal *ChemSusChem*. Together with his wife, he continued serving as associate housemaster in Ashdown House.

Gregory C. Rutledge was named a fellow of the Polymeric Materials Science and Engineering Division of the American Chemical Society in 2015 and represented the division at the Fifth Joint Symposium on Polymers. He was also named a Thinker in Residence at Deakin University in Geelong, Australia, for the 2016 spring term. His research group continues to develop molecular simulations for the study of fundamental processing-structure-property relationships in polymers, with a recent emphasis on crystallization kinetics of polymers and thermomechanical properties of multiphase polymers with complex morphologies. They are also active in the development of ultra-fine fibers (having diameters less than 1 micron) for various applications in clean air, clean water, and advanced materials. Professor Rutledge delivered a number of plenary or invited lectures at conferences, universities, and companies in the United States as well as Korea, China, Australia, England, and Italy. His group published 14 papers and filed two patents over the past year. He continues to serve as an editor for the *Journal of Materials Science* and on the editorial advisory boards of several other journals. He is a member of the Committee on the Undergraduate Program and the Committee on Research Computing at MIT.

George Stephanopoulos received the 2016 Demokritos Scientific Research and Innovation Award, and he continued his research activities in two areas: process systems engineering at the nanoscale and collaborative integrated design of biorefineries. He presented the paper "A Multi-Actor, Multi-Objective Framework for the Design of Economically Optimal Processing Networks" at the annual AIChE meeting in Salt Lake City. Also, he published the fourth part of a series, "Controlled Formation of Nanostructures with Desired Geometries," in *I&EC Research* and three papers on collaborative design of biorefineries in the proceedings of the 26th European Symposium on Computer-Aided Process Engineering in Portoroz, Slovenia. He presented lectures and participated in workshops at universities in Argentina and Uruguay. His game-theoretical interpretation of a two-level Lagrangian approach has been received enthusiastically as the first opening in a very important area.

Gregory Stephanopoulos, the W.H. Dow Professor of Biotechnology and Chemical Engineering, continued to serve as director of the Metabolic Engineering Laboratory. In this capacity, he supervises the work of 25 to 30 researchers who focus on engineering microbes to convert them into little chemical factories for the production of fuels and chemicals. Notable research successes this year included an integrated system for biological conversion of gaseous substrate into lipids, engineering of the oleaginous yeast *Yarrowia lipolytica* for overproduction of lipids from renewable feedstocks, and engineering of *Escherichia coli* for the overproduction of the commodity chemical ethylene glycol. All of these developments contributed to the replacement of fossil feedstocks and advanced the vision of a biobased economy. In parallel, he continued to investigate the metabolic aspects of cancer, with a particular focus on the identification of therapeutic metabolic targets.

Gregory Stephanopoulos continued his service on the advisory boards of four academic institutions. In January 2016, he assumed the duties of president of the American Institute of Chemical Engineers. He delivered the 2016 Abbott Lecture at the Rensselaer Polytechnic Institute, the CAPEC annual lecture at the Danish Technical University, and the 2015 Beiyang Lecture at Tianjin University in China, where he was also named an honorary professor. He continued to serve as editor-in-chief of *Metabolic Engineering* and *Current Opinion in Biotechnology*, and he was a member of the editorial boards of eight other scientific journals. In addition to numerous research presentations at professional society meetings, he delivered plenary and keynote lectures at the annual AIChE meeting in Salt Lake City, the International Conference on Yeast Genetics and Molecular Biology in Italy, the Metabolic Engineering Summit in China, and the annual conference of the Association for General and Applied Microbiology in Germany. Also, he was presented an honorary doctorate degree by the National Technical University of Athens.

