Department of Chemical Engineering

The Department of Chemical Engineering (ChemE) continues its global leadership in the field. For the 28th straight year, our undergraduate and graduate programs were both ranked number one by *US News and World Report*. The department was also ranked number one in the QS World University Rankings for Chemical Engineering for the fourth straight year. Our department has led each of these rankings since their inception, and our faculty members continue to receive major individual awards.

Sponsored research in the department has remained at a healthy volume, increasing by 1% this year to $61.7 million with $26.3 million of these funds handled directly through the department and the rest handled by different cost centers at MIT, such as the Koch Institute for Integrative Cancer Research, the MIT Energy Initiative (MITEI), and the Ragon Institute. Although our faculty members continue to attract significant direct funding for their research, the strong engagement with these interdisciplinary centers creates a fertile ground for innovation and provides our students with experience in solving challenging, real-world problems. In addition, several of our faculty members led the creation of large multi-investigator research initiatives. Responding to the critical need for innovation and advances in national manufacturing, our department played a major role in the creation of two new Manufacturing USA Institutes, each of which is a nonprofit corporation initially funded for five years by $70 million from the US Department of Energy (DOE), with a total of $140 million project spending for each institute.

Professor Richard D. Braatz led MIT's contribution to the Clean Energy Smart Manufacturing Innovation Institute (CESMII) to develop sensors, high-fidelity simulation, and data analytics for advanced manufacturing, including planned MIT test beds at Saint-Gobain Ceramics and Plastics plants in New England, arranged by Professor Martin Z. Bazant. CESMII was created in 2016, and the first call for proposed projects will be released in fall 2017. Professor Michael Strano led MIT's contribution to the Rapid Advancement in Process Intensification Deployment (RAPID) Manufacturing Institute, aiming to combine unit operations with new system designs to reduce the overall footprint in size, energy, and cost of key chemical engineering processes. RAPID was created in 2017 and will be governed by the American Institute of Chemical Engineers (AIChE). More than 15 faculty members have been involved in project planning with MIT, various other institutions, and industrial partners. Professors Klavs Jensen and Allan Myerson continued to lead the Defense Advanced Research Projects Agency (DARPA) Pharmacy on Demand (POD) project for continuous manufacturing of medicine, while Professors Jensen, Braatz, and Myerson continued another DARPA project on computational synthesis design integrating machine learning, computational chemistry, and retrosynthetic tools for reaction pathway identification and selection. Our faculty continues to attract funding for collaborative research initiatives directly from industry. Professor Bazant led the creation of D3BATT (Data-Driven Design of Lithium-Ion Batteries) with $6 million of initial funding for four years from the Toyota Research Institute, aiming to redefine the future of automated mobility.

Professor Paula T. Hammond completed her second year as department head. In July 2016, Professor Bazant began to serve as executive officer, taking over from Professor Patrick Doyle, who went on sabbatical and will return to his former position as graduate officer. During his absence, Professor Daniel Blankschtein served as the interim graduate officer, taking over from Professor Braatz, who assumed a new position, faculty research officer, tasked by Professor Hammond to coordinate the department's efforts to secure large collaborative research grants. Professor William Green completed his second year as postdoctoral officer, and Barry Johnston continued his long service as the undergraduate officer. Professor T. Alan Hatton continued as director of the David H. Koch School of Chemical Engineering Practice, which celebrated its 100th anniversary in 2016. Chemical Engineering continues to claim two Institute Professors as primary faculty members—Daniel I. C. Wang and Robert S. Langer. Several of our faculty members continued important leadership roles on campus: Professor Robert C. Armstrong is director of the MIT Energy Initiative, Professor Arup K. Chakraborty is director of the MIT Institute for Medical Engineering and Science, Professor Karl Dane Wittrup is associate director of the Koch Institute for Integrative Cancer Research, and Professor Karen Gleason is the associate provost. Among key staff in the department, Gerald Hughes took over the position of building manager from Steven Wetzel, who retired in 2016 after 24 years of service to the department. Suzanne Ronkin became the academic administrator, after 15 years of service by Suzanne Maguire. In 2017, Professor Hammond launched a new Chemical Engineering Communications Laboratory, directed by Jess Cohen-Tanugi. Cohen-Tanugi will also serve as the new career services manager, helping Course 10 graduates and undergraduates to develop their paths after graduation.

Research and Recognition

Several members of the Chemical Engineering faculty received major awards for their research achievements.

Paula Hammond received fellowships from the AIChE, the National Academy of Engineering, and the National Academy of Medicine. Klavs Jensen received the 2016 AIChE Founders Award for outstanding contributions to the field of chemical engineering, and was elected to the National Academy of Sciences. Greg Stephanopoulos won the Eric and Sheila Samson Prime Minister's Prize for Innovation in Alternative Fuels for Transportation as well as the Novozymes Award for Excellence in Biochemical and Chemical Engineering. William Green was elected a fellow of the American Association for the Advancement of Science. Michael Strano was elected to the National Academy of Engineering, and Professor Emeritus Ed Merrill was elected a fellow of the National Academy of Inventors. Greg Rutledge was named an AIChE Fellow. Kwanghun Chung received the McKnight Technological Innovations in Neuroscience Award, as well as a National Institutes of Health (NIH) New Innovator Award. Brad Olsen was named a Kavli Foundation Emerging Leader in Chemistry. Martin Bazant was named a fellow of the International Society of Electrochemistry. Karthish Manthiram garnered a grant from MIT's Abdul Latif Jameel World Water and Food Security Lab.

Kristala Prather, Hadley Sikes, and William Tisdale earned Institute-wide chairs: they are the Arthur D. Little Professor, the Edgerton Career Development Professor, and the ARCO Career Development Professor, respectively. Robert Langer and Bernhardt Trout once again made the annual Medicine Maker Power List. William Tisdale won the 2017 AIChE Nanoscale Science and Engineering Forum Young Investigator Award and the Camille Dreyfus Teacher-Scholar Award. Kristala Prather won the Society for Industrial Microbiology and Biotechnology's Charles Thorn Award. Martin Bazant, Fikile Brushett, Heather Kulik, and Zachary P. Smith earned MITEI seed fund grants.

It was an exciting year of research for the department, with many new developments coming out of our laboratories. Using a new strategy that can rapidly generate customized RNA vaccines, Daniel Anderson's lab developed a new way to fight the Zika virus. Karen Gleason's new self-assembly technique could lead to smaller microchips, while the Jensen Lab has devised new technology to offer fast peptide synthesis. Klavs Jensen also worked with Allan Myerson to develop a compact, portable pharmaceutical manufacturing system, which can be reconfigured to produce a variety of drugs on demand; he additionally worked with the Langer Lab to enhance protein imaging through cell-squeezing technology. The Greg Stephanopoulos Lab has genetically reprogrammed a strain of yeast so that it converts sugars to fats much more efficiently, an advance that could make possible the production of high-energy fuels such as diesel. The Langer Lab has developed a way to make tumor cells more susceptible to certain types of cancer treatment by coating the cells with nanoparticles before delivering drugs, and the Prather Lab designed a novel genetic switch that allows a dramatic boost in bacteria's production of useful chemicals by shutting down competing metabolic pathways. The Román Group developed nanoparticle catalysts that could reduce the need for precious metals in some technologies, from vehicle emissions-control systems to high-tech devices such as fuel cells and electrolyzers. Brad Olsen developed a theory of binding-assisted superdiffiusive transport in biological gels that explains observed gel point decay. Martin Bazant published a general mathematical theory of thermodynamic stability far from equilibrium, which explains how driven reactions can control phase transformations, for example, by electro-autocatalysis in batteries. Michael Strano was very productive during AY2017: his lab made the astounding discovery that inside the tiniest of spaces—in carbon nanotubes where inner dimensions are not much bigger than a few water molecules—water can freeze solid even at high temperatures that would normally set it boiling. He also continued his novel work in plant nanobionics, creating spinach plants that can detect explosives and wirelessly relay that information to a handheld device similar to a smartphone.

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

New Arrivals and Promotions

Kristala Prather was promoted to full professor, while Professors Brad Olsen and Yuriy Román received tenure. Two of our newer faculty, William Tisdale and Hadley Sikes, were each promoted to associate professor without tenure. Suzanne Ronkin joined the Student Office as academic administrator after four years at Simmons College, and Sharece Corner and Eileen Demarkles also joined the Student Office as undergraduate coordinator and graduate coordinator, respectively, both coming from other positions within the department. The department added Jackie Cen as a financial coordinator.

Karthish Manthiram joined the department as assistant professor. Manthiram received a BS in chemical engineering from Stanford University and his PhD in chemical engineering from the University of California, Berkeley. He received the Dan Cubicciotti Award of the Electrochemical Society, a Department of Energy Office of Science graduate fellowship, a Tau Beta Pi fellowship, the Mason and Marsden prize, a Dow Excellence in Teaching Award, and the UC Berkeley Chemical Engineering Departmental Teaching Award. As a graduate student, Manthiram developed transition-metal oxide hosts for redox-tunable plasmons and nanoparticle electrocatalysts for reducing carbon dioxide. His research program at MIT focuses on the molecular engineering of electrocatalysts for the synthesis of organic molecules, including pharmaceuticals, fuels, and commodity chemicals using renewable feedstocks.

