Department of Chemical Engineering

During AY2019, the Department of Chemical Engineering (ChemE) continued its long tradition of global leadership in the discipline. For the 30th straight year, our undergraduate and graduate programs were each 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 fifth straight year and contributed to the record-breaking eighth straight year that MIT was ranked number one among world universities overall. The department has maintained is reputation and record of excellence during a time of increasing competition, investment, and growth among chemical engineering programs at peer institutions.

A major effort in the department has been the revitalization and improvement of the undergraduate curriculum. A task force headed by Professor Kristala Prather has been examining the different components of a chemical engineering undergraduate education, refining our coursework to improve connectivity between subjects, and streamlining and updating the courses to enable students more flexibility and opportunities to shape their educational experience. These efforts have led to some implemented changes that provide flexibility and enhance the opportunity for design experiences in the junior and senior years, and we anticipate more changes will follow. We have also developed a popular exploratory class, 10.000 Engineering Molecular Marvels: Careers and ChemE at MIT, which introduces first-years to the field of chemical engineering using lab tours, industrial visits, and alumni or faculty speakers to explain the possibilities in the field. We have also expanded outreach and community building efforts across the department. These efforts, along with curricular reform, are anticipated to enhance the enrollment of undergraduate students in our programs.

In partnership with Bioengineering, the department created the first wet maker space on campus, the BioMaker Space in Building 26, with an initial budget of $3.5 million. The space features flexible lab space and equipment, as well as a student lounge area. This innovative project leverages the national trend in mechanical and electrical maker spaces to empower undergraduates to experiment with biological and chemical design, while also providing a home to a new community of undergraduates.

In the same year that MIT announced the Stephen A. Schwarzman College of Computing, the department launched three new computational concentrations for the 10-ENG flexible chemical engineering degree, an ABET accredited program in general engineering, with existing concentrations in energy, materials, polymers, biomedical engineering, and engineering ethics. Professor Richard Braatz led the development of new 10-ENG concentrations in process data analytics (10-ENG DATA), engineering computation (10-ENG COMP), and manufacturing design (10-ENG DESIGN), together with Professor Martin Bazant. The new concentrations immediately attracted students and will help the department respond to the growing interest and career opportunities in data science and computing within the field of chemical engineering.

Broader educational connections with computing were also made through advances in digital learning, which attracted global attention and paved the way for sustained innovation in this area, building on our 2015 digital learning strategy. Since most massive open online courses (MOOCs) on MITx, Edx, and other platforms cover introductory, undergraduate subjects, this year we decided to experiment with graduate-level teaching online. Professor Bazant created the award-winning 10.50.1x Analysis of Transport Phenomena: 1. Mathematical Methods, the first advanced engineering or applied mathematics MOOC on edX, which launched in fall 2018 with over 4,000 registered students, of whom 75 completed the class with a passing grade (nearly double the size of the residential class). This catalyzed broader interest among our faculty in MOOCs and digital tools for residential teaching, so the department hired its first Digital Learning Lab fellow, Zongyu "Joey" Gu, a recent graduate of the department and course coordinator for 10.50.1x, jointly supported by the MIT Office of Digital Learning.

The department continues to promote inclusivity through initiatives and programs geared toward women and underrepresented minorities. In recognition of multiple efforts within the department, ChemE won MIT's 2019 Change-Maker Award in the Outstanding Department/Lab/Center category. The whole department participated in an Inclusive Environments workshop, a collaboration between faculty and students. Students supported the creation of these workshops by helping Violence Prevention and Response and Title IX and Bias Response tailor the content to the relevant experiences within the department. Student feedback and guidance was instrumental to developing an interactive and engaging workshop for all lab groups. Additionally, graduate students coalesced to create a women in chemical engineering group, bringing an outside speaker to kick off a conversation about challenges that women face in order to achieve work-life balance. These examples underscore how the department and its students initiated change together.

In fall 2018, the department hosted its eighth ACCESS program, a weekend of educational and informative events introducing sophomores, juniors, and seniors to the benefits of a graduate education in chemistry, chemical engineering, and materials science. Through interactive workshops, hands-on activities, and presentations on MIT's campus, students from underrepresented minority groups were introduced to the life of a graduate student in science and engineering. Since 2009, there have been 129 participants in the Chemical Engineering section of the program; a number of the original participants have now joined ChemE to earn their graduate degrees: Abel Cortinas earned his PhD in 2018, Daniela Espinosa Hoyos is currently in the program, and K'yal Bannister and Mary Jones are arriving in fall 2019. Also in fall 2018, the department hosted its first Rising Stars in Chemical Engineering Workshop, a program aimed to prepare women for the challenges associated with a career in academia. During the two-day program, participants attended workshops, met individually with MIT faculty, presented their own research, received feedback, and learned strategies for job searching, building a career, balancing family and research, and thriving as a chemical engineering professor. Twenty-three women from around the country attended; the second workshop is planned for fall 2019.

The department continues to attract significant research funding at an annual volume of $56.3 million, of which $22.1 million are handled directly through the department. The faculty continue to secure healthy funding for their individual research programs while also participating in the creation and direction of larger multi-investigator projects.

Our department plays a major role in several Manufacturing Innovation Institutes (MII), 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, including their extensive networks of national industrial partners. Professor Richard Braatz led MIT's contribution to the Clean Energy Smart Manufacturing Innovation Institute (CESMII), which is a consortium of academia, industry, and nonprofits supported by DOE. CESMII is developing a software platform for the real-time capture, sharing, and processing of information at manufacturing facilities, and maintains a national network of regional manufacturing centers that promotes technology transfer and workforce development. Professor Braatz also contributes to the road-mapping and research activities of the National Institute for Innovation in Manufacturing Biopharmaceuticals, which is a public-private partnership supported by the National Institute of Standards and Technology in the US Department of Commerce to advance biopharmaceutical manufacturing innovation and workforce development. Professor Gregory Rutledge is the lead principal investigator (PI) for MIT in the Advanced Functional Fabrics of America (AFFOA), another MII created in 2016 and headquartered in Cambridge, Massachusetts, with $75 million in funding over five years from the US Department of Defense (DOD), with additional funding from the Commonwealth of Massachusetts. AFFOA's mission is to enable a manufacturing-based revolution in fibers, yarns, and fabrics as integrated and networked devices and systems.

Professor Prather served as co-director of the Energy Biosciences Low-Carbon Energy Center of the MIT Energy Initiative. Professor Hadley Sikes led chemical engineering efforts in the Singapore-MIT Alliance for Research and Technology (SMART) Antimicrobial Resistance Integrated Research Group (IRG). Professor Michael Strano continued as the lead PI for Disruptive and Sustainable Technology for Agricultural Precision (DiSTAP), a $40 million effort. This new SMART IRG is based in part on his recent advances in plant nanobionics, and focuses on new technology for urban farming and biomanufacturing to advance food security. Professor Gregory Stephanopoulos is a co-PI for DiSTAP, focusing on the biosynthesis of hydrophobic vitamins. Professor Strano is also the lead PI on an MIT engineering frontier research center called the Center for Nanofluidic Transport that involves seven universities and Lawrence Livermore National Laboratory. This $11 million center sponsored by the Department of Energy investigates new physical phenomena observed in single digit nanopores (< 10 nm in diameter), where fluid flow and molecular transport exhibit exotic behavior with the potential to revolutionize chemical separations and desalination. Professors Heather Kulik, Daniel Blankschtein, and Martin Bazant are the co-principal investigators from MIT, leading efforts in continuum theory, quantum chemistry, and molecular simulation, respectively. Professor Bazant completed his second year as director of the Data-Driven Design of Rechargeable Batteries (D3BATT), with nearly $10 million from the Toyota Research Institute, where his physics-based modeling is complemented by data analytics and machine learning from MIT co-PI, Professor Braatz. With colleagues in computer science and chemistry, Jensen and Green have started a new MIT-industry consortium on Machine Learning for Pharmaceutical Discovery and Synthesis. The new consortium includes eight industry partners, all major players in the pharmaceutical field. Professors Jensen, Braatz, and Allan Myerson continued another DARPA project, Make-It, on automated robotic chemical synthesis combined with computational synthesis design integrating machine learning, computational chemistry, and retrosynthetic tools for reaction pathway identification and selection.