Michael S. Strano continued his research focusing on the chemical engineering of low-dimensional systems and nanomaterials. The concept of CoPhMoRe (Corona Phase Molecular Recognition), recently introduced by the Strano laboratory, was extended to protein targets for the first time and published in *Nature Communications*. Strano has continued to pursue the "smart tattoo" concept, using infrared fluorescent nanosensors to monitor biochemical analytes in the human body. His study on biocompatible hydrogel systems for implantation form factors recently appeared in the *Journal of Biomedical Nanotechnology*. In his research on thermopower waves, highlighted in an MIT news article (and published in *Energy & Environmental Science*), he developed a novel method of generating portable electrical power using carbon nanomaterials with sucrose as a fuel. He recently visited the King Abdullah University of Science and Technology in Saudi Arabia to initiate an effort to study marine animals using his innovative sensor platform.

Professor Strano was named to the Thomson Reuters World's Most Influential Scientific Minds list for 2016. In addition, he was selected as a finalist for the Blavatnik National Award for Young Scientists in chemistry. He continues to serve on the Defense Science Board's Task Force on Deterring, Preventing and Responding to the Threat or Use of Weapons of Mass Destruction. He delivered the Vaughn Lecture at the California Institute of Technology this past fall, along with the Edison Lecture at Notre Dame's College of Engineering. He also delivered invited presentations or seminars at Pittcon 2016 (Atlanta, GA), the Erlangen Symposium (Erlangen, Germany), Drexel University, the University of South Carolina, and at the Sensor Innovation Workshop at King Abdullah University of Science and Technology (Thuwal, Saudi Arabia). He continues to serve as the volume editor for the Materials Research Society's *MRS Bulletin*.

James W. Swan began his third year in the Department of Chemical Engineering, where he is currently the Texaco-Mangelsdorf Career Development Professor. His research focuses on computation and modeling of colloidal-scale self-assembly, and he works to advance scalable manufacturing of ordered materials with applications to sustainable energy and biomedical technologies. He has developed and begun publishing new algorithms for dynamic simulation of nano-particle fluid mechanics using graphics processing units. This research has already enabled new studies of materials such as gels and protein solutions, and his first publications, appearing in high-profile journals, have demonstrated the important role of fluid mechanics in the assembly of soft materials. Professor Swan received an NSF CAREER Award and an ACS Petroleum Research Fund Doctoral New Investigator Award over the past year. The Swan research group consists of five graduate students, one visiting master's student, and two undergraduate students.

Bernhardt L. Trout continues as director of the Novartis-MIT Center for Continuous Manufacturing, an $85 million partnership. In addition, he is director of the new E^3 (Engineering, Ethics, Entrepreneurship) educational program. He runs a laboratory of 15 graduate students, postdocs, and staff focusing on pharmaceutical small-molecule manufacturing and biopharmaceutical formulation and stabilization. His methods are used by pharmaceutical companies around the world. He is a consultant to the FDA and was named for the second consecutive year to the Top 50 Medicine Maker list. During the past year, he gave many invited talks and published or submitted almost 20 research papers and five patents. He is on the scientific advisory boards of three companies. He co-organized the recent MIT Mastery of Nature conference and coordinated the papers presented there, including his own.

Daniel I.C. Wang continued to be involved with the Singapore-MIT Alliance (SMA). He has two PhD candidates at the National University of Singapore. He is continuing his SMA research on high-throughput systems for mammalian cells, and he has been invited by Genentech, Life Technologies, Momenta Pharmaceutical, Molecular Devices, and Pfizer to give seminars on this research. He is actively pursuing licensing this technology on his own (MIT has decided not to file any patent on the technology because the patent, if granted, would be difficult to police) and has presented his research at the AIChE, ACS, and Society for Industrial Microbiology and Biotechnology annual meetings. Professor Wang completed his research with Saudi Aramco on microbial desulfurization of crude oil. One PhD thesis and three papers from this research have been published.

Professor Wang was invited to serve as chairman of the scientific advisory board of A*STAR in Singapore. The journal *Biotechnology and Bioengineering* has established the Daniel I.C. Wang Award for Research Excellence for investigators under the age of 35. Also, his former students have established a second award, the DIC Wang Award of Excellence in Biochemical Engineering, to be jointly presented by AIChE, ACS, and the Society for Biological Engineering.