Zachary P. Smith also joined the department as assistant professor. Smith earned his BS in chemical engineering from the Schreyer Honors College at the Pennsylvania State University, and completed his PhD in chemical engineering at the Univeristy of Texas at Austin, where he worked under the guidance of Professors Benny Freeman and Donald Paul. Smith's research focuses on the molecular-level design, synthesis, and characterization of polymers and inorganic materials for applications in membrane and adsorption-based separations. In particular, these research efforts are promising for gas-phase separations critical to the energy industry and to the environment, such as the purification of olefins and the capture of CO2 from flue stacks at coal-fired power plants. Smith has co-authored over 20 peer-reviewed papers and has been recognized with several awards, including the DOE Office of Science graduate fellowship, and he was selected as a US delegate to the Lindau Nobel Laureate Meeting on chemistry in 2013.

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, 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 on 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. Fifty SB degrees were conferred in June 2017, 72% of which were awarded to women. Student quality remains high. The distribution of undergraduate students by class over the last 12 years is shown in Table 1.

Table 1. Undergraduate Enrollment over the Last 10 Years

Class year	07–08	08–09	09–10	10–11	11–12	12–13	13–14	14–15	15–16	16–17
Sophomores	96	87	87	80	72	61	67	57	56	58
Juniors	67	77	68	71	73	63	63	66	53	51
Seniors	77	75	73	75	75	69	58	64	67	55
Total	**240**	**239**	**228**	**226**	**220**	**193**	**188**	**187**	**176**	**164**

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 of 10-ENG as a degree in engineering. The initial specialization tracks are Energy, Materials, Biomedical, and Environmental. Student response has been cautious, with an enrollment of six students in fall 2015.

The average starting salary for graduates of the Department of Chemical Engineering is $72,600 (from a 2017 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 senior survey indicates that for 2017, 38% 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 AY2017 student officers of AIChE were Emma Valentine, Michelle Tai, Jessie Zhao, Linh Nguyen, Brian Zhong, Mackenzie Donnelly, Amy Wang, Marjorie Buss, Andrea Blankenship, Morgan Matranga, Natalie Delumpa-Alexander, Robert Mahari, Jessica Greer, Sarah Coleman, Sarah Curtis, Hannah Capponi, and Raja Selvakumar.

Graduate Education

Current Status of the Graduate Program

The graduate program in the Department of Chemical Engineering offers master of science degrees in chemical engineering (SM) and in chemical engineering practice (SMCEP), 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 total graduate student enrollment is currently 232, with 222 in the doctoral degree program and 10 in the master's degree program. In the doctoral degree program, 214 students are in the PhD/ScD track and eight are in the PhDCEP track. In the master's degree program, eight are in the SMCEP track. Twenty-nine percent of our graduate students are women and 4% are underrepresented minority students. Forty-one of our graduate students were recipients of outside fellowship awards, including those from the National Science Foundation (NSF), the National Institutes of Health, the Department of Defense (DOD), and others. The distribution of graduate students by degree for the last 10 years is shown in Table 2. In AY2017, the department awarded 28 doctoral degrees (PhD, ScD) and 2 master's degrees (SM) in chemical engineering, along with 35 master's degrees in chemical engineering practice and one PhDCEP, for a total of 66 advanced degrees conferred.

The department received 444 applications for admission to the doctoral program, offered admission to 55 individuals, and received 36 acceptances of offers, for an acceptance rate of 66%. Out of 80 applications to the master of science program, the department made 11 offers and received 10 acceptances of offers, for a yield of 91%. Among the incoming graduate class for 2017, 15 are women and one is an underrepresented minority student. On average, the incoming graduate class held an undergraduate grade point average (GPA) of 3.97 (out of 4.0).

Table 2. Graduate Enrollment over the Last 10 Years

Degree level	07–08	08–09	09–10	10–11	11–12	12–13	13–14	14–15	15–16	16–17
Master's	26	32	38	28	20	10	11	15	15	10
Doctoral	212	228	203	212	224	212	211	222	218	222
Total	**238**	**260**	**241**	**240**	**244**	**222**	**222**	**237**	**233**	**232**

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 are highlighted here.

Biologically-derived Medicines on Demand

Manufacturing solutions today for biologic medicines are not well-aligned with emerging interests in precision medicine, which rely on improved stratification of disease based on molecular profiles. A DARPA-sponsored program, called Integrated Scalable Cyto-Technology (InSCyT), aims to establish an end-to-end manufacturing system for making small batches of recombinant biologic therapeutics in a few days at or near the point of care. The team, led by Professor J. Christopher Love at the Koch Institute at MIT 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 systems to produce dozens to thousands of purified doses of different biologic drugs that have quality attributes comparable to those of existing commercial products. The ability to make biologic drugs at small scales anywhere could substantially improve healthcare for precision medicine, including addressing rare and orphan diseases, and potentially lower costs of supplying these drugs for global health.

Figure 1: (a) Schematic concept for agile, distributed production of biologic medicines. (b) High-quality human growth hormone produced by Pichia pastoris in an automated and integrated production system shows comparable potency to WHO standard.

The objectives of this project are ambitious. Today, manufacturing biologics requires weeks, if not months to produce and release, using many separate operations, often spread physically across global facilities. To envision a system more akin to a 3D printer in capability, we have developed a benchtop-sized manufacturing system designed to be portable and flexible, making many different high-quality therapeutics for patients. The interdisciplinary research team comprises labs in chemical engineering at MIT (Professors Braatz and Love), as well as labs from the Barnett Institute at Northeastern University (Professor William Hancock), and Rensselaer Polytechnic Institute (Professor Steven Cramer). Research topics include small-scale perfusion fermentation of a yeast host, novel purification strategies, and systems control strategies. An essential element of the program is the integration of technologies to realize an efficient and small manufacturing platform that could be portable enough to reach remote locations. Examples of high-quality products made to date include a human growth hormone used to treat pediatric growth disorders, and two common cancer therapeutics (interferon alpha and G-CSF). Significant advances in the biological understanding of the microbial host, process intensification, and system operations have increased both the productivity and the quality of all proteins made. With additional financial support to the project, the team has constructed a complete, next-generation prototype designed for aseptic operations and ready for transitioning to good manufacturing practice. Success in this program has also led to a related new Grand Challenge project, sponsored by the Bill and Melinda Gates Foundation, for ultra-low-cost, large-scale vaccine manufacturing (Professors Braatz, Kripa Varanasi [Mechanical Engineering], and Love) in collaboration with University College London and the University of Kansas.

Novartis-MIT Center for Continuous Manufacturing

May 2017 marked the end of the 10th year of a now 12-year collaboration with Novartis on continuous manufacturing of pharmaceuticals. We have continued to work on a large set of projects to overcome technical problems, which would allow the transition from batch manufacturing to the more efficient continuous mode. Work has continued to be conducted in 12 research groups spread across three departments (ChemE, Chemistry, and Mechanical Engineering).

Although we are working closely with Novartis on the projects, the advances and findings are published in a wide variety of journals and new intellectual property being captured in patents. In the last year alone, researchers published over 30 publications and the center has filed more than five patent applications for breakthrough technologies.

We have not only made great strides in solving the technical problems related to the continuous manufacturing of complex and high-value drug molecules, but we have also engaged the global pharmaceutical industry, academics, and regulators to attack the regulatory and mind-set challenges, with the latter often being the greatest challenge for adoption. For example, we jointly organized the second International Symposium on Continuous Manufacturing of Pharmaceuticals from September 26–27, 2016, at the Royal Sonesta in Cambridge. Janet Woodcock, head of the Federal Drug Administration's Center for Drug Evaluation and Research presented the keynote address. The meeting brought together the global leaders in the pharmaceutical world to report on the advances in the past two years and to discuss the challenges remaining ahead. One of the major outputs of the symposium is our regulatory white paper on the continuous manufacturing of pharmaceuticals.

The Novartis-MIT Center is led by Bernhardt L. Trout, MIT center director, and Markus Krumme, Novartis head of Continuous Manufacturing.

The David H. Koch Institute for Integrative Cancer Research

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

Faculty Notes

Professor 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; General Electric and Iberdrola are our newest sustaining members. Altogether, 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 over its first 10 years of operation and 350 energy graduate fellowships spread over 25 departments. During the past year, MITEI has begun launching eight Low Carbon Energy Centers which are key components of MIT's Climate Action plan. This past year we finished and rolled out the "Utility of the Future" report and launched a "Mobility of the Future" study. Professor Armstrong serves on the Scientific Commission of the Eni Enrico Mattei Foundation, and the External Advisory Committee of the National Renewal Energy Laboratory. He serves on the advisory boards of chemical engineering departments at Northwestern University and Washington University in St. Louis, and at the Energy Institute at Texas A&M 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, while completing his first year as executive officer of the department. He published more than 15 papers, including a general theory of thermodynamic stability of driven open systems for Faraday Discussions, which was invited and featured on the journal cover. A key prediction of the theory, the control of phase separation by electro-autocatalysis, was directly confirmed by in *operando* x-ray imaging experiments on Lithium-ion battery nanoparticles published in Science with his collaborators at Stanford, stemming from his sabbatical there the previous year. Based on these results, he led a successful proposal with MIT, Stanford, and Purdue to the Toyota Research Institute for a six-million-dollar D3BATT center, which he now directs. He delivered 10 invited talks and was elected a fellow of the International Society of Electrochemistry.