Professor Paula T. Hammond completed her fourth year as department head, and Professor Bazant completed his third year as executive officer. Professor Patrick Doyle continued to serve as the graduate officer. Professor William Green completed his fourth year as postdoctoral officer, and Barry Johnston continued his long service as the undergraduate officer. Professor T. Alan Hatton continued as the director of the David H. Koch School of Chemical Engineering Practice. Chemical Engineering continues to claim two Institute professors as primary faculty members—Daniel I. C. Wang and Robert S. Langer. Professor Robert C. Armstrong is the director of the MIT Energy Initiative.

Research and Recognition

Many members of the Chemical Engineering faculty received major awards for their research and related teaching achievements.

Martin Bazant was elected a fellow of the American Physical Society and was awarded the 2019 MITx Prize for Teaching and Learning in MOOCs. Richard Braatz was elected to the National Academy of Engineering. Fikile Brushett earned the 2019 Electrochemical Society Supramaniam Srinivasan Young Investigator Award. Arup Chakraborty received an honorary doctorate from Hong Kong University of Science and Technology. Kwanghun Chung earned a 2019 Presidential Early Career Award. Karen Gleason was named the 2019 American Institute of Chemical Engineers (AIChE) John M. Prausnitz Institute Lecturer. William Green earned the AIChE R. H. Wilhelm Award in Chemical Reaction Engineering. Paula Hammond was elected to the National Academy of Sciences and earned the 2019 AIChE Margaret H. Rousseau Pioneer Award. Heather Kulik received the 2019 American Association for the Advancement of Science (AAAS) Marion Milligan Mason Award for Women in Chemical Sciences and a 2019 National Science Foundation (NSF) CAREER Award, and was named a 2019 *Journal of Physical Chemistry* and PHYS Division Lecturer award winner. Robert Langer won the 2019 Dreyfus Prize for Chemistry in Support of Human Health. Karthish Manthiram received a 3M Non-Tenured Faculty Award and American Chemical Society PRF New Investigator Award. Brad Olsen won the 2019 AIChE Owens Corning Early Career Award. Kristala Prather was elected a 2018 AAAS fellow. Yuriy Roman received the 2019 Rutherford Aris Award, a 2018 Bose Grant, and the American Chemical Society (ACS) Early Career in Catalysis Award. Hadley Sikes received an MIT Committed to Caring Award. Gregory Stephanopoulos received the 2019 Gaden Award for Biotechnology and Bioengineering. Michael Strano won the 2019 AIChE Andreas Acrivos Award for Professional Progress in Chemical Engineering.

It was an exciting year of research for the department, with many new developments coming out of Chemical Engineering laboratories. Daniel Anderson's lab developed new materials to improve delivery of therapeutic mRNA and inhalable mRNA. The Anderson and Langer labs worked together to develop an oxygen-tracking method to improve diabetes treatment and living drug factories. The Blankschtein and Strano labs connected to catalog defects in 2D materials. Richard Braatz worked with Bazant and other colleagues to study the lifespan of lithium-ion batteries. The Chung lab developed a new technique to create maps of neural circuits with single-cell resolution. The Doyle lab learned to control knots that form in DNA molecules and developed a nanoemulsion gel as a new way to deliver drugs. Karen Gleason and colleagues developed a new surface treatment that could improve refrigeration efficiency. The Hammond lab developed a potential arthritis treatment that prevents cartilage breakdown and new optical imaging for tiny tumors. Bob Langer explored a targeted approach to treating glioma, a new pill to deliver insulin, and a drug delivery system for tuberculosis. The Love lab developed a new way to manufacture small batches of biopharma on demand. Karthish Manthiram researched ways to shrink the carbon footprint of plastics. Work in the Rutledge lab included a new technique that makes it possible to image the fouling of membranes in 3D, which could lead to better antifouling materials. The Sikes lab developed a new sensor for cancer therapy, while Zachary Smith's lab created a novel membrane material that removes more impurities than current filters, without the need for toxic solvents. The Strano lab made several breakthroughs, including cell-sized robots that can sense their environment, nanoparticles to engineer plants, ambient plant illumination, artificial blubber, and self-healing material that can build itself from carbon in the air. The Swan lab also made insights into particle networks.

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

New Arrivals and Promotions

William Tisdale and Hadley Sikes received tenure, and Kwanghun Chung, Heather Kulik, and James Swan were promoted to associate professor without tenure. The department has hired three new faculty who will start during FY2020 and FY2021. Katie Galloway and Ariel Furst will start during the summer of FY2020 and Connor Coley will begin in early FY2021.

Professor Coley is already very familiar with the department, as he was a graduate student in the laboratories of MIT professors William Green and Klavs Jensen. His research will work toward a new paradigm of computational assistance for molecular discovery through an interdisciplinary approach combining chemistry, chemical engineering, and computer science in close partnership with experts in application domains such as chemical biology and human health. He's been named a DARPA Riser, one of *C&EN*'s Talented 12, and one of *Forbes*'s 30 under 30: Healthcare.

Professor Furst was born and raised in St. Louis, Missouri. She received her BS in chemistry from the University of Chicago, during which time she worked with Shelley Minteer at Saint Louis University and Stephen B. H. Kent. She completed her PhD in the lab of Jacqueline Barton at the California Institute of Technology and was most currently an Arnold O. Beckman Postdoctoral Researcher at the University of California at Berkeley, in the lab of Matthew Francis. Professor Furst's research combines electrochemical methods with biomolecular and materials engineering to address challenges in human health and clean energy. She plans to develop new technologies to combat antimicrobial resistance, detect disease, and improve microbial interactions with electrodes.

Professor Galloway has engineered systems for dynamic behaviors across multiple scales, from the molecular design of noncoding RNA devices to optimization of large transcriptional networks. Her graduate work in the Christina Smolke lab at Caltech, constructing synthetic gene circuits to regulate cellular decision making, was published as a first author research article in *Science*. As a postdoctoral researcher, she examined the molecular processes that direct cell fate during cellular reprogramming in the laboratory of Dr. Justin Ichida, assistant professor in the Department of Regenerative Medicine at the University of Southern California. Her lab at MIT will focus on developing integrated gene circuits and elucidating the systems-level principles that govern complex cellular behaviors. The ultimate goal of her research is to leverage synthetic biology to transform how we understand cellular transitions and engineer cellular therapies.

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, the department introduced the 10-ENG flexible SB degree in engineering. Department undergraduate enrollment has been gradually declining since AY2007, but the department 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 first-year advising seminars, fall and spring term open houses, Parent's Weekend, and other activities. Fifty SB degrees were conferred in June 2019, 56% 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	2009–2010	2010–2011	2011–2012	2012–2013	2013–2014	2014–2015	2015–2016	2016–2017	2017–2018	2018–2019
Sophomores	87	80	72	61	67	57	56	58	44	41
Juniors	68	71	73	63	63	66	53	51	53	37
Seniors	73	75	75	69	58	64	67	55	50	59
Total	**228**	**226**	**220**	**193**	**188**	**187**	**176**	**164**	**147**	**137**

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. While maintaining ABET accreditation as a general engineering program, the 10-ENG cwurriculum 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. The initial concentrations included energy, materials process and design, biomedical, environmental, and society, engineering, and ethics. In 2019, the department introduced three new computational concentrations in process data analytics (10-ENG DATA), engineering computation (10-

ENG COMP), and manufacturing design (10-ENG DESIGN), in response to growing student interest and career opportunities in data science and computational methods.

The department continued its multiyear effort to review and revise its undergraduate curriculum and improve the overall student experience in our programs. Professor Prather completed her second year leading the task force on undergraduate curriculum revitalization, appointed by Professor Hammond in 2017. The task force has studied and implemented ways to reduce the number of required units and increase curricular flexibility for electives, while examining and updating laboratories and core subjects in each major subfield of chemical engineering (transport, reaction engineering, thermodynamics, and separations). The department also introduced several exploratory subjects for first-years to learn about our major, as well as various outreach and extracurricular activities, such as department-wide undergraduate project-lab presentations and prizes, ChemE Research Day, Science Slam, undergraduate chemical engineering career seminars, social events with faculty, and the creation of the first "wet" maker space on campus—the Bio-Maker Space—jointly developed with the Department of Biological Engineering. These efforts contributed to our successful reversal of the decreasing enrollment trend of the past 10 years with 53 first-years declaring chemical engineering majors, up from 33 last year, including eight new students in 10-ENG.