Research Highlights

On-Demand Chemical Synthesis and Automation (Klavs Jensen)

Over the past two decades, continuous reaction and work-up for fine chemicals and pharmaceutical production have matured from microreaction devices and simple reactions to diverse commercial equipment and applications. All major pharmaceutical companies have internal programs focusing on continuous manufacturing, and organic chemists are developing new approaches based on continuous reaction techniques (so-called "flow chemistry"). This evolution has occurred in parallel with larger-scale process intensification efforts, and it is been stimulated by inherent advantages of continuous flow, advances in equipment fabrication technology, and a resulting expanded toolbox of organic reactions. The reduced-length scales provide controlled mixing, enhanced heat and mass transfer, low inventory, and ease of integration. These characteristics enable safe operation of highly exothermic and potentially hazardous reactions and provide easier access to reaction regimes not readily accessed via conventional means. Furthermore, continuous flow reduces accumulation of reactive or toxic intermediates relative to batch processing. The result has been a rapid expansion of feasible reactions and conditions.

Our research program has benefited tremendously from the continued support of the Novartis-MIT Center for Continuous Manufacturing and, more recently, the Defense Advanced Research Projects Agency. The Novartis Center brought chemical engineers, chemists, and mechanical engineers together to demonstrate the first end-to-end (chemicals to pills) continuous manufacture of a pharmaceutical, aliskiren hemifumarate, in a shipping-container-sized unit. This research experience enabled Professors Jensen, Myerson, and Timothy Jamison (Chemistry) to initiate the DARPA-sponsored Pharmacy on Demand program.

The resulting PoD continuous manufacturing platform combines synthesis and final drug product formulation into a single, reconfigurable, highly compact unit the size of a large refrigerator. In contrast, typical batch manufacturing involves multiple large-scale reactors and tanks along with transport and formulation of the final active pharmaceutical ingredient (API) in a separate processing plant. The system (Figure 1) consists of reconfigurable upstream and downstream units that allow for synthesis of multiple compounds. It has tight integration of process streams for reduced footprints and includes innovations in chemical reaction, purification, crystallization, and formulation. With the necessary regulatory approvals, this proof-of-principle system could enable a gradual phase-in of pharmaceutical production in response to demand. Reproduction of the system would be simpler and less costly than a full batch plant and so could produce pharmaceuticals needed only for small patient populations or to meet humanitarian needs. It could be particularly advantageous for drugs with a short shelf life. Furthermore, the ability to manufacture the active ingredient on demand could reduce formulation complexity relative to tablets needing yearlong stability.

The upstream unit houses reaction-based equipment for producing APIs (e.g., feeds, pumps, reactors, separators, and pressure regulators). Alternatively, the backside (Figure 1A) represents the downstream unit (Figure 1B) dedicated to purification and formulation of the drug product (e.g., tanks to precipitate the crude API from reaction mixtures, crystallizers, and filters) (Figure 1D). Temperature, pressure, flow, and level sensors are included at strategic positions and coupled with data acquisition units in order to facilitate operational monitoring and support real-time production control. Because very few commercial chemically compatible components were available and suitable for the gram-per-hour size scale, and due to elevated temperatures and pressures, we developed the majority of the unit operations used in the upstream and downstream systems. These elements included pressure sensors, clamshell reactors with an outer aluminum body and inner PFA (perfluoro alkoxy polymer) tubing for chemical compatibility (Figure 1C), surface tension liquid-liquid-driven extraction units (Figure 1C), multiline back pressure regulators, automated formulation, and automated precipitation, filtration, and crystallization tanks (Figure 1D).