Professor Daniel Blankschtein's group conducts fundamental theoretical and experimental research in the area of colloid and interface science, with emphasis on industrial and biomedical applications. Recent research advances include molecular dynamics simulation of the exfoliation, dispersion, and stabilization of 2D materials such as molybdenum disulfide (MoS2) and hexagonal boron nitride (hBN) in various solvents; molecular modeling of the wetting behavior of water on graphene, MoS2, and hBN; experimental studies of emulsion stabilization using nanoparticles and surfactants; molecular thermodynamic and simulation modeling of the surface tension of aqueous surfactant solutions; modeling and experimental studies of gas separation and water desalination using carbon nanotubes and 2D porous membranes; lipid nanoparticle-assisted messenger RNA delivery for potent cancer immunotherapy; 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 the core Chemical Engineering graduate course 10.40 Chemical Engineering Thermodynamics in fall 2016 and the interdisciplinary graduate course 10.43 Introduction to Interfacial Phenomena in spring 2017. Professor Blankschtein's group delivered invited talks, regular talks and seminars, and presented posters, at the 252nd ACS National Meeting in Philadelphia; the 11th International Conference on Surfaces, Coatings, and Nanostructured Materials in Aveiro, Portugal; the 2016 AIChE Annual Meeting in San Francisco; the 2016 MRS Fall Meeting in Boston; the Free University of Berlin; Politecnico di Torino; University College London; and the Nanotech France 2017 Conference in Paris. Professor Blankschtein continues to serve on the Editorial Board of Marcel Dekker's *Surfactant Science Series*.

Professor Richard D. Braatz served as president-elect of the American Automatic Control Council, which is a federation of nine professional societies. As faculty research officer for Chemical Engineering, he facilitated strategic planning and informed faculty of potential opportunities at Manufacturing USA's many National Manufacturing Innovation Institutes. For the Clean Energy Smart Manufacturing Innovation Institute, he led its roadmapping activities in process control and related technologies, as well as MIT's involvement. He continued to lead systems engineering research in several large advanced manufacturing projects on campus. He also served on numerous advisory and editorial boards.

Raymond A. (1921) and Helen E. St. Laurent Career Development Assistant Professor Fikile Brushett continued advancing electrochemical technologies that enable a sustainable energy economy. These efforts are supported by multiple sources including the Joint Center for Energy Storage Research, Shell, the MIT Center for Materials Science and Engineering, and the MIT Deshpande Center. He continues to serve as the lead technologist for the joint center's Grid Arc. He taught 10.492 Integrated Chemical Engineering and 10.301 Fluid Mechanics in fall 2016 and spring 2017, respectively. He received the C. Michael Mohr Outstanding Faculty Award for Undergraduate Teaching and the Innovative Seminar Award for Freshman Advising (with Professors Johnston, Love, Olsen, and Prather).

Professor Arup K. Chakraborty continued efforts to understand the mechanistic bases of how a specific and systemic immune response to pathogens occurs, and how its aberrant regulation leads to disease. Research aimed toward understanding how this knowledge can be harnessed for the rational design of vaccines and therapies is also an important facet. In the last year, Chakraborty, in collaboration with Professors Phillip Sharp and Richard Young launched a new project on understanding how genes critical for maintaining healthy cell states are regulated. Chakraborty also serves as the director of the Institute for Medical Engineering and Science (IMES). With Tyler Jacks he coordinated the crafting of the campaign white paper on health, and is currently co-chair of MIT's committee on Digital Health. 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).

Professor Kwanghun Chung started his position as the Samuel A. Goldblith Career Development assistant professor in October 2013 in the Department of Chemical Engineering and IMES. He is also a principal investigator at the Picower Institute for Learning and Memory. His lab is an interdisciplinary research team that is devoted to developing and applying novel technologies for holistic understanding of large-scale, complex biological systems. In the past year, his group has continued to develop their recent technologies (SWITCH, MAP, and Stochastic Electrotransport) to accelerate the pace of scientific discovery and development of therapeutic strategies in a broad range of biomedical research. Recent research advances by the Chung Lab include advancing their SWITCH 3-D imaging to reveal network-specific amyloid progression and subcortical susceptibility related to Alzheimer's disease. Professor Chung was named a 2016 National Institutes of Health New Innovator awardee. He has traveled extensively, including visits to Seoul National University, Yale University, as well as VIB and Gordon Research Conferences to speak about his group's technologies and their applications. Professor Chung taught 10.302 Transport Processes and HST.562 Imaging and Sample Processing in Biology and Medicine. He also served on the IMES Committee for Academic Programs, as well as the IMES graduate admission and faculty search committees. Professor Chung has recently founded a start-up, LifeCanvas Technologies, which aims to advance the adoption and usage of Chung Lab technologies developed at MIT.

Professor Charles L. Cooney, the Robert T. Haslam (1911) Professor of Chemical and Biochemical Engineering, emeritus, teaches the capstone subject 10.491 Integrated Chemical Engineering, introducing 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 (SMART) Innovation Center in Singapore, is a member of the Masdar MIT executive committee, and a member of the steering committee for the Deshpande Center for Technological Innovation. He is the faculty director of the Downstream Processing summer course held through MIT Professional Education and co-faculty lead on a custom Sloan executive education program for Takeda Pharmaceuticals. Professor Cooney is also on the board of the Norman B. Leventhal Map Center at the Boston Public Library, an overseer emeritus of the Boston Symphony Orchestra, and a trustee emeritus of the Boston Ballet.

Professor Patrick S. Doyle, the Robert T. Haslam (1911) Professor of Chemical Engineering, spent seven months in Singapore at the SMART Center where is he part of the BioSystems and Micromechanics program. In Singapore, he advanced his research related to biofilm ecomechanics and DNA polymer knots. His research continues to focus on fundamental studies of DNA polymer physics and microfluidic synthesis of functional microparticles using stop flow lithography. A newer thrust area in his group is fundamental studies and applications of nanoemulsions. He published several articles that provide a fundamental understanding of nanoemulsion formation using high-energy methods, and he translated this knowledge to the formulation of hydrophobic small molecular drugs. In other work, he is translating developments in his lab on upconverting barcoded particles for anticounterfeiting applications through his company Motif Micro. He delivered several invited lectures, including the Engineering Product Development Distinguished Lecture Series at the Singapore University of Technology and Design. Professor Doyle serves on the Scientific Advisory Board at Lariat Biosciences, Achira Labs, and Motif Micro.

Professor William H. Green was named a fellow of the American Association for the Advancement of Science for developing methods for predicting chemical reactions and the overall kinetics of complicated reacting mixtures. He co-organized the first Telluride Science Workshop on Advanced Methods for De Novo Prediction of Chemical Reaction Networks, helped organize the 10th International Conference on Chemical Kinetics, and presented invited plenary lectures at several meetings, including the conference on Atmospheric Chemical Mechanisms. He invented a method for inferring negative results not published in the organic chemistry literature, leading to a method for using machine learning to predict which organic synthesis reactions will form the desired products. He plays a leading role in several MITEI projects and is the faculty chair of MIT's Mobility of the Future consortium.

AY2017 was a very active period for Department Head Paula Hammond. She worked with faculty to complete a year-long, long-range planning process, which has led to new strategic initiatives in the department. She introduced new career and communications services for students, and her current focus on undergraduate education continued with the engagement of the visiting committee. Professor Hammond received several academic recognitions in the past year. She was elected into the National Academy of Medicine in October 2016 and into the National Academy of Engineering in February 2017. Dr. Hammond also became an AIChE Fellow in fall 2016 and received the Women in Science Award from the Controlled Release Society in July 2017. Over the past year, she delivered several named award lectures in departments across the country, including the Patten Distinguished Lecture at the University of Colorado Boulder, the Gaden Lecture at Columbia University, the Dow Lecture at Northwestern University, the Amundson Lecture at the University of Minnesota, the Katz Lecture at the University of Michigan, and the Abbott Lecture at the Rensselaer Polytechnic Institute. She also delivered the NIH Margaret Pittman Lecture last summer at the National Institutes of Health, and gave a plenary talk at the 2017 Controlled Release Society meeting. Professor Hammond continues to serve as associate editor for *ACS Nano*, the American Chemical Society's journal. Her research continues in the areas of targeted cancer nanotherapies, wound healing, and tissue regeneration, with new technologies also directed toward infectious disease, vaccines, and emergency field care medicine.

Professor T. Alan Hatton continued to serve as the director of the David H. Koch School of Chemical Engineering Practice, where he has placed student teams at host companies in Australia, Brazil, Dubai, Ireland, and the United States. He is a co-director of the MITEI Low Carbon Energy Center on Carbon Capture, Utilization, and Storage (CCUS). In this role, Hatton participated in a number of MITEI workshops and meetings. He is a co-founder of the Metals and Minerals for the Environment program, which ran a successful symposium on campus in May. Hatton holds an honorary professorial fellow appointment at the University of Melbourne, and an adjunct professorship at Curtin University in Perth, Australia. He is an advisory board member of the Engineering Conferences International (ECI) in New York; a member of the Green and Sustainable Manufacturing Science Advisory Board, Singapore; and sits on the ENI-MITEI Steering Committee. Invited and keynote lectures include those presented at the ISE Meeting, the Hague, Netherlands; the Chemical Heritage Foundation, Philadelphia; ChemIndix, Bahrain; the ECI Conference on Separations Technology, Albufeira, Portugal; and the Gordon Conference on CCUS. He hosted the weekend-long Centennial Celebration of the practice school program in fall 2016.