The average starting salary for graduates of the Department of Chemical Engineering is $85,895 (2019 senior survey). This attests to the success of the graduates of the Course 10 and Course 10-B programs and to the continued high demand for our students. The senior survey indicates that for 2019, 36% 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 student officers of AIChE were Sarah Coleman, Nancy Wang, Luis Sandoval, Kaitlyn Hennacy, Zach Schmitz, Kedi Hu, Delaney Burns, Crystal Tsui, Jacky Chin, Daiyao Zhang, Michelle Huang, Emily Yan, Michal Gala, Caroline Kenton, Morgan Matranga, and Liruonong Zhang.

Graduate Education

The graduate program in the Department of Chemical Engineering offers master of science degrees in chemical engineering (MS) and in 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 MIT Sloan School of Management. The total graduate student enrollment is currently 237, with 224 in the doctoral program and 13 master's level degree candidates. In the doctoral program, 207 students are in the PhD or ScD track and seven are in the PhDCEP track. In the master's level program, 10 are in the MSCEP track. Of our graduate students, 29% are women; 4% are students from underrepresented minority groups; and 49 were recipients of outside fellowship awards, including those from the National Science Foundation, the National Institutes of Health (NIH), the Department of Defense, and others. The distribution of graduate students by degree for the last 10 years is shown below in Table 2. During AY2019, 50 doctoral degrees were awarded, along with 38 master's degrees (35 MSCEP, 3 MS) for a total of 88 advanced degrees conferred.

The department received 456 applications for admission to the doctoral program, offered admission to 63 individuals, and received 35 acceptances of offers, for an acceptance percentage of 56%. Out of 93 applications for master's degrees, the department made 12 offers and received 11 acceptances of offers, for a yield of 92%. Among the incoming graduate class for 2019, 16 are women and three are from underrepresented minority groups. On average, the incoming graduate class held an undergraduate GPA (grade point average) of 3.92 (out of 4.0).

Table 2. Graduate Enrollment over the Last 10 Years

Degree level	2009–2010	2010–2011	2011–2012	2012–2013	2013–2014	2014–2015	2015–2016	2016–2017	2017–2018	2018–2019
Master's	38	28	20	10	11	15	15	10	12	13
Doctoral	203	212	224	212	211	222	218	222	214	224
Total	**241**	**240**	**244**	**222**	**222**	**237**	**233**	**232**	**226**	**237**

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. As faculty research officer, Professor Braatz facilitated the continuous updating and evolution of the department's strategic plan and the generation of multiple faculty proposals to support the specific research directions defined in the strategic plan.

Biologically-derived Medicines on Demand

Manufacturing solutions today for biologic medicines are not well-aligned with emerging interests in precision medicine that rely on improved stratification of disease based on molecular profiles. A DARPA-sponsored program, called Integrated Scalable Cyto-Technology, 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 for Integrative Cancer Research emphasizes small-scale continual production and purification, incorporating concepts of quality-by-design, process analytics, plant-scale control, and real-time release. The team published their demonstration of the system and its capabilities to produce three different recombinant proteins used as biopharmaceuticals with clinical-grade quality in *Nature Biotechnology* in October 2018. The work was highlighted in several media outlets, including *Stat News*. The ability to make biologic drugs at small scales anywhere could substantially improve health care for precision medicine, including addressing rare and orphan diseases, and potentially lower costs of supplying these drugs for global health. Efforts to explore new potential therapies for manufacturing on these systems for medical countermeasures and vaccines are under way.

Data-Driven Design of Lithium-Ion Batteries

Professors Bazant and Braatz continued their collaboration on data-driven design of lithium-ion batteries with researchers at MIT, Stanford University, and Purdue University through the D3BATT center, funded by the Toyota Research Institute and directed by Bazant. D3BATT is developing a multiscale modeling framework for rechargeable batteries to accelerate materials discovery and design by leveraging physics-based machine learning on large databases of images and videos at matching length- and timescales, electrochemical characterization, and atomistic calculations of material properties. Their publications included a major advance in battery lifetime prediction that was the cover article of the May 2019 issue of *Nature Energy* and was the topic of a News and Views article in *Nature*.

Smart Data Analytics in Biomanufacturing

Professors Braatz, Anthony Sinskey (Department of Biology), Retsef Levi (MIT Sloan School of Management) and Stacy Springs (Center for Biomedical Innovation) co-led a new project: Smart Data Analytics for Risk Based Regulatory Science and Bioprocessing Decisions. This project was funded by the US Food and Drug Administration's (FDA) Emerging Technology Program, which promotes the development of innovative technologies for the manufacturing of pharmaceutical products. Professor Braatz leads the development of a decision framework to automate the optimal selection of machine learning algorithms for biopharmaceutical manufacturing applications to generate solutions at the same level of performance as a team of experienced human experts.

Novartis-MIT Center for Continuous Manufacturing

May 2019 marked the end of the 12-year collaboration with Novartis on continuous manufacturing of pharmaceuticals. We have continued to work on a large set of projects to overcome the technical problems that 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 the Departments of Chemistry, Chemical Engineering, and Mechanical Engineering.

We are working closely with Novartis on the projects. Advances and findings have been published in a wide variety of journals, and new intellectual properties are being captured in patents. We have not only made strides in solving the technical problems related to continuous manufacturing of complex and high-value drug molecules, but we have also engaged the global pharmaceutical industry, academics, and regulators to solve the regulatory and mindset challenges, with the latter often being the greatest challenge. We organized the third International Symposium on Continuous Manufacturing of Pharmaceuticals, in London. Janet Woodcock, head of the FDA's Center for Drug Evaluation and Research presented the keynote address. The meeting brought together global leaders in the pharmaceutical world to report on the advances in the past two years and to discuss the challenges remaining. One of the major outputs of the symposium will be a strategic white paper on continuous manufacturing of pharmaceuticals.

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

Defense Advanced Research Projects Agency Make-It Project

Professor Jensen continued to lead the DARPA Make-It program to develop machine learning algorithms for planning organic synthesis and to realize a robotic system for automated chemical synthesis. With colleagues in Electrical Engineering and Computer Science ([EECS] Regina Barzilay and Tommi Jaakkola) and Chemistry (Timothy Jamison), Professors Jensen, Green, and Myerson combined artificial intelligence–driven synthesis planning from historical data and a robotically controlled experimental platform to realize 15 drug or drug-like substances. A robotic arm reconfigured the modular continuous flow platform, set up the required unit operations, and carried out each synthesis automatically. The team continued to expand the MIT-industry Machine Learning for Pharmaceutical Discovery and Synthesis Consortium, which now includes 13 major pharmaceutical industry partners (Amgen, AstraZeneca, BASF, Bayer, GSK, Janssen, Leo Pharm, Lilly, Merck, Novartis, Pfizer, Sunovion, and WuXi).

Disruptive and Sustainable Technology for Agricultural Precision

The Disruptive and Sustainable Technology for Agricultural Precision (DiSTAP) Integrated Research Group in the MIT-Singapore SMART program completed a highly successful first year. Initiated in January 2018, the $40 million IRG is producing next generation sensors and analytical instrumentation, plant delivery, and environmental tools for the urban farm of the future. Led by Michael Strano, the DiSTAP team includes Greg Stephanoplous and Kristala Prather, as well as Rajeev Ram (EECS) and Anthony Sinskey (Biology). In this first year, DiSTAP produced three new agricultural technologies, including a Swept Source Raman Spectrometer small enough to be field-portable for agriculture; nanosensors capable of intercepting the immunological signaling of a living plant, sending the information in real time to a user's cell phone; and nanocarrier technology capable of targeting specific organelles within plants for the first time. The latter contribution was published in the journal *Nature Nanotechnology*, highlighted by major media platforms globally, and celebrated at a media event by the prime minister of Singapore. DiSTAP is currently forming partnerships with regional and global agricultural companies and urban farming concerns.

Center for Enhanced Nanofluidic Transport

The Center for Enhanced Nanofluidic Transport (CENT) is an $11 million Energy Frontier Research Center funded by the US Department of Energy starting July 2018. Professor Michael Strano is the lead PI and scientific director. Also participating are Professors Heather Kulik, Daniel Blankschtein, and Martin Bazant. CENT is focused on what it identifies as knowledge gaps in our basic understanding of fluidic transport under extreme confinement. When fluids are confined to nanometer-size channels below approximately 10 nm, flow becomes significantly enhanced under certain circumstances and thermodynamic properties become highly distorted in ways not predicted by existing theory. The work of CENT will produce fundamental insights into geologic transport and lead to new membrane and other separation technologies for energy efficiency and chemical process intensification. CENT completed a highly successful, two-day symposium on the MIT campus in March 2019. It also held special sessions at the on-campus International Electrokinetics Symposium (ELKIN) meeting on electrokinetics and fluid mechanics, organized by Martin Bazant. The CENT team jointly published a cover article for the *Journal of Physical Chemistry* highlighting seven distinct knowledge gaps in the nanofluidic field requiring the collaborative effort of the center to address.