We used elevated temperatures (130–180°C) and pressures (approximately 1.7 MPa) in controlled environments to enable fast reactions with low impurity profiles and to reduce total synthesis times from hours in batch to minutes in flow. Reagents were in high concentrations, close to saturation, and in some cases even neat, which ensured high productivity while reducing waste and solvent amounts. In the continuous flow system, reaction and purification occurred at the same time at different locations within the same uninterrupted reactor network. In batches, each of the operations would be spatially and temporally separated and would have much larger time, space, and workforce requirements, thus drastically increasing the global footprint and decreasing the global output of a given process.

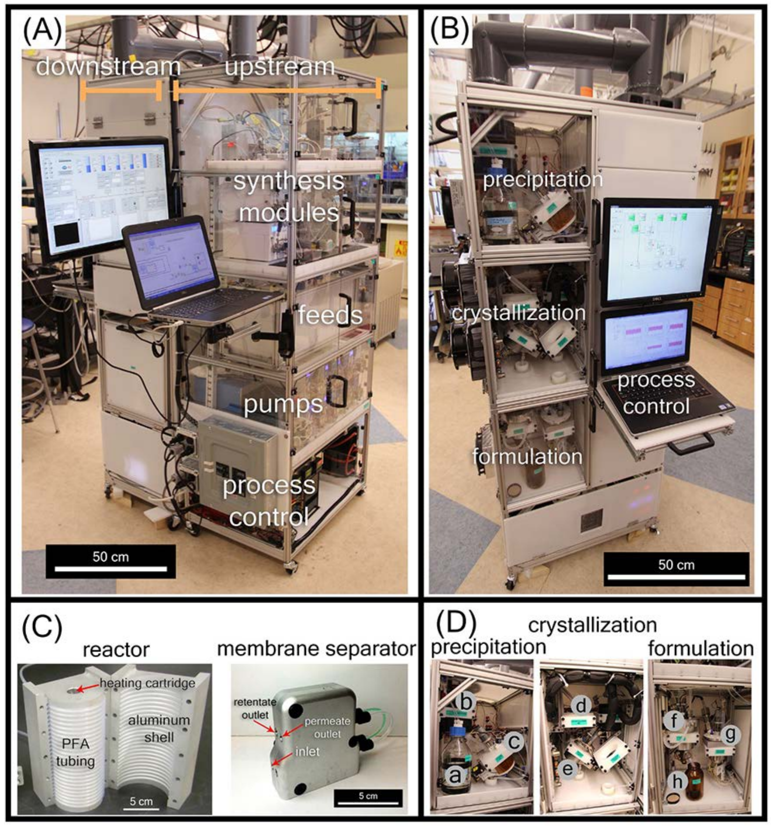

Figure 1. Reconfigurable system for continuous production and formulation of pharmaceuticals. (A) Upstream synthesis modules. (B) Downstream purification and formulation modules. (C) Examples of upstream units: PFA tube flow reactors in an aluminum shell for heating (left) and membrane surface tension separation units (right). (D) Some of the main components of the downstream unit: (a) buffer tank, (b) precipitation tank, (c) filtration unit, (d) crystallization unit, (e) filtration unit, (f) formulation tank, (g) solution holding tank, and (h) formulated API.

In order to demonstrate the capabilities of the PoD platform, we produced from raw materials sufficient quantities to supply hundreds to thousands of consumable oral or topical liquid doses per day of four different pharmaceuticals: diphenhydramine hydrochloride, lidocaine hydrochloride, diazepam, and fluoxetine hydrochloride. Diphenhydramine hydrochloride, known by the trade name Benadryl®, is an ethanolamine-based antihistamine used to treat the common cold, lessen symptoms of allergies, and act as a mild sleep aid. Lidocaine hydrochloride is a common local anesthetic and class 1b anti-arrhythmic drug. Diazepam, also known as Valium®, is a central nervous system depressant. Fluoxetine hydrochloride is a widely used antidepressant with the trade names Prozac® and Sarafem®. These generic molecules from different drug classes have differing chemical structures and synthesis routes and thus challenge the capabilities of the continuous flow system.