Professor Klavs F. Jensen conducted research on continuous flow synthesis and separation as part of the Novartis-MIT Center for Continuous Manufacturing and the DARPA-sponsored Pharmacy on Demand program. The POD effort, in collaboration with Professor Timothy Jamison (head of the Department of Chemistry) and Professor Myerson, expanded beyond the initial demonstration of continuous synthesis of four common pharmaceuticals in a small, integrated, reconfigurable and transportable system to the end-to-end synthesis of seven different pharmaceuticals in a month in the same platform. With colleagues in chemical engineering, chemistry, and computer science, he worked on a DARPA-sponsored program on systems for knowledge-based, continuous organic synthesis. As part of this effort, the group demonstrated machine learning for planning organic synthesis and developed a robotic system for automated chemical synthesis. With Professors Moungi Bawendi (of the Department of

Chemistry) and Heather Kulik, he explored growth mechanisms underlying formation of indium phosphide quantum dots. Microfluidic devices enabling the transport of macromolecules across cell membranes through cell squeezing and electroporation were pursued in collaboration with Professor Langer. During the past academic year, he gave plenary lectures on microfluidics and microreaction technology at international conferences and at universities. He served on scientific advisory boards to chemical engineering departments, research institutes, and companies. Professor Jensen received the Founders Award from AIChE and was elected to the National Academy of Sciences.

Associate Professor Jesse H. Kroll and his research group continued their research on the organic chemistry of the atmosphere and the formation of atmospheric particulate matter. In October 2016 they participated in the National Oceanic and Atmospheric Administration-sponsored mission, Fire Influence on Regional and Global Environments Experiment, at the United States Department of Agriculture's Fire Sciences Laboratory in Missoula, MT. His group also launched a new Environmental Protection Agency-funded initiative on the big island of Hawaii, for monitoring volcanic air pollution and providing residents with real-time air quality data. Since July 1, 2017, Kroll has served as graduate officer for the Department of Civil and Environmental Engineering.

Joseph R. Mares '24 Career Development Assistant Professor Heather J. Kulik continued her research focused on developing new approaches to inorganic molecular design, large-scale electronic structure modeling for predictive enzyme mechanism studies, and developments in advancing the accuracy of electronic structure methods. In the past year, Kulik has published 16 papers (15 as senior author), one book chapter, and gave 11 invited lectures. She was the recipient in 2016 of Editors' Choice honors from both the *Journal of Physical Chemistry* and the *Journal of Chemical Physics* for two original research articles. Along with publishing an invited cover article as part of the *Industrial and Engineering Chemistry Research* "Class of Influential Researchers" special online issue, she also published two other invited articles. Her research is supported by Eni SpA, Bosch, the NSF, and the Burroughs Wellcome Fund, among others. The Kulik Group consists of one postdoc, six graduate students, two Undergraduate Research Opportunities Program (UROP) students, and one research assistant. Kulik began co-teaching 10.37 Chemical Kinetics and continues to develop 10.637 Quantum Chemical Simulation—her elective in computational chemistry—which is well-received across the Institute and by neighboring institutions.

In AY2017, Professor Robert Langer received honorary degrees from the Gerstner Graduate School at Memorial Sloan Kettering Cancer Center, Carnegie Mellon University, the Karolinska Institutet and the Hong Kong University of Science and Technology. He received the Memorial Sloan Kettering Medal for Outstanding Contributions to Biomedical Research, the Raymond and Beverly Sackler Award for Sustained National Leadership, the Benjamin Franklin Medal in Life Science, the Irving Weinstein Foundation Distinguished Lecture Award, and the European Inventor Award (Non-European Countries). Numerous named lectures include the Inaugural Distinguished Lecture in Bioengineering (University of California, Berkeley), the Inaugural Frank and Grace Yin Distinguished Lecture (Washington University), the Deloitte Endowed Lecture (Dana-Farber Cancer Institute), the Stetson Lecture (University of Vermont Larner College of Medicine), the Alfred Stracher Memorial Lecture (SUNY Downstate Medical Center), the Henry Louis Smith Lecture (Davidson College), the Anderson Distinguished

Lecture (University of Virginia School of Medicine), the AACR-Irving Weinstein Foundation Award Distinguished Lecture (American Association for Cancer Research), and the Thomas K. Hunt Endowed Lecture (Wound Healing Society Foundation).

Professor 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. The lab developed a new method for single-cell RNA-sequencing in collaboration with Professor Alex Shalek (IMES/Chemistry) that is highly portable and accessible for other research labs working with sparse clinical samples. Professor Love's lab joined with a team of leading labs in immunology, medicine, and technologies in a new Food Allergy Science Initiative to understand the basic biology of food allergy and approaches to improve diagnosis. His lab continues to advance biomanufacturing research to lower the costs of producing protein therapeutics to promote global access. Professor Love continued to lead a team of investigators from MIT, Rensselaer Polytechnic Institute, the Pall Corporation, and Northeastern University under DARPA's Biologics Manufacturing on Demand (Bio-MOD) program for end-to-end manufacturing of biologic drugs in small-scale systems. His team also began work on a Gates Foundation Grand Challenge focused on ultra-low-cost vaccine manufacturing. In collaboration with the Broad Cancer Program, he also continued to advance a scalable platform for sequencing metastatic cancer from blood biopsies. He delivered several invited lectures, including at the Pittsburgh Conference on Analytical Chemistry and Applied Spectroscopy; the University of Virginia—his alma mater; the Human Cell Atlas; the Keystone Symposia on Single Cell Omics; the plenary session of the Well-Characterized Biologic Pharmaceuticals; and the 25th anniversary gala dinner for the Boston chapter of the International Society of Process Engineers. He also continued serving as a scientific advisor to several groups in biomanufacturing and immunotherapies and on the steering committee for the Society for Biological Engineering's Accelerating Biopharmaceutical Development meeting.

Karthish Manthiram started as the Warren K. Lewis Career Development Assistant Professor of Chemical Engineering in January 2017. The Manthiram Laboratory is developing modular and sustainable methods for transforming molecules using renewable electricity. The current members of the group (four graduate students and one postdoctoral researcher) are creating catalytic technologies through which farmers in developing countries can produce their own ammonia fertilizers and for the conversion of carbon dioxide into methanol to mitigate greenhouse gas emissions. Professor Manthiram taught 10.426/626 Electrochemical Energy Systems this past year using a Socratic dialogue method based on a new set of lecture notes he developed.

Professor Allan S. Myerson continued his research on fundamental and applied problems in crystallization and pharmaceutical manufacturing. He was a principal investigator in the Novartis-MIT Center in Continuous Manufacturing and the DAPRA Pharmacy on Demand project, which involves the development of a tabletop pharmaceutical manufacturing device. Professor Myerson serves as an associate editor of the American Chemical Society Journal *Crystal Growth and Design*. He serves on the scientific advisory boards of Gensyn Technologies, a company devoted to particle engineering applications in pharmaceuticals; Blue Spark, a company that develops novel flexible batteries; and Continuus Pharmaceuticals, a spin-off of the Novartis-MIT Center in Continuous Manufacturing.

Associate Professor Bradley D. Olsen's research group continued its work in the areas of bioinspired and biofunctional block co-polymers, polymer gels, and protein-based materials for applications in defense, sustainability, and human health. Major accomplishments included developing a new theory of transport in biological gels that predicts how binding can accelerate transport, developing methods to explain superdiffusive transport in polymer gels, and producing theories to quantitatively predict gel point delay in polymer network materials. This research is supported by the DOD, DOE, and NSF, in addition to collaborative work that is in development with the rubber and cosmetics industries. During the past year, Olsen published 16 peer-reviewed papers and presented 17 invited lectures. He was awarded the Sigma-Aldrich Lectureship at Carnegie Mellon University, the Colburn Lectureship at the University of Delaware, the Kavli Emerging Leader in Chemistry Award, and a freshman advising award at MIT. He served as an instructor for 10.567 Structure of Soft Matter, and 10.00 Molecule Builders, where he taught a heavily revised curriculum to improve the course for the second offering, including a new design-focused curriculum and new projects.

Professor Kristala L. J. Prather was selected as the recipient of the 2017 Charles Thom Award from the Society for Industrial Microbiology and Biotechnology. Her award presentation will feature work published in *Nature Biotechnology* on the development of autonomously controlled biological devices designed to regulate metabolic flux. Prather continues to serve on several scientific advisory boards and was recently appointed as an associate editor of *ACS Synthetic Biology*. She was sworn in as a member of the US Department of Energy's Biological and Environmental Research Advisory Committee and appointed a member of the National Academies of Sciences, Engineering, and Medicine Committee on Strategies for Identifying and Addressing Biodefense Vulnerabilities Posed by Synthetic Biology. Within MIT, Prather 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. She also serves as the faculty co-director of the Energy Biosciences Low-Carbon Energy Center of the MIT Energy Initiative. This year, she concluded her term of service on the Committee for Academic Performance. Prather was most recently promoted to full professor (effective July 1, 2017), and selected to hold the Institute-wide Arthur D. Little Professorship.

Professor Gregory C. Rutledge was named a fellow of the AIChE in 2017. He also assumed the role of lead principle investigator for MIT's engagement with Advanced Functional Fabrics of America (AFFOA), a $317 million Manufacturing Innovation Institute headquartered in Cambridge, MA. AFFOA's mission is to enable a manufacturing-based revolution in fibers, yarns, and fabrics. In teaching, Professor Rutledge is responsible for the junior and senior level in 10.26/27/29 Chemical, Energy, and Biological Engineering Project Laboratories. His research group develops molecular simulations for the study of fundamental process-structure-property relationships in polymers, with particular emphasis on crystallization kinetics and thermomechanical properties of polymers with complex morphologies. They are also active in the development of ultra-fine fibers (diameters less than 1 micron) for various applications in clean air, clean water, and advanced materials. Over the past year, Professor Rutledge delivered invited lectures in Germany, Australia, and the United States. He continues to serve as an editor for the *Journal of Materials Science*, on the International Union of Pure and Applied Chemistry's task force for Terminology in Modeling and Simulation of Polymers, and on the committees for the Undergraduate Programs and for Research Computing at MIT.