The David H. Koch Institute for Integrative Cancer Research

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

Faculty Notes

Professor Robert C. Armstrong serves as director of the MIT Energy Initiative (MITEI). MITEI continues to grow rapidly in its research, education, and outreach components. Ten companies sponsor research as founding, sustaining, or startup members of MITEI. We are particularly excited about our newest startup member, Commonwealth Fusion Systems, whose technology may revolutionize the world's energy systems. All together the Energy Initiative has more than 80 industrial and public partners and individual members across four continents. MITEI has helped to bring in nearly $800 million in support over the past 10 years and 400 named energy fellowships spread over 25 departments. The MITEI Low Carbon Energy Centers, which were announced in 2015 as key components of MIT's Climate Action Plan continue to develop. This past year we announced the formation of the Mobility Systems Center, which is planned to launch later this summer. It builds on the *Mobility of the Future* study, which is planned for release in November 2019. The *Future of Storage* study continues, which is the latest in a series of multi-faculty, multi-disciplinary studies aimed at informing the discussion between industry and policymakers around the role of key technologies in meeting future energy demand growth in a carbon constrained world. Professor Armstrong serves on the scientific commission of the Eni Enrico Mattei Foundation, the editorial board of *World Energy* magazine, the external scientific advisory committee of Argonne National Laboratory, and on the board of the National Renewal Energy Laboratory. He serves on the advisory boards of chemical engineering departments at Northwestern University and Washington University, the Energy Institute at Texas A&M University, and the scientific evaluation committee of the Energy and Environmental Solutions Project at the University of Pau and Pays de l'Adour. 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 third year as executive officer of the department. He was elected a fellow of the American Physical Society by the Division of Fluid Dynamics and was awarded the 2018 Andreas Acrivos Award for Professional Progress in Chemical Engineering, the highest midcareer honor bestowed by the American Institute of Chemical Engineers. In fall 2018, he launched the first graduate-level MOOC in engineering mathematics—10.50.1x Analysis of Transport Phenomena: 1. Mathematical Methods—with over 4,000 registered students (75 passing), for which he was awarded the MITx Prize for Teaching and Learning in MOOCs. He published more than 25 papers, including the first theory of the double layer in water-in-salt electrolytes and a new method of capillary filtration of particles from suspensions by dip coating on fibers, which he invented and patented through his industrial consulting. After serving on the board of the International Electrokinetics Symposium for over a decade, he organized an ELKIN meeting at MIT in June 2019 with over 175 participants. At the meeting, he announced the creation of the International Electrokinetics Society, for which he will serve as the first president, to broaden the scope of ELKIN to include awards and outreach as the first professional society devoted to the field of electrokinetic phenomena. He also continued to serve as chief scientific advisor for Saint Gobain Ceramics and Plastics, North America R&D Center, in Northborough, MA.

Professor Daniel Blankschtein's group carries out fundamental theoretical simulations and experimental research in the area of colloid and interface science, with emphasis on practical applications. He interacts with several companies that make use of software developed by his group to facilitate surfactant formulation design. Professor Blankschtein's group delivered invited talks, regular talks, and seminars, and presented posters at various scientific meetings in the United States and abroad. He is a member of the newly established Center for Nanofluidic Transport that involves seven universities and Lawrence Livermore National Laboratory. As part of this center, Professor Blankschtein's group is investigating how fluids behave under extreme confinement. New, intriguing equilibrium and transport phenomena are observed. For example, inside very narrow carbon nanotubes, water freezes at a temperature of about 100°C, a temperature at which bulk water normally boils! Professor Blankschtein continues to serve on the editorial board of Marcel Dekker's Surfactant Science book series.

Professor Richard D. Braatz served as president 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 managed interactions with Manufacturing USA Institutes. He led the mathematical modeling, data analytics, and control research in several large advanced manufacturing projects, including $6.8 million in new grants from US Health and Human Services to validate his methodologies in fully automated experimental platforms for monoclonal antibody and viral vector manufacturing. His publications include a highly publicized major advance in battery lifetime prediction that was the cover article of the May 2019 issue of *Nature Energy* and was the topic of a News and Views article in *Nature*. He served on numerous advisory and editorial boards, and gave numerous invited lectures, including plenaries and keynotes. In 2019 he was elected to the National Academy of Engineering "for contributions to diagnosis and control of large-scale and molecular processes for materials, microelectronics and pharmaceuticals manufacturing."

Associate Professor without Tenure Fikile R. Brushett, the Green Career Development Chair, and his research group continue to advance the science and engineering of electrochemical systems needed for a sustainable energy economy. Recent work has focused on synthesis and characterization of new electroactive materials, design and engineering of electrochemical reactors, and mathematical modeling of electrochemical systems. This spring, he was honored with the Supramaniam Srinivasan Young Investigator Award by the Electrochemical Society. In addition, Brushett serves as the research integration co-lead for the Joint Center for Energy Storage Research (JCESR), a United States Department of Energy–funded energy innovation hub. Last fall, the JCESR scientific and operational leadership team, of which he is a member, received the Secretary of Energy's Achievement Award.

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. Chakraborty, in collaboration with Professors Phillip Sharp and Richard Young, also continued to work on a project initiated in 2016 on understanding how genes critical for maintaining healthy cell states are regulated. Their latest collaboration on this subject, published in 2018, was listed as one of the top 10 Breakthroughs of The Year by *Science* magazine. Chakraborty is also working on two books on immunology, one for an audience of physical scientists who want to, or have entered the field, and one for a general audience. Chakraborty 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). Chakraborty was awarded an honorary doctorate by the Hong Kong University of Science and Technology in 2019.

Professor Kwanghun Chung is leading 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 new technologies 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 the development of SHIELD technology that simultaneously and globally protects tissue physicochemical properties while allowing multiscale molecular imaging. The Chung lab has openly shared the SHIELD reagents and protocols with over 100 labs worldwide. His group has active collaborations with many researchers at MIT, the Broad Institute, Massachusetts General Hospital, and Harvard University. He has traveled extensively, including visits to the University of Washington, Stanford University, ETH Zurich, Université Laval, as well as Cold Spring Harbor Asia, to speak about his group's technologies and their applications. Professor Chung taught 10.302 Transport Processes and HST.562 Pioneering Technologies for Interrogating Complex Biological Systems. He also served on the International Metabolic Engineering Society Committee for Academic Programs, as well as the Chemical Engineering graduate admission and Brain and Cognitive Science graduate admission committees. Professor Chung has recently founded a startup, LifeCanvas Technologies, that aims to advance the adoption and usage of Chung Lab technologies developed at MIT.

Professor Emeritus Charles L. Cooney, the Robert T. Haslam (1911) Professor of Chemical and Biochemical Engineering, teaches the capstone subject, 10.490 Integrated Chemical Engineering, introducing seniors to batch processes through the design of a manufacturing facility for therapeutic monoclonal antibodies. This open-ended design project has teams select a product, identify a business model, forecast demand through 2030, complete a process design along with a road map for the project and facilities costing. He also teaches in 10.547 Principles and Practice of Drug Development.

Professor Cooney continues as an advisor to the SMART Innovation Center in Singapore 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's Professional Institute, and co-faculty lead on a custom Sloan School executive education program on research and development (R&D) leadership for Takeda Pharmaceuticals. Professor Cooney is also on the board of the Norman B. Leventhal Map and Education Center at the Boston Public Library, an advisor 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, continues to serve as the graduate officer for the department. His research focuses on soft matter, including fundamental studies of DNA polymer physics, miRNA sensing, and microfluidic synthesis of functional microparticles. He received a J-WAFS (Abdul Latif Jameel Water and Food Systems Lab) seed grant to explore new ways to remove micropollutants from water. He also led a mixed academic-industrial team to receive funding from the Pharma Innovation Programme Singapore to develop new methods for formulating small molecule drugs. A significant publication from his group in *Nature Communications* showed a new way to synthesize and trigger thermal gelation of nanoemulsions upon exposure to in vitro temperatures. The nanoemulsion system can be used in drug delivery and cosmetic applications, and was designed using FDA-approved materials for quick translation to industry. He delivered several invited lectures at companies, conferences, and universities, including the Gordon Research Conference on Preclinical Form and Formulation for Drug Discovery. Professor Doyle currently serves on the scientific advisory board at NPlex Biosciences and Achira Labs, and is on the National University of Singapore Chemical Engineering Department visiting committee.