To date, we have considered 14 APIs in the PoD program with the aim of exploring the technology for increasingly complex chemical syntheses. In the process, we have further developed the underlying reactor and purification technology to reduce the size of the unit by 40%. In the coming year, we plan to demonstrate the synthesis of seven APIs over a three-week period. The experience and data from these studies will provide further insights into the operation and sustainability of the PoD platform.

The Jensen lab has also been developing continuous automated flow and high-throughput tools for reaction characterization and optimization. The use of feedback in process optimization enables product yields to be maximized and kinetic models to be generated with a minimum number of experiments. We are particularly interested in developing a system and strategy for optimizing simultaneously discrete and continuous variables of chemical reactions. The approach couples automated feedback with high-throughput reaction screening in droplet flow microfluidics (Figure 2). Sub-20-μL droplets with interchangeable reagents and catalysts are generated in an automated liquid handler, reacted in a microfluidic system, and analyzed online via high-performance liquid chromatography and mass spectroscopy. Case studies conducted with the automated optimization platform include competitive alkylation chemistry and catalyst-ligand selection in heteroaromatic Suzuki-Miyaura cross-coupling reactions.

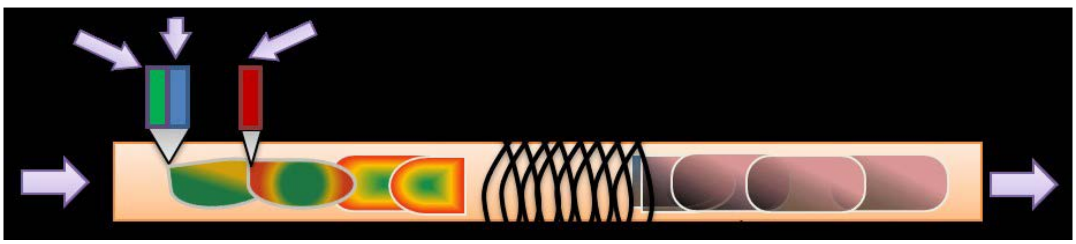

Figure 2. Diagram of an automated reaction optimization and screening system consisting of droplet preparation, reaction, and analysis combined with feedback.

This year faculty from Chemical Engineering (Braatz, Jensen, Myerson), Chemistry (Jamison), and Computer Science and Electrical Engineering (Regina Barzilay, Tommi Jaakkola), along with colleagues at Columbia and Virginia Commonwealth University, initiated a cross-disciplinary effort to revolutionize chemical synthesis. In this DARPA-sponsored program, computational synthesis route design aims to integrate retrosynthetic tools, machine learning, and computational chemistry for reaction pathway identification, scoring, and selection. The computer-selected reaction pathway will then be implemented in a reconfigurable feedback-controlled automated system for multistep synthesis, work-up, and purification. The project aims to enable fast chemical synthesis rather than the months or years of effort now needed to transform a chemical idea into reality.

Controlling Self-Assembly at the Nanoscale (James Swan)

Twenty-first-century society faces monumental challenges: continued access to clean water, development of sustainable energy resources, and availability of efficient methods to diagnose and treat disease. Advanced materials hold great promise as one path to resolution; nano-structured filtration media, highly efficient energy storage solutions, and targeted drug-delivery vehicles are examples of technologies being investigated to meet these issues. Their synthesis through controlled self-assembly of nanoscale components into structures with useful electronic, photonic, thermal, mechanical, and chemical properties is a grand challenge in soft condensed matter science. However, there are frontiers in the manufacturing of nanoscale materials that have proven difficult to survey because of the intimate coupling between the thermodynamic forces driving self-assembly and the kinetics of the assembly process. In recent work, the Swan research group has investigated novel, alternative assembly strategies that break this coupling and allow for rapid and hierarchical assembly of complex nano-structures.