Assistant Professor Zachary P. Smith joined the Department of Chemical Engineering in January 2017 and currently holds the Joseph R. Mares Career Development Chair. His research focuses on the development of polymers and porous materials for applications in energy-efficient separations, gas storage, and catalysis. Professor Smith has been awarded several grants, including funding from the MIT Energy Initiative Seed Fund, MITEI's Carbon Capture Utilization and Storage programs, Saudi Aramco, MIT's Research Support Committee Solomon Buchsbaum Research Fund, and MIT's Tata Center for Technology and Design. Professor Smith's external recognitions include the North American Membrane Society's Young Membrane Scientist Award, and a faculty research participant status through the US Department of Energy. In April 2017, he co-founded Flux Technologies, a company that focuses on using composite materials as gas-separation membranes. Professor Smith taught 10.569 Synthesis of Polymers in the spring term and implemented a pitch competition for an end-of-semester design project. He currently advises three graduate students and one postdoctoral scholar.

Professor George Stephanopoulos was honored with a two-day symposium at MIT, 2040 Visions of Process Systems Engineering, June 1–2, 2017. Academic and industrial leaders from around the world along with Professor Stephanopoulos's former PhD students provided a series of compelling and exciting visions for the future of process systems engineering. At the educational front, George Stephanopoulos taught for the first time an intensive two-week Independent Activities Period course, Introduction to Process Control, and in research he successfully concluded the three-year flagship project—Biorefinery: Integrated Sustainable Processes for Biomass Conversion to Biomaterials, Biofuels and Fertilizers—a collaboration between MIT and Masdar Institute Cooperative Program. He and his Masdar collaborators contributed a chapter to the book Hydrothermal Processing in Biorefineries, published by Springer, and presented the paper "Design of Multi-Actor Distributed Processing Systems: A Game-Theoretical Approach" at the San Francisco annual meeting of AIChE. He also presented three papers, which were published in the P*roceedings of the 26th European Symposium on Computer-Aided Process Engineering*.

W. H. Professor of Biotechnology and Chemical Engineering Gregory Stephanopoulos continued to serve as director of the Metabolic Engineering Laboratory. In this capacity he supervises the work of 25 to 30 researchers attempting to engineer microbes to convert them to little chemical factories for the production of fuels and chemicals. Notable research successes this academic year include the development of a novel method that prevents the use of antibiotics in fermentations of recombinant organisms that was published in Science. Furthermore, his group continued the advancement of an integrated system for biological conversion of gaseous substrates into lipids and engineering the oleaginous yeast Yarrowia lipolytica to achieve the highest reported lipid yields from renewable feedstocks and also to convert dilute acetate streams to high concentration lipids. All these developments contribute to the replacement of fossil feedstocks and advance the vision of a bio-based economy. In parallel, he continued the investigation of the metabolic aspects of cancer with particular focus on the identification of therapeutic metabolic targets. Professor Stephanopoulos continued his service on the advisory boards of four academic institutions. He continues to serve on the managing board of the Society for Biological Engineering. He delivered the 2017 Kroc Memorial Lecture at the University of Chicago, and the 2016 Henry A. McGee Lecture at Virginia Commonwealth University. He continued 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, he delivered plenary and keynote lectures at the 11th Metabolic Engineering Conference in Awaji, Japan (June 26–30, 2016); the Biocatalysis Gordon Research Conference, (July 10–14, 2016); the 13th International Symposium on the Genetics of Industrial Microorganisms in Wuhan, China, (October 16–20, 2016); and the International Conference on Metabolic Science in Shanghai, China, (October 20–23, 2016). Professor Greg Stephanopoulos was honored with the 2016 Samson Prime Minister Prize for innovation in alternative fuels for transportation, and the 2017 Novozymes Award for Excellence in Biochemical and Chemical Engineering.

Professor Michael S. Strano continues research on the chemical engineering of low-dimensional nanomaterials. His research on corona phase molecular recognition, graphene-polymer composites, extreme phase transitions of nanoconfined water, and explosive detection using nanobionic spinach were published in *Nature Communications*, *Science*, *Nature Nanotechnology*, and *Nature Materials*, respectively, and were highlighted by news outlets. Professor Strano continues the study of thermopower wave systems, and of marine animals using nanosensor platforms. He delivered invited seminars at the University of Texas at Austin, Kyoto University, and École Polytechnique Fédérale de Lausanne. Strano was elected to the National Academy of Engineering, and serves as an editor of *Carbon* and on the Defense Science board.

Professor James W. Swan's group performs fundamental theoretical research in the areas of soft matter physics and fluid mechanics. Recent work has focused on developing new simulation methods capable of modeling complex soft materials at the mesoscale, and application of those methods to materials of industrial and societal interest including food and consumer care products, and biopharmaceuticals. His work was featured in six peer-reviewed publications including a paper in the *Journal of Chemical Physics* illustrating the principles of new modeling algorithms for colloidal fluid physics, which improves on state-of-the-art computational throughput by more than two orders of magnitude. The Swan Group currently has six graduate students, four undergraduates (as part of the UROP program), and was host to one S. N. Bose scholar over the summer period.

William A. Tisdale was promoted to associate professor without tenure, effective July 1, 2017, and now holds the ARCO Career Development Chair in Energy Studies. In 2016 he traveled to Washington, DC, where he was honored at the White House by President Barack Obama with the Presidential Early Career Award in Science and Engineering. This past year, he also received an Alfred P. Sloan Fellowship in Chemistry, the Camille Dreyfus Teacher-Scholar Award, and the AIChE Nanoparticle Science and Engineering Forum Young Investigator Award. Professor Tisdale leads an experimental research team investigating the synthesis and photophysical properties of colloidal semiconductor nanocrystals for use in next-generation energy technologies. He teaches 10.27 Energy Engineering Projects Laboratory and 10.302 Transport Processes, for which he received the Department Undergraduate Teaching Award this spring.

Professor Bernhardt L. Trout continues in his role as director of the Novartis-MIT Center for Continuous Manufacturing, an $85 million partnership, which just finished its second successful phase. In addition, he is director of E3: Engineering, Ethics, and Entrepreneurship, which held courses for 140 students this past year. The program enhances the breadth and depth of engineering students' knowledge, teaching them the connections between engineering and society. He runs a laboratory of 15 graduate students, postdocs, and staff focused 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 Federal Drug Administration, a member of a US Pharmacopeia (USP) panel, and was named for the third year in a row on the Top 50 Medicine Maker List. He delivered many invited talks, research papers, and patents. He is on the scientific advisory boards of several major companies and involved in several start-up companies. He is co-editor of the volume *Mastery of Nature* and wrote for it a contribution on quantum mechanics and political philosophy. He is also co-chair of the 2nd International Symposium on Continuous Manufacturing of Pharmaceuticals, which hosted 300 leaders of industry, regulatory bodies, and academia.

Professor Daniel I. C. Wang continues to be involved with the Singapore-MIT Alliance (SMA), and is continuing his SMA research on a high throughput system for mammalian cells. He has two PhD candidates at the National University of Singapore. Professor Wang was 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 since MIT has decided not to file a patent on this technology because of the difficulty of policing it. Wang has submitted six proposals to six companies. He has presented his research at the AIChE, ACS, and SIM annual meetings. Professor Wang has completed his research with Saudi Aramco on the microbial desulfurization of crude oil. One PhD thesis and three papers have been published from this research. Professor Wang was invited by the Bioprocessing Technology Institute of A*STAR, Singapore, to serve as the chairman of the 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 years. His former students have also established a second award to be jointly presented by the AIChE, ACS, and the Society for Biological Engineering. Finally, two of his former students have established the Daniel I. C. Wang Chair in the Department of Biological Engineering.

Research Highlights

Engineering Microbial Cells for Agile Manufacturing of Biologic Drugs

J. Christopher Love

Over the past 30 years, the field of biotechnology has matured such that it is now possible to manufacture many safe and efficacious drugs comprising recombinant proteins such as monoclonal antibodies, growth hormones, and enzymes. These drugs treat cancers, autoimmune diseases, and genetic diseases, among others. This successful era of new drugs foreshadows continued improvements in medicine. Examples include the approaching era of precision medicine that will rely on molecular profiles of disease, potential new treatments for prevalent diseases such as Alzheimer's disease, and the future vision of personalized medicines. Yet these directions also present potential challenges for manufacturing. Small-volume production for precise indications and very large-volume production trend away from conventional manufacturing capacities in the industry. The diversity of engineered products in development also suggest rapid and agile means of process development could improve the efficiency of clinical programs. The Love Lab has pursued a broad set of objectives addressing these challenges, while also considering how advancing biomanufacturing practices could facilitate improved global access to this class of drugs (Love et al. 2013).