Professor William H. Green's research on predicting chemical reactions continues to make excellent progress, with dozens of journal publications and conference presentations this year. His student, Connor Coley (co-supervised by Klavs Jensen) made several high-profile conference presentations, including giving one of *C&EN*'s Talented 12 addresses at the 2018 American Chemical Society meeting in Boston. Coley, Green, and Jensen described the line of research in computer-aided organic synthesis planning that led to this award in an article in *Accounts of Chemical Research*. Professor Green gave one invited talk at the Boston ACS meeting, and two more invited talks at the 2019 ACS meeting in Orlando, FL, each in different ACS divisions. Professor Green also gave an invited talk at the Society for Industrial and Applied Mathematics Numerical Combustion meeting in Aachen, Germany. Professor Green was the keynote lecturer of the Mathematics in Chemical Kinetics and Engineering conference in Ghent, Belgium. His talk at the 2018 AIChE national meeting in Pittsburgh (co-authored with his student Alan Long) was named Best Paper of the Session. With his student Colin Grambow and his postdoc Yi-Pei Li, he developed a transfer learning method for molecular properties, which allows one to make high-accuracy predictions with relatively small amounts of high-accuracy training data. This promises to make machine learning much more useful in the chemical sciences. In addition to his extensive work on chemical reactions, kinetics, and machine learning, Professor Green continues as the faculty chair of MIT's Mobility of the Future consortium, which will release its report in Washington, DC this fall, and he was named co-chair of MITEI's new Mobility Systems Center. His paper with Professor Yet-Ming Chiang and two of their students projecting the future cost of producing electric vehicle batteries attracted significant attention. He and his student Ryan Gillis also patented a method for reacting the toxic waste product H_2S with water to make hydrogen (H_2). Professor Green continues as the department's postdoctoral officer and as the chair of the Institute's Faculty-Postdoc Advisory Committee.

This year, Professor Paula Hammond was elected to the National Academy of Science, making her one of a very small group of people who are members of all three National Academies (Engineering, Science, and Medicine), joining the company of Chemical Engineering faculty members Chakraborty and Langer. She will receive AIChE's Margaret H. Rousseau Pioneer Award for Lifetime Achievement by a Woman Chemical Engineer on November 10, 2019, at the annual meeting in Orlando, FL. The award honors the memory of Margaret Hutchinson Rousseau, who was the first woman to earn a PhD in chemical engineering from MIT, the first woman member of AIChE, the first woman AIChE Fellow, and the first woman to receive AIChE's Founders Award. Professor Hammond was elected to the College of Fellows in the Controlled Release Society in 2019. She also was the Stein-Covestro Lecturer for the Chemistry Department at the University of Massachusetts at Amherst, and gave the UCLA Founders Lecture in 2019. During this past academic year, she gave the Katz Award Lecture at City College of New York and the BASF Distinguished Lecture at Wayne State University. Professor Hammond continues to serve as associate editor for the American Chemical Society journal, *ACS Nano*, and on the scientific advisory board of Moderna Therapeutics. Her research continues to focus on the areas of targeted cancer nanotherapies and immuno-oncology, wound healing, and tissue regeneration, with new technologies also directed at infectious disease, emergency field care medicine, and targeted delivery treatments for osteoarthritis. As department head, Professor Hammond has been working closely with faculty on graduate and undergraduate student culture, the undergraduate curriculum, and increased recruitment of our undergraduate students.

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 the United States, United Kingdom, Ireland, Dubai, and Australia. He is a co-director of the MITEI Low Carbon Energy Center on Carbon Capture, Utilization, and Storage, and, in this role, participated in a number of MITEI workshops and meetings. Hatton is a member of the ENI-MITEI Steering Committee, and is also an adjunct professor at Curtis University in Perth, Australia. Invited keynote and plenary lectures have been delivered at ACS Meetings in Boston (August) and Orlando, FL (April); Fundamentals of Adsorption FOA13 in Cairns, Australia; ELKIN at MIT; and TechConnect in Boston—two talks and a panel. Other talks were given to Federal University of Rio de Janeiro, Brazil; Eni in Milan; ExxonMobil; Columbia University; University of KwaZulu-Natal in South Africa; Penn State; GHGT 14 in Melbourne, Australia; as well as by group members at professional society meetings both domestically and internationally.

Professor Klavs F. Jensen conducted research with colleagues in the Departments of Chemical Engineering, Chemistry, and EECS on the DARPA Make-It Program to develop machine learning algorithms for planning organic synthesis and to realize a robotic system for automated chemical synthesis. The team combined artificial intelligence-driven synthesis planning from historical data and a robotically controlled experimental platform to realize 15 drug or drug-like substances. The lab also continued its efforts to use automated platforms to optimize chemical reactions and extract chemical kinetics. With Professor Barzilay, Professor Jensen continued to co-direct the MIT-industry consortium on Machine Learning for Pharmaceutical Discovery and Synthesis. During the past academic year, he gave plenary lectures on microfluidics and flow chemistry technology at international conferences and at universities, including the John Prausnitz American Institute of Chemical Engineers Institute Lecture. He served on scientific advisory boards to chemical engineering departments, research institutes, and companies.

Professor Jesse H. Kroll and his group continued their research on the organic chemistry of the atmosphere, the formation of atmospheric particulate matter, and distributed air quality measurements. Specific topics of interest have included comprehensive measurements of organic carbon, the chemical fate of wildfire smoke, and new techniques for measuring atmospheric composition; the group also began new projects on the atmospheric chemistry of organosulfur compounds, organic and inorganic nitrate particles, and volatile organic compounds in indoor air. In AY2019 Kroll served as chair of the 2019 Atmospheric Chemical Mechanisms conference, was a member of the scientific steering committee for the International Global Atmospheric Chemistry conference, and joined the board of directors for the American Association of Aerosol Research. In July 2018 he began serving as director of the R. M. Parsons Laboratory for Environmental Science and Engineering, located in Building 48 on MIT's campus.

Associate Professor Heather J. Kulik leads a group that carries out interdisciplinary research in computational, first-principles modeling and machine learning for accelerated inorganic design and large-scale, predictive modeling of catalyst (both biological and nonbiological) and materials properties. Major accomplishments in the past year have included discovery of unique protein-substrate interactions critical for natural product biosynthesis and methyltransferases as well as new methods in machine learning to predict calculation outcomes and quantify uncertainty. This past year, she received the *Journal of Physical Chemistry* lectureship (ACS PHYS Division award), an AAAS Marion Milligan Mason Award, and an NSF CAREER Award. She has traveled extensively, presenting over 30 talks in the past year, both at national and international conferences and universities. This past year, she published 16 peer-reviewed papers, including invited articles as an Inorganic Chemistry Emerging Investigator, Frontiers in Chemistry Rising Star, and a Reaction Chemistry and Engineering Emerging Investigator. Her group's research is supported by DOD, DOE, and NSF, in addition to collaborations with industry. Kulik teaches 10.37 Chemical Kinetics and Reactor Design and continues to develop her elective in computational chemistry, 10.637 Quantum Chemical Simulation, which provides an immersive experience in simulation and is well received both across the Institute and by neighboring institutions. The Kulik group consists of four postdocs, nine graduate students, and several visiting and undergraduate researchers.

Throughout 2018 and early 2019, Professor Robert Langer received honorary degrees from Columbia University, the University of Illinois, the University of Limerick in Ireland, and Université Laval in Quebec, Canada. He received the American Chemical

Society Leadership Award for Historic Scientific Advancement, the Alpha Omega Dental Fraternity Achievement Medal Award, the Hope Funds for Cancer Award of Excellence in Basic Sciences, and the Dreyfus Prize in the Chemical Sciences. Professor Langer presented the Ferenc Jolesz Memorial Lecture (12th Interventional MRI Symposium), as well as lectures for the New York Stem Cell Foundation Fellowship Alumni Meeting and the Broad Institute. He also presented for the Netherlands Life Sciences and IVA Royal Swedish Academy of Engineering. He became an Elected International Fellow of the Royal Society of Canada and was named one of five US Science Envoys for 2018.