This novel process, termed dynamic self-assembly, differs from typical approaches by being inherently dissipative and far from equilibrium. The interactions between nanoscale components are varied dynamically through use of external controls in order to steer the components efficiently toward their assembled state. Figure 3 illustrates numerical simulations of self-assembly using attractive spherical nano-particles. In one circumstance, "passive self-assembly," the interactions between particles are steady and the assembly arrests in a dis-ordered, gel-like structure. In the other circumstance, "dynamic self-assembly," the attractive portion of the interaction between particles is changed periodically in time at a fixed frequency. The pulsed interaction promotes rapid and controlled growth of highly ordered crystallites.

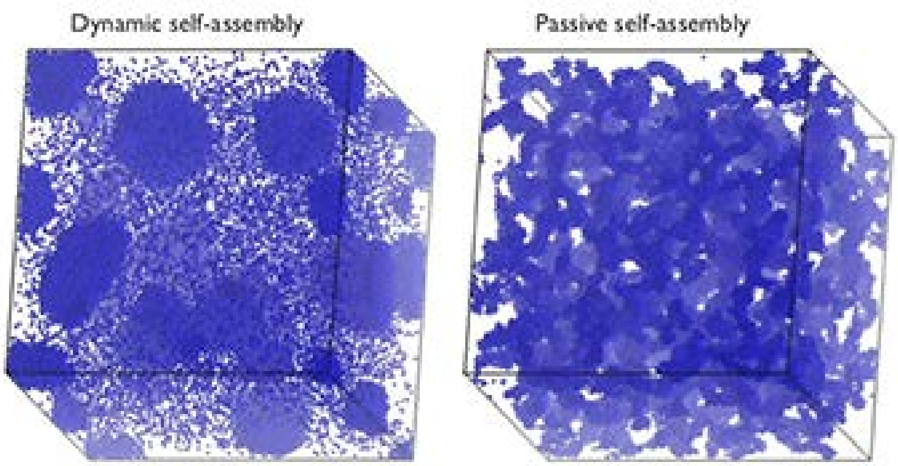

Figure 3. Outcomes of two different self-assembly processes with the same attractive interactions between spherical nano-particles: passive self-assembly, in which the interactions are steady, and dynamic self-assembly, in which the interactions periodically vary.

Such temporal control over interactions between nano-particles has long been possible experimentally through use of dielectrically, magnetically, optically, and chemically responsive particle moieties. However, a fundamental understanding of how to wield this control has been lacking. Recent work from the Swan group has defined a new form of "active matter" in which the interactions among nanoscale components vary periodically in time. In our recent work, we have developed a theoretical framework capable of predicting the structures assembled and assembly kinetics from effective equations of state for these exotic materials. We have also validated these predictions with computer simulations and through experimental collaborations. Figure 4 depicts some of the rich phase behavior possible with just a simple dispersion of attractive spherical nano-particles.

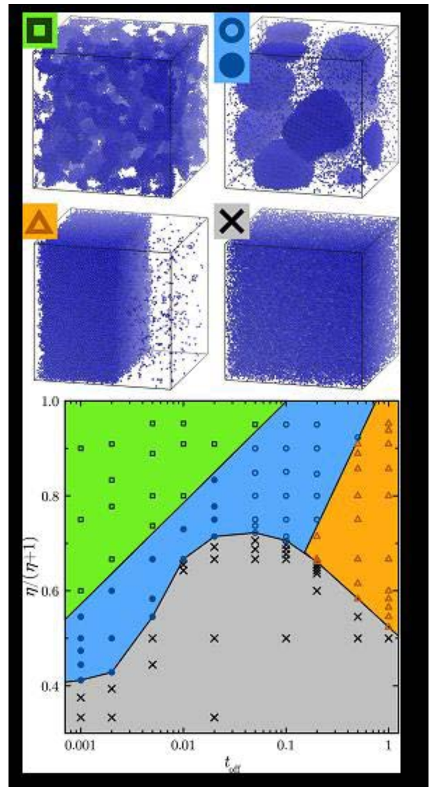

Figure 4. Outcomes of dynamic self-assembly of attractive spheres: gels (square), crystallites (circles), droplets (triangle), and no assembly (x). Two dynamic parameters are varied: the time over which the attractive interactions are active (bottom, y-axis) and the time over which the interactions are inactive (bottom, x-axis).