Today, the majority of protein drugs—especially monoclonal antibodies such as Herceptin or Keytruda—are produced by recombinant expression using mammalian cells such as Chinese hamster ovary (CHO) cells. MIT Chemical Engineering and Biology made significant contributions to improving the engineering and culture of these cells in the early days of the biotechnology revolution, and played a major role in training many leaders in the industry through the Biotechnology Process Engineering Center (BPEC) in the late 1980s and 1990s. Nonetheless, the advent of new technologies for genome sequencing and editing are making it possible to rapidly test and engineer new host cells for recombinant expression that could offer benefits compared to CHO in some instances. For example, eukaryotic microorganisms such as yeast or fungi offer many of the same capabilities for secreting recombinant proteins, and can be engineered to produce proteins with appropriate glycosylation for human use. Importantly, these cells grow faster than mammalian cells, can potentially use low-cost raw materials, and can be engineered in rapid cycles of development that are from three to five times faster than mammalian cells. The potential gains in speed and lower costs of production emphasize the opportunity to develop these alternative hosts further using state-of-the-art approaches from systems biology, genome editing, and single-cell analysis.

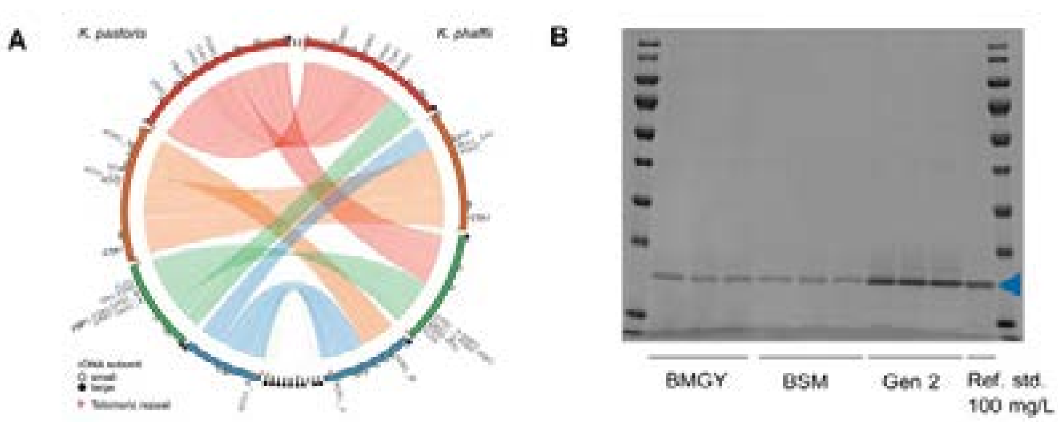

Figure 2: (a) Genomic structure of the four chromosomes in Komagataella phaffii and Komagataella pastoris. (b) SDS-PAGE gel of cell culture fluids from Pichia pastoris expressing human growth hormone in conventional media (BMGY and BSM) and our improved media (Gen 2). Expression is enhanced five to ten times in the rich defined media.

One promising alternative host already used to produce certain biopharmaceuticals in the United States and abroad is the methylotrophic yeast *Pichia pastoris*. To enable routine, systems-level understanding of the organism's biology in the course of production and targeted engineering, the Love Lab recently resequenced the two organisms collectively used under the trade names *Pichia: Komagataella phaffii* and *Komagataella pastoris* (Love et al. 2016). Using a combination of long-read and short-read sequencing technologies, researchers compared the genomes and transcriptomes of the two wild type organisms and one auxotrophic derivative strain widely used (GS115). The two organisms share similar genomic features, yet have distinct chromosomal rearrangements (fig. 2a). Interestingly, analyzing the transcriptomes by RNA-sequencing also showed that an extremely high percentage (>95%) of their genomes were expressed in cultivation—suggesting these are highly compact genomes for eukaryotic organisms. The ability to rapidly assess the biological state of the cells during fermentation by genomic analysis for relatively low costs has significant implications for improving all aspects of their cultivation. In one example, the lab developed a new media formulation to support the cell's growth that is both fully defined chemically—a benefit for regulatory considerations of the manufacturing processes—and, in instances tested to date, has improved overall productivity at lower costs compared to conventional media (fig. 2b). The key insights to these improvements were gained through systems-level analysis of the biology of the cells during cultivation to assess metabolic needs.

Transitioning a lead candidate for a new drug into manufacturing requires developing one or more cell lines that express the protein. Even before this step, discovery of new lead candidates of monoclonal antibodies today often requires testing multiple different molecules as well. We and others have demonstrated a range of approaches to discover new candidate antibody drugs by directly screening human B cells from patients (e.g., HIV or West Nile virus) (Tsioris et al. 2015). These technologies yield many candidate antibodies in the form of the genes encoding the key variable regions, but to advance such candidates requires cloning and expressing each one. Today, that process is largely conducted by bacterial cloning of DNA and transient expression in mammalian cells, followed by subsequent cloning to produce stable cell lines. This process is slow, and often takes months to complete. One benefit of alternative hosts such as *Pichia pastoris* is the ability to directly generate a stable cell line by homologous recombination. With support from both the Gates Foundation and DARPA, we have demonstrated a rapid approach to clone candidate antibodies from discovered genes in less than two weeks in a semiautomated process (Shah et al. 2015). This approach is scalable and modular to allow variations on the antibodies to be made in parallel. It is also amenable to rapid scale up in process development for manufacturing. These studies suggest integrated discovery and manufacturing solutions leveraging a common fast host could offer significant benefits for developing personalized medicines and responding to emergent situations, e.g.,outbreaks of new diseases such as the Zika virus or Ebola.

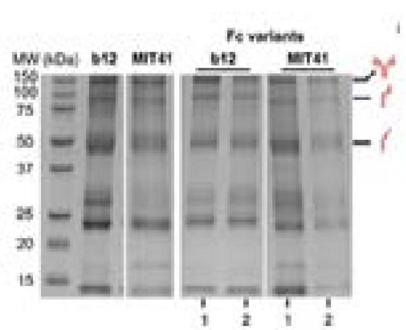

Figure 3: SDS-PAGE gel of anti-HIV antibodies produced by rapid cloning and expression in Pichia pastoris.

Aside from rapid strain development, we have also explored the implications of a host like *Pichia pastoris* on streamlining and intensifying manufacturing processes. One strategy for reducing facility sizes and costs being widely explored today is continuous manufacturing. For cell cultivation, this approach requires operating a bioreactor so that cell products are continuously harvested with or without retention of the cells themselves. We have demonstrated that perfusion fermentation of *Pichia pastoris* can maintain production of recombinant proteins over weeks (Mozdzierz et al. 2015). One obvious benefit of stable fermentation is that the raw purity of the proteins in the supernatants of the culture are high even before purification. This quality has meant that it is possible to simplify the purification required to achieve high-quality proteins similar to marketed drugs. With generous support from DARPA in the Bio-MOD program and in collaboration with the Braatz Lab, Rensselaer Polytechnic Institute (Steven Cramer), and Northeastern University (William Hancock), we have explored how this attribute of producing proteins with *Pichia* can enable small-volume, modular manufacturing systems that allow end-to-end production of biologic medicines within days. To date we have produced human growth hormone used to treat growth disorders, and two common cancer drugs—G-CSF and Interferon alpha2-b—with comparable qualities to existing products. We are actively exploring a range of other products with the system.

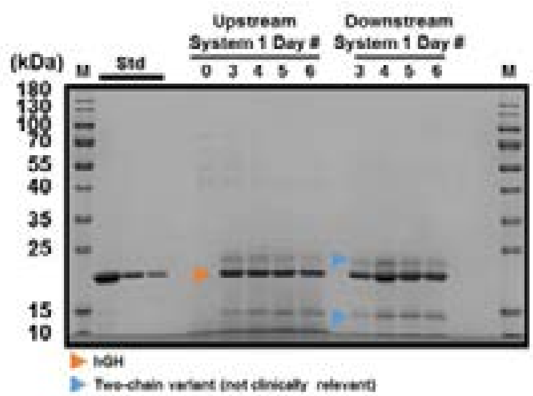

Figure 4: SDS-PAGE gel of human growth hormone expressed in Pichia pastoris *and purified using an automated benchtop production system.*

The examples of facile learning, development, and advancement of processes using *Pichia pastoris* in our lab have helped to stimulate additional considerations across the industry for alternative hosts (Matthews et al. 2017). Last year, Biogen (where Professor Love spent a sabbatical in AY2016) embarked together with Amyris on a project funded by the Gates Foundation to assess eight alternative hosts for their potential to achieve higher productivity than current processes. The Love Lab, along with the Braatz and Varanasi Labs at MIT, also embarked on a Gates Foundation Grand Challenge in collaboration with the University College London (Tarit Mukhopadhyay) and University of Kansas (David Volkin) to develop new manufacturing approaches that would provide line of sight to ultra-low-cost recombinant vaccines (less than 15¢ per dose). Continuing to transform biomanufacturing processes using state-of-the-art technologies that inform rational biological engineering of alternative hosts (and the processes that support them) could have tremendous implications for making biopharmaceuticals more accessible for a range of diseases and patients globally.

Mesoscale Dynamics in Nanocrystal Solids

William A. Tisdale

Semiconductor nanomaterials have the potential to revolutionize the way we make and use energy. Unlike traditional bulk semiconductors, colloidal nanomaterials can be synthesized at lower temperatures and processed using scalable, inexpensive solution-phase strategies. Through surface functionalization, these materials can be made more defect tolerant than their bulk counterparts, and they can be assembled into complex hybrid structures with emergent functionality. Understanding the behavior of colloidal nanomaterials requires constant feedback between synthetic modification and spectroscopic characterization, and the integration of both activities in the Tisdale Lab has enabled rapid research progress in this area.