Professor J. Christopher Love continued to advance his research to address the speed of development and accessibility for new biopharmaceuticals and vaccines. The collaboration involving MIT, Rensselaer Polytechnic Institute, and the Barnett Institute at Northeastern University published its demonstrations of an integrated, bench-top manufacturing system and its operation to produce clinical-grade examples of three recombinant biopharmaceuticals in *Nature Biotechnology* in October 2018. The lab is following on the successes of this work and related efforts on ultra-low cost vaccines to pursue additional new targets for medical countermeasures and vaccines. In addition, these successes also facilitated the launch of the AltHost Research Consortium to advance an open-source model for developing alternative hosts with the industry. The lab continued its productive collaborations with Professor Alex Shalek to advance its jointly developed technologies for single-cell RNA sequencing using arrays of nanowells, including improved chemistries for cDNA synthesis and capture of specific immune receptors used by T cells important for characterizing immune responses in disease and interventions. He helped co-found two new spin-off companies aiming at commercializing single-cell analytical technologies developed at MIT (Honeycomb Biotechnologies and OneCyte Biotechnologies). He also continued serving as a scientific advisor to several groups in biomanufacturing and immunotherapies and participated on the steering committee for the Society for Biological Engineering Accelerating Biopharmaceutical meeting.

Professor Karthish Manthiram, the Warren K. Lewis Career Development Professor of Chemical Engineering, leads a research group that develops methods by which air, water, and renewable electricity can be used to make all the chemicals and materials we use in our everyday lives. The current members of the group (eight graduate students, two postdocs, and two undergraduate students) have developed new technologies in the past year to synthesize carbon-neutral fuel, fertilizers, and plastics. His research is supported by Cenovus Energy, Oprex, 3M, J-WAFS, MITEI, and Lincoln Laboratory. In 2019, Professor Manthiram received the 3M Nontenured Faculty Award, the American Chemical Society Petroleum Research Fund Doctoral New Investigator Award, and the Young Innovator in NanoEnergy Award. He continues to develop new methods of increasing student engagement in heat and mass transfer, 10.302 Transport Processes, and 10.426/10.626 Electrochemical Energy Systems, for which he was awarded the Outstanding Graduate Teaching Award in 2019.

Professor Allan S. Myerson continued his research on fundamental and applied problems in crystallization and pharmaceutical manufacturing. He continued his work as a principal investigator in the Novartis-MIT Center in Continuous Manufacturing and the DAPRA project, Pharmacy on Demand, which involves the development of a tabletop pharmaceutical manufacturing device. The third edition of Professor Myerson's co-edited book (along with Alfred Y. Lee and Deniz Erdemir) *The Handbook of Industrial Crystallization* was published in June 2019 by Cambridge University Press. Professor Myerson serves as an associate editor of the ACS Journal *Crystal Growth and Design*. He serves on scientific advisory boards of BlueSpark, a company which develops novel flexible batteries, and Continuus Pharmaceuticals.

Associate Professor Bradley D. Olsen was on sabbatical as a visiting professor at the State University of Campinas in Brazil. There, he worked on projects exploring how biomass may be used to produce new sustainable chemistries for a variety of different applications. During this time, Olsen also won the Young Investigator Award from the State Key Lab for the Molecular Engineering of Polymers in Shanghai, China. Olsen's research group continued its work in the areas of bioinspired and biofunctional polymers and polymer networks, with new areas of emphasis in sustainability, informatics, and automation. The group published 13 papers. Major accomplishments included the development of a new chemoinformatics language for polymer science, a new theory for predicting the properties of networks with high defect concentrations, and development of high throughput methods for screening protein-based materials libraries. In Brazil, Olsen served as an instructor for IQ401, the local equivalent of MIT's chemical engineering thermodynamics for graduate students, and participated as a reader on two PhD dissertations and one masters thesis.

Professor Kristala L. J. Prather is the Arthur D. Little Professor of Chemical Engineering and a member of the Synthetic Biology Center at MIT. Her research continues to focus on microbial synthesis of chemical compounds. She plays an active role in service to the scientific community through several scientific advisory and editorial boards, including service as an associate editor of *ACS Synthetic Biology* and *Metabolic Engineering Communications*; as co-chair of two international meetings (Metabolic Engineering 13 in 2020 and Biochemical and Molecular Engineering 12 in 2021); and as vice president of the International Metabolic Engineering Society. Prather is also a member of the DOE Biological and Environmental Research Advisory Committee. In February, she was inducted as a fellow of the American Association for the Advancement of Science. Within MIT, Prather serves as director of the long-running Fermentation Technology course popularized by Professor Daniel I. C. Wang and offered through the MIT Professional Education program. In addition , she is a core member of the School of Engineering New Engineering Educational Transformation (NEET) Committee, and the faculty co-director of the Energy Biosciences Low-Carbon Energy Center of the MIT Energy Initiative. This year, she completed a two-year appointment as a provost's representative to the Faculty Policy Committee. Beginning July 1, she will begin a one-year term of service as chair of the Committee on Academic Performance. Within the department, Prather chairs the Task Force on the Undergraduate Curriculum, which has shepherded significant changes to the SB degree requirements. Changes implemented thus far have been well received by the students, with additional modifications planned for adoption over the next academic year.

Professor Gregory C. Rutledge and his research group develop molecular simulations for the study of fundamental process-structure-property relationships in polymers.

Areas of particular interest currently are crystallization kinetics and thermomechanical properties of polymers with complex morphologies. This year, his collaboration with Richard Braatz and ExxonMobil to define a materials genome of nucleating agents for semicrystalline polymers, sponsored by the NSF, was highlighted by the Materials Research Society in a short video at the national meeting in Boston. The group is 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. Their work on the use of 3D imaging to understand how emulsified oil is removed from water during microfiltration appeared this spring on the MIT News website, as well as several other media outlets. Professor Rutledge continues to serve as lead PI for technical, education, and workforce development activities related to MIT's membership in Advanced Functional Fabrics of America, a manufacturing innovation institute headquartered in Cambridge, MA, whose mission is to enable a manufacturing-based revolution in fibers, yarns, and fabrics. In collaboration with the Fashion Institute of Technology (FIT) in New York City, he oversaw the development of the second FIT/MIT Workshop on Advanced Fibers and Fabrics, bringing together students with diverse interests in design, fashion, engineering, and materials, to rethink the clothing of the future. In teaching, Professor Rutledge leads the junior- and senior-level courses 10.26/10.27/10.29 Chemical Engineering Projects Laboratory, which was also profiled on the MIT News website in May 2019. He has been an active member of the Chemical Engineering Undergraduate Curriculum Task Force, led by Kristala Prather, and serves as chair of the Laboratories Focus Group. At the graduate level, he is reinventing 10.568 Physical Chemistry of Polymers, a core class for the Program in Polymers and Soft Matter. Over the past year, Professor Rutledge delivered numerous keynote or invited lectures in Australia, China, and the United States. He continues to serve as editor for the *Journal of Materials Science*.

Professor Hadley D. Sikes, Esther and Harold E. Edgerton Career Development Chair, was promoted to the rank of associate professor with tenure. She continued to lead her team in using an engineering design-based approach to invent and integrate protein and polymer technologies into point-of-care medical diagnostic tests. In addition to ongoing clinical studies with partners in Boston-area hospitals and in the Asia Pacific as part of the Singapore-MIT Alliance for Research and Technology's Antimicrobial Resistance Integrated Research Group, Professor Sikes and her team engaged with several industrial partners to work on scale-up and commercialization of their new medical tests. Professor Sikes served her research communities as an editorial advisory board member for two journals of the American Chemical Society, *ACS Applied Bio Materials* and *Chemical Research in Toxicology* and her undergraduate alma mater by joining its external advisory board.

Professor Zachary P. Smith joined the Department of Chemical Engineering in January 2017 and currently holds the Joseph R. Mares Career Development Chair. He is a recipient of the Department of Energy Early Career Award, the American Chemical Society Petroleum Research Fund Doctoral New Investigator Award, and the North American Membrane Society Young Membrane Scientist Award. He also served as a committee member for the National Academies of Sciences, Engineering, and Medicine to help write the recently published report "A Research Agenda for Transforming Separation Science." His research focuses on the development of polymers and porous materials for applications in energy-efficient separations. In 2019, the Smith lab grew to seven PhD students, four postdoctoral scholars, and four undergraduate researchers. Invited seminar presentations have been presented to Auburn University and at the ACS National Meeting in both the Division of Inorganic Chemistry and the Division of Polymer Chemistry. An invited seminar will be presented at the Georgia Institute of Technology later this year. Group members have been awarded several recognitions, including a Ford Fellowship, the National Science Foundation Graduate Research Fellowship, and an Energy Fellows Fellowship through MITEI. Several papers related to transport characterization and materials development have been published in *Advanced Materials*, *ChemSusChem*, *AIChE Journal*, *Macromolecules*, and *ACS Applied Materials & Interfaces*. A featured article in MIT News was released earlier this year related to the *Advanced Materials* publication, and seed funding through the Deshpande Center has been awarded to consider translating this work into a potential startup company. Professor Smith taught 10.569 Synthesis of Polymers in the spring term and will teach 10.467 Polymer Science Laboratory in fall.