We used recent results to show how dynamic self-assembly can be used to grow nano-structures faster than relaxation to thermodynamic equilibrium. An additional and especially surprising result of this investigation is a prediction that dynamic self-assembly can stabilize nano-structures that are only meta-stable or simply not observed at equilibrium. We are now investigating the design of dynamic self-assembly pathways capable of yielding more complex and hierarchical nano-structures through a combination of fundamental theory, discrete element simulations, and experimental collaborations.

Lectures and Seminars

During 2015–2016, the Chemical Engineering Department hosted a distinguished group of academic and industry leaders speaking on topics highlighting cutting-edge research that addresses today's energy and health-related challenges.

13th Daniel I.C. Wang Lecture on the Frontiers of Biotechnology (November 20, 2015): "Building a Better Biotech: The Regeneron Story." George D. Yancopoulos, president and chief scientific officer of Regeneron Laboratories, discussed his work in the biotech arena and his founding of Regeneron. Yancopoulos, together with key members of his team, is a principal inventor and developer of Regeneron's four FDA-approved drugs—PRALUENT® (alirocumab) Injection, EYLEA® (aflibercept) Injection, ZALTRAP® (ziv-aflibercept) Injection for Intravenous Infusion, and ARCALYST® (rilonacept) Injection—as well as the company's foundational technologies for target and drug development (e.g., its proprietary TRAP technology, VelociGene®, and VelocImmune®). These technologies have produced Regeneron's robust pipeline of fully human antibodies targeting eye disease, cardiovascular disease, asthma and other allergic diseases, inflammatory conditions, and cancer. In 2014, Yancopoulos and his team launched the Regeneron Genetics Center, a major new initiative in human genetic research.

30th Hoyt C. Hottel Lecture (October 2, 2015): "Towards a Rational Design of Solid Catalysts for Single and Multistep Reactions." Professor Avelino Corma of the Universitat Politècnica de València in Spain discussed his work with solid catalysts. Professor Corma has been carrying out research on heterogeneous catalysis in academia and in collaboration with companies for nearly 30 years. He is an internationally recognized expert on solid acid and bifunctional catalysts for oil refining, petrochemistry, and chemical processes, especially the synthesis and application of zeolite catalysts. He has published more than 1,000 research papers and holds more than 130 patents.

22nd Alan S. Michaels Lecture (May 6, 2016): "Venture Capital—Riding the Winds of Change." Terry McGuire, co-founder and general partner at Polaris Venture Partners Inc., discussed his experience and expertise in the venture capital area. As a founding partner of Polaris, McGuire brings more than 30 years of successful early-stage investing experience in medical and information technology companies. As a venture capitalist, McGuire has invested in over 50 companies, many which were born in the labs at MIT. In 2015, he was listed as one of *Scientific American*'s Worldview 100, visionaries who continue to reshape biotechnology and the world. He is a board member of MIT's David H. Koch Institute for Integrative Cancer Research. Also, he chairs the board of the Thayer School of Engineering at Dartmouth College and is a member of the board of the Arthur Rock Center for Entrepreneurship at Harvard Business School.

38th Warren K. Lewis Lecture (May 8, 2015): "Skin-Inspired Organic Electronic Materials." Zhenan Bao, professor of chemical engineering and material science and engineering at Stanford University, discussed her biomedical research. Professor Bao has over 400 refereed publications and more than 60 US patents. She is a member of the National Academy of Engineering and has served as a member of the MRS Board of Directors. She has been the recipient of the AIChE Andreas Acroivos Award for Professional Progress in Chemical Engineering, the ACS Polymer Division's Carl S. Marvel Creative Polymer Chemistry Award, the Royal Society of Chemistry Beilby Medal and Prize, and the ACS Team Innovation Award. In 2003, she was named one of the top 100 young innovators by *MIT Technology Review*.