In solution-processed nanocrystal solids, energetic and structural disorder feature prominently in the transport of free charge carriers (electrons and holes) and excitons (bound, electron-hole pairs having a net neutral charge). Low-energy sites within the nanocrystal solid act as sinks temporarily impeding transport through the film. Disorder adversely affects the performance of quantum dot (QD) solar cells (due to reduced minority carrier diffusion length and reduction of the open-circuit voltage) and QD light-emitting devices (due to asymmetric exciton formation and diffusion).

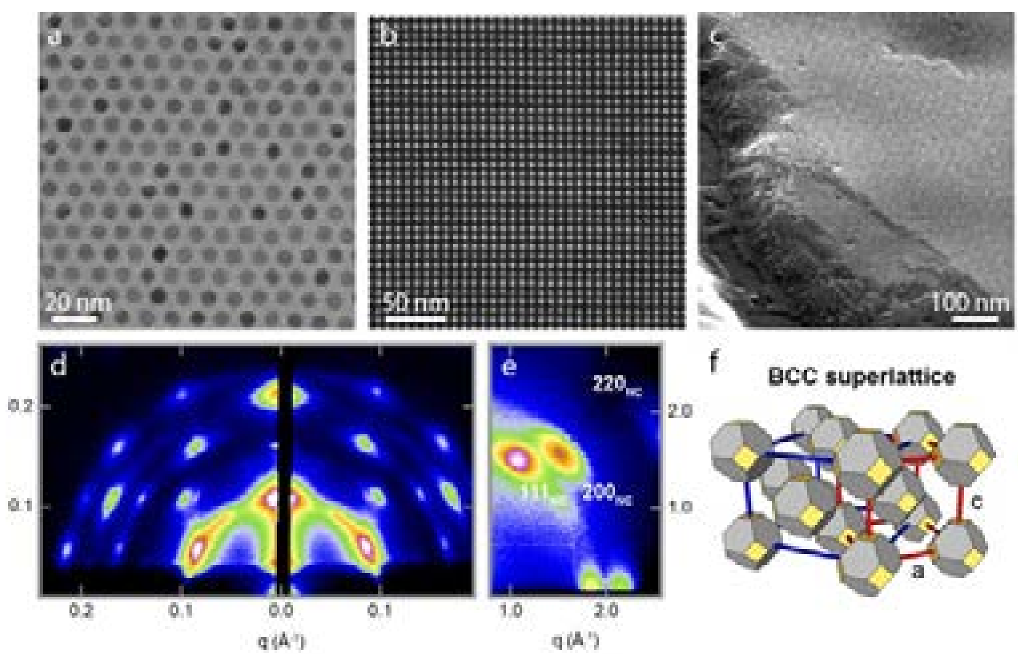

Figure 5: Self-assembled superlattices of colloidal PbS quantum dots (QDs). (a, b) TEM images. (c) SEM image. (d, e) Small- and wide-angle X-ray scattering patterns revealing long-range translational symmetry and epitaxial registry. (f) Cartoon illustration of an atomically-aligned body-center cubic PbS QD superlattice. (From Weidman et al. 2014, and Weidman et al. 2016.)

Energetic disorder is particularly prominent in quantum dot solids because of the strong dependence of the QD energy on its size and shape—a variability that is inevitably present in each QD batch. Understanding the effect of disorder on charge and exciton transport in QD solids and developing materials strategies for minimizing its occurrence have been key focal points of research in the Tisdale Lab.

To study the impact of disorder on exciton transport in QD solids, we used a newly-developed superresolution photoluminescence microscopy technique for time-resolved visualization of exciton transport (Akselrod, Deotare et al. 2014). We showed that exciton transport in inhomogeneously broadened QD solids is actually subdiffusive, wherein the spatial variance of the exciton distribution grows sublinearly with time (Akselrod, Prins et al. 2014). Through complementary kinetic Monte Carlo simulations (Lee et al. 2015) and spectrally resolved transient photoluminescence (Poulikakos et al. 2014), we established that this behavior arises from nonequilibrium occupation of the disordered site energy distribution. Recently, the microscopic insights offered by our studies have been adapted to explain mechanisms of light harvesting by photosystem II in plants.

These early studies motivated the need to minimize size polydispersity in colloidal QD batches, which is the primary cause of energetic disorder. We discovered that, by carefully controlling precursor concentrations during the nucleation and growth stages of PbS QD synthesis, batches with unprecedented monodispersity could be achieved (Weidman et al. 2014). These nanocrystals self-assembled into atomically ordered superlattices, further minimizing disorder (Weidman et al. 2015). Furthermore, recent ultrafast transient absorption measurements have shown that inhomogeneous broadening can be almost completely eliminated in these ordered arrays (Gilmore et al. 2017).

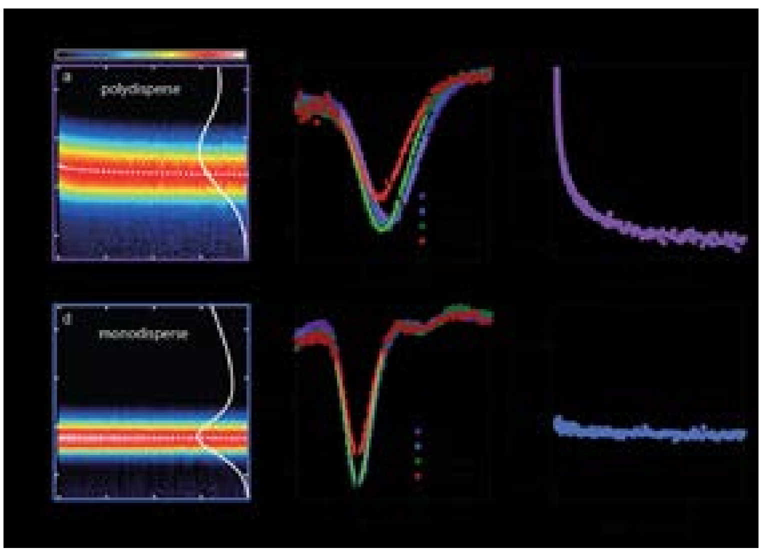

Figure 6: Transient absorption measurement of charge carrier thermalization in ligand-exchanged PbS QD solids. (a, b) In polydisperse QD solids, charge carriers migrate energetically downhill over time. (d, e) In highly monodisperse QD solids, a homogeneously-broadened "flat" energy landscape facilitates charge transport.

Using a novel *in situ* time-resolved synchrotron X-ray scattering technique, we were able to visualize the self-assembly of QD superlattices in real time for the first time, revealing surprising new insights into the complex multiscale pathway of self-organization (Weidman et al. 2016). This technical advance will enable us to refine our existing understanding of colloidal nanocrystal self-assembly, develop new strategies for achieving desired superlattice configurations, and provide the technical foundation for real-time feedback control of nanoscale self-assembly. This exciting new capability will be a key component of future research efforts in the Tisdale Lab.

Lectures and Seminars

During AY2017, the Department of Chemical Engineering hosted a distinguished group of academic and industry leaders, who spoke on topics highlighting cutting-edge research addressing today's energy and health-related challenges. Webcasts for all major lectures can be accessed on our events webpage.

Fourteenth Daniel I. C. Wang Lecture on the Frontiers of Biotechnology (September 23, 2016): "Redesigning Iron-Sulfur Proteins to Improve Biological Electronics." James R. Swartz SM '75, ScD '78, professor of chemical engineering and bioengineering at Stanford University, discussed his work. Following a scientific exchange visit to the USSR and an initial research position at Eli Lilly and Company, Dr. Swartz joined Genentech in 1981, where he served in both scientific and managerial positions related to rDNA protein production and protein pharmaceutical development for nearly 18 years. In 1998, he moved to Stanford University as professor of chemical engineering focusing on cell-free biology. In 1999, he was elected to the National Academy of Engineering and in 2003 helped initiate Stanford's new Department of Bioengineering. He was named the Leland T. Edwards Professor in the School of Engineering in 2006 and the James H. Clark Professor in 2009. He is a founder of Sutro Biopharma, dedicated to developing cell-free protein pharmaceutical technologies; of GreenLight Biosciences, a cell-free metabolic engineering company; and of Bullet Biotechnology, a company developing anticancer therapeutics. His research seeks to reproduce and direct complex metabolism in a cell-free environment. Current applications include improved vaccine architectures, new cancer diagnostics, and biological hydrogen production from sunlight and biomass.

Thirty-First Hoyt C. Hottel Lecture (September 9, 2016): "Grand Challenges in Science for a Clean Energy Future." Dr. Cherry Murray, director of the US Department of Energy's Office of Science, presented how her organization is addressing today's clean energy challenges. Dr. Murray oversees research in the areas of advanced scientific computing, basic energy sciences, biological and environmental sciences, fusion energy sciences, high energy physics, and nuclear physics. She has responsibility not only for supporting scientific research, but also for the development, construction, and operation of unique, open-access scientific user facilities. The Office of Science manages 10 of the department's 17 national laboratories. Dr. Murray was elected to the National Academy of Sciences in 1999, the American Academy of Arts and Sciences in 2001, and the National Academy of Engineering in 2002. Dr. Murray was appointed to the National Commission on the BP Deepwater Horizon Oil Spill and Offshore Drilling in 2010. She was also awarded the National Medal of Technology and Innovation by the White House in 2014 for contributions to the advancement of devices for telecommunications, the use of light for studying matter, and for leadership in the development of the STEM workforce in the United States. Dr. Murray received a SB and a PhD in physics from the Massachusetts Institute of Technology.