Professor Gregory Stephanopoulos, the W. H. Professor of Biotechnology and Chemical Engineering, continued as director of the Metabolic Engineering Laboratory, supervising research on engineering microbes for the production of fuels and chemicals. Notable research achievements this year include the discovery of a new pathway for the synthesis of isoprenoid compounds and the development of substrate co-feeding methods for maximizing the performance of engineered microbes with applications to the fixation of CO_2 into acetate and conversion of the latter into lipids and liquid fuels. The ultimate goal of this work is the replacement of fossil feedstocks and advancing the vision of a biobased economy. Professor Stephanopoulos graduated three doctoral students and continued serving on the advisory boards of four academic institutions and the managing board of the Society for Biological Engineering. He delivered the 2019 Chairman's Distinguished Lecture at the University of Washington. He continued to serve as editor-in-chief of the journal *Current Opinion in Biotechnology*, and on the editorial boards of eight other scientific journals. Besides numerous research presentations at professional societies' meetings, he also delivered plenary and keynote lectures at the Metabolic Engineering Conference in Munich, Germany, in June 2018; the International Biotechnology Symposium in Montreal in June 2018, and a symposium on biology for the production of chemicals at Academia Sinica, Taipei, in June 2019. This year Professor Greg Stephanopoulos was honored with the Gaden Award of the American Chemical Society BIOT Division.

Professor Michael S. Strano, the Carbon P. Dubbs Professor, has continued his research at the interface of nanotechnology and chemical engineering. In the past year, his laboratory has pioneered a new field of synthetic, cell biological-sized autonomous electronic devices called Colloidal State Machines, capable of bringing electronic functions such as sensing, memory, computation and communication to environments only accessible to micron-sized particles. Over the past year, his laboratory published two papers, one in *Nature Nanotechnology* on aerosolizable electronics and another in *Nature Materials* on a new technique called autoperforation as a fabrication method. A newly awarded multiuniversity team grant will explore the topic of emergent computation with these new systems. Professor Strano continues his work as lead principal investigator of the Disruptive and Sustainable Technology for Agricultural Precision (DiSTAP) IRG in the MIT-Singapore SMART program. DiSTAP completed a highly successful first year after its start in January 2018. It is focused on next-generation sensors and analytical instrumentation, plant delivery, and environmental tools for the urban farms of the future. In February 2019, the Strano laboratory published a pioneering paper in *Nature Nanotechnology* on nanocarriers capable of organelle specific delivery to plants. The work was highlighted by the prime minster of Singapore at a spring media event. Professor Strano is also the founder and scientific director of the Center for Enhanced Nanofluidic Transport. This $11 million Energy Frontier Research Center funded by the DOE starting July 2018 includes three other Course 10 PIs at MIT, and 12 other national academics. CENT focuses on understanding fundamental questions of nanofluidic transport. In June 2019, Professor Strano was one of five global thought leaders featured at the WATS Forum in Bangkok, Thailand, where he delivered an address highlighting the transformative potential of nanotechnology and plant biology. Strano continues his editorial duties at the journals *Carbon* and *Advanced Energy Materials*, and has recently joined the editorial board of *Scientific Advances.*

Professor James 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 meso-scale, and application of those methods to materials of industrial and societal interest, including food and consumer care products, and bio-pharmaceuticals. His work was featured in 10 peer-reviewed publications, including a feature on the cover of the *Journal of Fluid Mechanics* and articles in *Nature Communications* and the *Proceedings of the National Academy of Sciences*. The Swan group currently has six graduate students, three undergraduates (as part of the UROP program), and hosted several international students in the spring and fall. James Swan was promoted to associate professor without tenure this spring and was awarded the MIT Class of '22 Professorship.

Professor William A. Tisdale, the ARCO Career Development Professor in Energy Studies, was promoted to associate professor with tenure in 2019. His research is dedicated to the development of novel, solution-processable semiconductor nanomaterials for use in next-generation energy technologies. Significant research accomplishments during the past year include the development of a class of 2D, hybrid, organic-inorganic lead halide perovskite materials with potential in solid state lighting, lasers, and photovoltaics, and the identification of a key defect limiting the performance of lead sulfide (PbS) quantum dots in solar cells (published in the inaugural issue of *Matter*). His research accomplishments have been recognized through numerous awards, including the Presidential Early Career Award in Science and Engineering and the DOE's Early Career Award. In 2019, Professor Tisdale will deliver plenary lectures at the AIChE Annual Meeting and the nanoGE conference in Berlin, Germany. This past year, Professor Tisdale worked closely with Professor J. Christopher Love to revitalize Course 10's sophomore-level thermodynamics subject, 10.213 Chemical and Biological Engineering Thermodynamics. The revised subject earned its highest overall rating in the past 20 years, and Tisdale was selected by the students to receive this year's C. Michael Mohr Outstanding Undergraduate Teaching Award. Outside of Course 10, Professor Tisdale serves on the NEET Renewable Energy Machines Task Group and is faculty advisor to the student-led Baker Foundation advisory committee.

Professor Bernhardt L. Trout wrapped up his role as director of the Novartis-MIT Center for Continuous Manufacturing, an $85 million, 12-year partnership. In addition, he developed and continues to teach with colleagues the seminal 10.01/16.676/20.005/22.014 Ethics for Engineers course, which educates close to 15% of the MIT student body on ethical issues related to engineering. The program enhances the breadth and depth of engineering students' knowledge, teaching them the connections between engineering and society. His laboratory focuses on pharmaceutical small molecule manufacturing and biopharmaceutical formulation and stabilization, including predictive methods that are used by pharmaceutical companies around the world. He is a consultant to the FDA, a member of a USP panel, and co-chair of the International Symposium on Continuous Manufacturing of Pharmaceuticals. He delivered many invited talks, research papers, and patents. He is on the scientific advisory boards of several major companies and involved in several startup companies.

Research Highlights

Advancing Lithion-Ion Battery Predictions Via Multiscale Modeling and Machine Learning (Richard D. Braatz)

Lithium-ion batteries are deployed in a wide range of applications due to their low and falling costs, high energy densities, and long lifetimes. Accurate, early prediction of future battery degradation and lifetime would unlock new opportunities in battery production, use, and optimization. For example, manufacturers could accelerate the cell development cycle, perform rapid validation of new manufacturing processes, and sort and grade new cells by their expected lifetime. In addition, advanced battery management systems could better manage these rechargeable batteries, to better protect against unsafe operations, monitor the battery states, control their operation, and balance battery packs so as to improve the available capacity and increase each cell's longevity. An emerging application enabled by early prediction is high-throughput optimization of processes spanning large parameter spaces, such as multistep fast charging, which are otherwise intractable due to the extraordinary time required for the experiments. The task of predicting lithium-ion battery lifetime is critically important given its broad utility but challenging due to nonlinearity of degradation with cycling and wide variability, even when controlling for operating conditions.

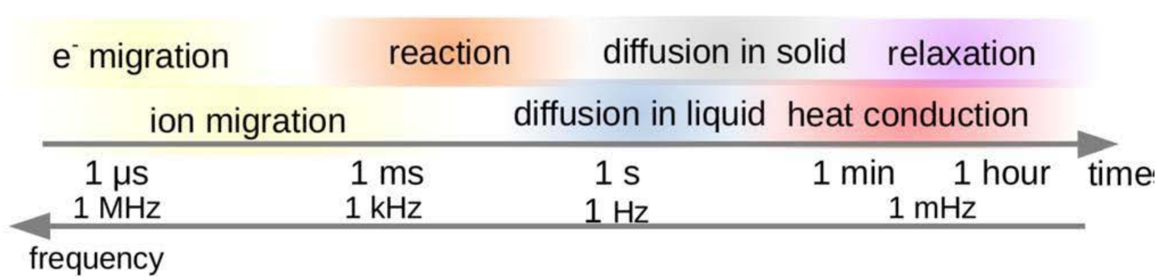

Figure 1. Dynamic processes in lithium-ion batteries with typical range of their time constants. Aging and degradation processes cover an even wider range.