Departmental Awards

In May 2016 the department recognized this year's recipients of the Outstanding Faculty Awards: William M. Deen was the graduate students' choice, and Kristala J. Prather was selected by the undergraduate students.

The Edward W. Merrill Outstanding Teaching Assistant Award was presented to undergraduate student Kelsey Jamieson for her work in 10.302 Transport Processes. PhD student Zachary Sherman won the Outstanding Graduate Teaching Assistant Award for his work in 10.40 Chemical Engineering Thermodynamics. All third-year graduate students are required to present a seminar on the progress of their research, and the two recipients of the Award for Outstanding Seminar were Harry Watson and Eric Miller.

Chemical Engineering Special Service Awards were conferred to the members of the Graduate Student Council: Catie Bartlett, Christy Chao, Connor Coley, Stephanie Doong, Mike Orella, German Parada, Nick Schickel, Sarah Shapiro, Ryan Shaw, Krishna Shrinivas, Kassi Stein, and Lisa Volpatti. Members of the Graduate Student Advisory Board were also recognized: Catie Bartlett, Connor Coley, Garrett Ryan Dowdy, Jose Gomez, Lisa Guay, Ankur Gupta, Anasuya Mandal, Kristen Severson, and Sarah Shapiro. In addition, awards were given to the following members of the REFS (Resources for Easing Friction and Stress) group: Garrett Dowdy, Mark Goldman, Kevin Kauffman, Mark Keibler, Anasuya Mandal, Natasha Seelam, and Lisa Volpatti. The members of the intramural basketball team won the Chemical Engineering Rock Award for their contributions to athletic achievement within the department, and the following undergraduate students were recognized for their service to the student chapter of the American Institute of Chemical Engineers: Andrea Blankenship, Pam Cai, Kiara Cui, Mary Delaney, Natalie Delumpa-Alexander, Cody Diaz, Jessica Greer, Allison Hallock, Kelsey Jamieson, Barbara Lima, Lauren Liou, Linh Nguyen, Michelle Tai, Emma Valentine, Jessie Zhao, and Brian Zhong.

Our undergraduates earned numerous accolades over the course of the year. The Robert T. Haslam Cup, which recognizes outstanding professional promise in chemical engineering, went to Pam Cai. The department's oldest prize, the Roger de Friez Hunneman Prize, is awarded to an undergraduate who has demonstrated outstanding achievement in both scholarship and research; this year's winner was Micha Ben-Naim. The Wing S. Fong Prize, awarded to a chemical engineering senior of Chinese descent with the highest cumulative GPA, went to Pam Cai, Kiara Cui, and Eric Lau. The 2016 Phi Beta Kappa inductees were Pam Cai and Melissa Kreider. Kelsey Jamieson received the Schwarzman Scholar Award, and Chelsea Edwards was presented the National Goldwater Scholarship Award. The Global Studies and Languages Distinguished Scholars Award went to Eva de la Serna. The winners of the BP award for outstanding academic achievement by sophomore women chemical engineers were Andrea Blankenship, Marjorie Buss, and Amy Wang. Zi-ning Choo was awarded the BP outstanding academic achievement prize 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 Moriel Levy. Francesca Majluf earned the BP award for outstanding performance in research by a junior woman chemical engineer.

The department was pleased to recognize Sharece Corner as the Chemical Engineering's Outstanding Employee of the Year for her dedication and exceptional service to faculty, staff, and students. Chemical Engineering Individual Accomplishments Awards were presented to Lauren Liou, Anasuya Mandal, Lilian Hsiao, and Kristal Kilmain. Two members of the Chemical Engineering staff received School of Engineering awards: Sandra Lopes received the Infinite Mile Award, and Stephen Wetzel won the Ellen J. Mandigo Award.

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

Paula T. Hammond
Department Head
David H. Koch Professor of Chemical Engineering

Patrick S. Doyle
Executive Officer
Robert T. Haslam (1911) Professor of Chemical Engineering