Twenty-Third Alan S. Michaels Lecture (April 21, 2017): "Re-design of Metabolism for Carbon Management." James C. Liao, president of Academia Sinica, Taiwan, discussed his research. Professor Liao started his academic career at Texas A&M University in 1990 and moved to University of California, Los Angeles from 1997 to 2016. He has served as president of Academia Sinica in Taiwan since June 2016. His research focuses on metabolism, including its biochemistry, regulation, and redesign. He uses metabolic engineering, synthetic biology, and systems biology to construct microorganisms to produce next-generation biofuels and to study the obesity problem in humans. Dr. Liao and his team also develop mathematical tools for investigating metabolism and guiding engineering design. Currently, their main projects include engineering proteins and biochemical pathways for CO2 fixation and production of fuels and chemicals. The ultimate goal is to use biochemical methods to replace petroleum processing and to treat metabolic diseases.

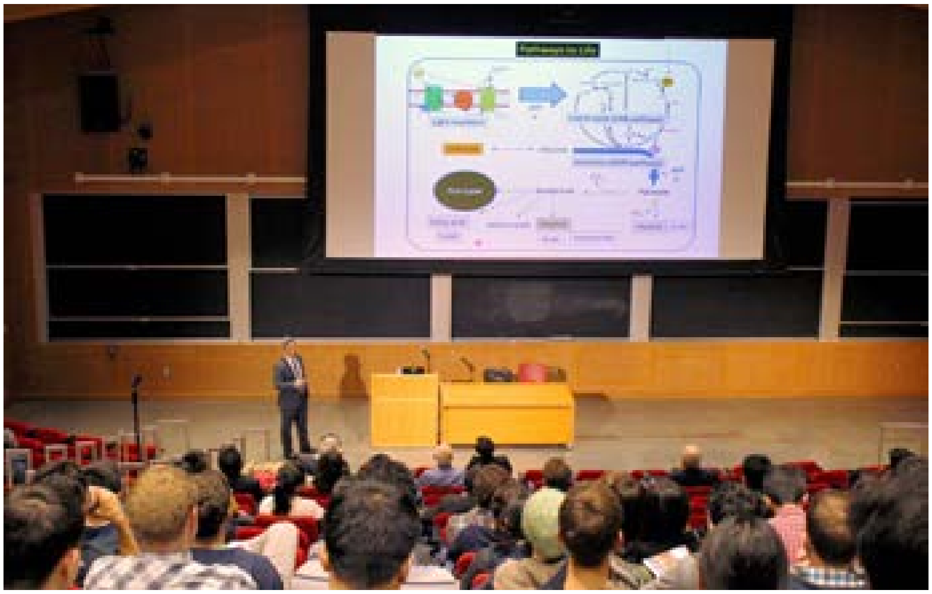

Figure 7: James C. Liao, the 23rd Alan S. Michaels Lecturer, discusses his work in metabolic engineering during his lecture on April 21, 2017.

Thirty-Ninth Warren K. Lewis Lecture (May 5, 2017): "The Next Frontier of Optimization in the Process Industries—Asset Optimization: Opportunities and Challenges." Antonio J. Pietri, president and CEO of Aspen Technology, lectured on the future of process engineering. Prior to his appointment to president and CEO, Pietri served as executive vice president, worldwide field operations, where he led global sales, sales operations, professional services, and customer support and training. He previously served as senior vice president and managing director, regional operations, Asia Pacific, based in Singapore and Beijing, China. Pietri joined Aspen Technology through the company's acquisition of Setpoint. in 1996. At Setpoint, Pietri oversaw integration of Aspen Technology solutions at European refinery and process manufacturing sites. In 2002, he relocated to Singapore as vice president, business consulting, and was subsequently promoted to managing director of the Asia Pacific region. Pietri began his career at ABB Simcon as an applications engineer focused on advanced control and multivariable controllers for refining. Pietri holds an MBA from the University of Houston and a BS in chemical engineering from the University of Tulsa.

Special Symposia

Along with the major lectures, the department hosted two special events: the centennial of the David H. Koch School of Chemical Engineering Practice and a symposium to honor Professor George Stephanopoulos on the occasion of his 70th birthday and retirement.

The Practice School Centennial, September 30 to October 2, 2016, was a weekend of alumni panel discussions, talks from the Department of Chemical Engineering and Institute leaders, and a gala event held at MIT's Media Lab, with a view of the Charles River and Boston's Back Bay. Over 200 alumni attended. It was thrilling to celebrate 100 years of chemical engineering student engagement with industry, solving some of its most complicated and challenging problems. Since 1916, Course 10 students have worked with organizations such as General Mills, Corning Glass, Novartis Pharmaceuticals, BP, Cabot Corporation, and many other energy, materials, manufacturing, food, pharmaceutical, and research companies helping them address pertinent and pressing issues. Thanks to the hard work of our faculty, staff, and alumni, we had two exciting projects emerge from the centennial: a documentary of the past, present, and future of the ChemE Practice School and a book of interviews with three generations of alumni.

Figure 8: Practice School alumni gather at the opening reception for the centennial event Friday, September 30, 2016.

On June 1 and 2, 2017, the department hosted "2040 Visions of Process Systems Engineering." This symposium celebrated the 70th birthday of Professor George Stephanopoulos, as well as his many contributions to process systems engineering (PSE) education and research at MIT and beyond as he steps down from his professorship at MIT. The symposium included presentations and discussions on the future visions for process systems engineering, as well as a reunion of Stephanopoulos's former and current students, postdocs, academic and industrial friends and colleagues. About 200 alumni and colleagues in the PSE area attended.

Figure 9: George Stephanopoulos reflects on his career during the "2040 Visions of Process Systems Engineering" symposium Friday, June 2, 2017.

Departmental Awards

The Department Awards Ceremony took place on May 15, 2017, in the Gilliland Auditorium, Room 66-110. We were pleased to recognize this year's recipients for the Outstanding Faculty Awards: Professor James W. Swan was the graduate students' choice and Professors Fikile Brushett and William A. Tisdale were selected by the undergraduate students.

The Edward W. Merrill Outstanding Teaching Assistant Award was presented to undergraduate student Robbie Shaw for his work in 10.213 Chemical Engineering and Biological Engineering Thermodynamics. The Outstanding Graduate Teaching Assistant Award was presented to PhD student Albert Liu for his work in 10.50 Analysis of Transport Phenomena. 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 Garrett Dowdy and Catherine Bartlett.

Chemical Engineering Special Service Awards were conferred to the members of the Graduate Student Council: Alex Abramson, Kimberly Dinh, Anastasia Nikolakopoulou, Ki-Joo Sung, Joseph Brady, Colin Grambow, Will Records, Hursh Sureka, Christina Dinh, McLain Leonard, Luke Rhym, and Sam Winslow. Members of the Graduate Student Advisory Board were also recognized: Joseph Brady, Connor Coley, Kristen Severson, Jose Gomez, Junli Hao, Sarah Shapiro, and Lisa Guay. Awards were also given to the members of the Resources for Easing Friction and Stress group: Garrett Dowdy, Mark Goldman, Kevin Kauffman, Mark Keibler, Michael A. Lee, Anasuya Mandal, Natasha Seelam, and Lisa Volpatti. In addition, Joseph Brady was awarded the Chemical Engineering Rock Award for his contributions to athletic achievement within the department. The following undergraduate students were also recognized for their service to the student chapter of AIChE: Emma Valentine, Michelle Tai, Jessie Zhao, Linh Nguyen, Brian Zhong, Mackenzie Donnelly, Amy Wang, Marjorie Buss, Andrea Blankenship, Morgan Matranga, Natalie Delumpa-Alexander, Robert Mahari, Jessica Greer, Sarah Coleman, Sarah Curtis, Hannah Caponni, and Raja Selvakumar.

Our undergraduates also earned numerous accolades over the course of the year. The Robert T. Haslam Cup, which recognizes outstanding professional promise in chemical engineering, went to Andres Badel. 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 Carolina Fejgielman. The Wing and Lourdes Fong Prize, awarded to a chemical engineering senior of Chinese descent with the highest cumulative GPA, was established by the late Lourdes Fong to honor her husband Wing Fong, for his hard work and dedication to their adopted home, university, and country. This year's prize is awarded to Zi-Ning Choo and Anni Zhang. Additionally, the 2017 Phi Beta Kappaelects were Orlando Arevalo, Andres Badel, Zi-Ning Choo, Chelsea Edwards, Carolina Fejgielman, and Jason Hyun. Andrea Blankenship was awarded the BP Outstanding Academic Achievement Prize for a junior woman chemical engineer. Yung Wei Hsaio earned the BP Outstanding Performance in Research Award by a junior woman chemical engineer.

The department is quite pleased to recognize Sharece Corner as the department's Outstanding Employee of the Year for her dedication and exceptional service to faculty, staff, and students. Six Chemical Engineering Individual Accomplishments awards were given out to Ankur Gupta, Lisa Guay, Michelle Tai, Gwen Wilcox, Tricia Campbell, and Marwan Cheguenni. Beth Tuths received the School of Engineering's Ellen J. Mandigo Award, which was presented at the Infinite Mile Awards Ceremony.

Figure 10: Department Head Paula Hammond recognizes the recipients of the fall 2016 and spring 2017 Awards for Outstanding Graduate Student Seminar, Catherine Bartlett and Garrett Dowdy.

The Department of Chemical Engineering at MIT has had a 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

Martin Z. Bazant
Executive Officer
E. G. Roos '44 Professor of Chemical Engineering