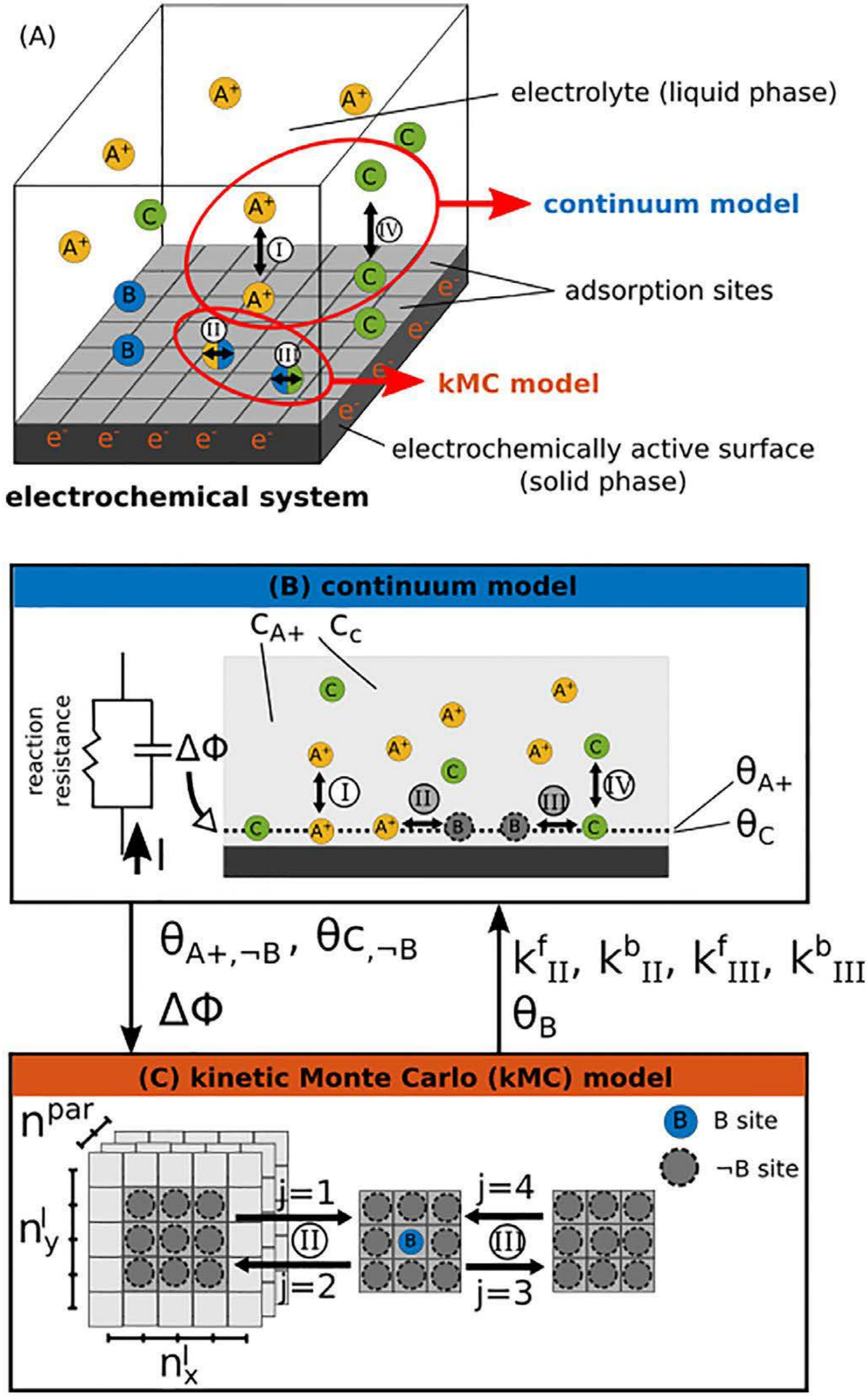

Figure 2. Schematic of (A) an electrochemical system and its multiscale simulation that dynamically couples (B) continuum and (C) molecular kMC models.

Multiscale Models

Physicochemical models have been developed for modeling battery degradation, which account for diverse mechanisms, such as lithium plating, active material loss, and impedance increase. Multiscale simulation models have been developed that dynamically couple continuum electrochemical kinetic and transport models with molecular models of surface film growth mechanisms, to capture the large span of time and length scales. Such models enable detailed investigations into the spatiotemporal evolution of all states in a lithium-ion battery—including temperature, potential, current densities, and electrolyte and solid-state compositions—and to simulate key phenomena, such as heterogeneous surface film growth that are not captured by continuum or molecular models individually.

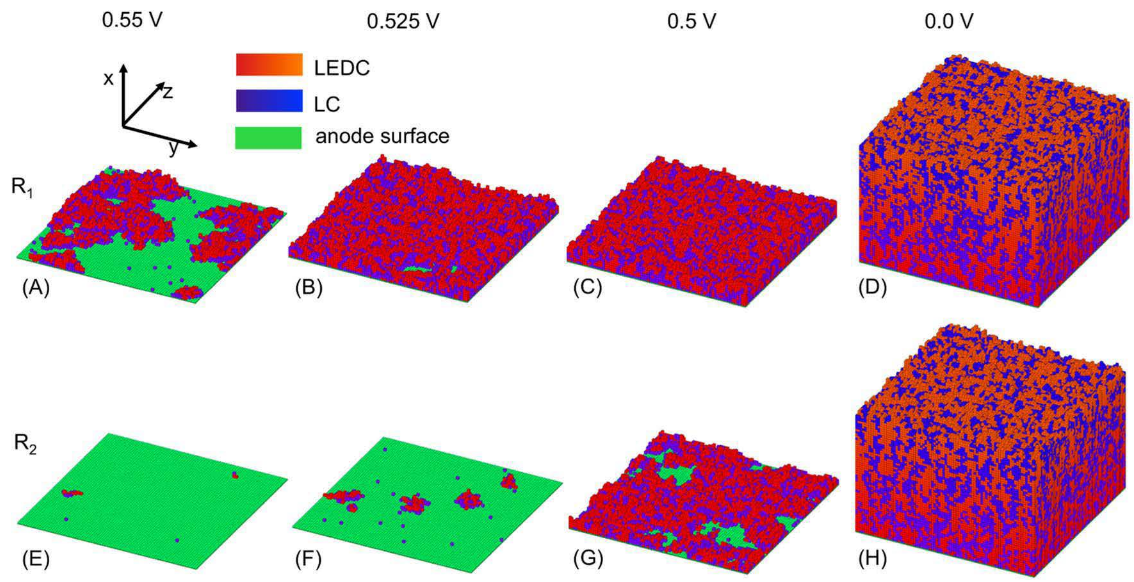

Figure 3. Configurations of the dense surface film on an electrode particle of radius R1 = 3 µm (A–D) and R2 = 10 µm (E–H) at electrode potentials of 0.55 V (A,E), 0.525 V (B,F), 0.5 V (C,G), and 0.0 V (D,H) during the film formation process.

Machine Learning

While multiscale models have shown some success in predicting battery degradation and lifetime, developing such models that describe full cells cycled under relevant operating conditions (for example, fast charging) remains challenging, given the many degradation modes and their coupling to thermal and mechanical heterogeneities within a cell. Approaches using machine learning to predict cycle life are alternatives that would be especially useful for application to the promising new battery chemistries and materials that are being invented, which have significant improvements over today's commercial batteries but for which much less qualitative and quantitative information is known about their degradation mechanisms. Recently, advances in computational power and data generation have enabled machine learning techniques to accelerate progress for a variety of tasks, including the prediction of material properties and materials discovery for energy storage. A growing body of literature applies machine learning techniques for predicting the remaining useful life of batteries using cycling data collected during operation. These works make predictions after accumulating data corresponding to degradation of at least 25% along the trajectory to failure or using specialized measurements. Accurate, early prediction of cycle life with significantly less degradation is challenging because the associated physiochemical mechanisms are highly nonlinear, the capacity degradation is negligible in early cycles, the lifetimes vary between batteries even when purchased from the same commercial production lot and the operating conditions are identical, and the relatively small quantity of datasets that span a limited range of lifetimes. Machine learning approaches are especially attractive for high-rate operating conditions where multiscale simulation models of battery degradation are often unavailable. In short, opportunities for improving upon state-of-the-art prediction models include higher accuracy, earlier prediction, greater interpretability, and broader application to a wide range of cycling conditions.

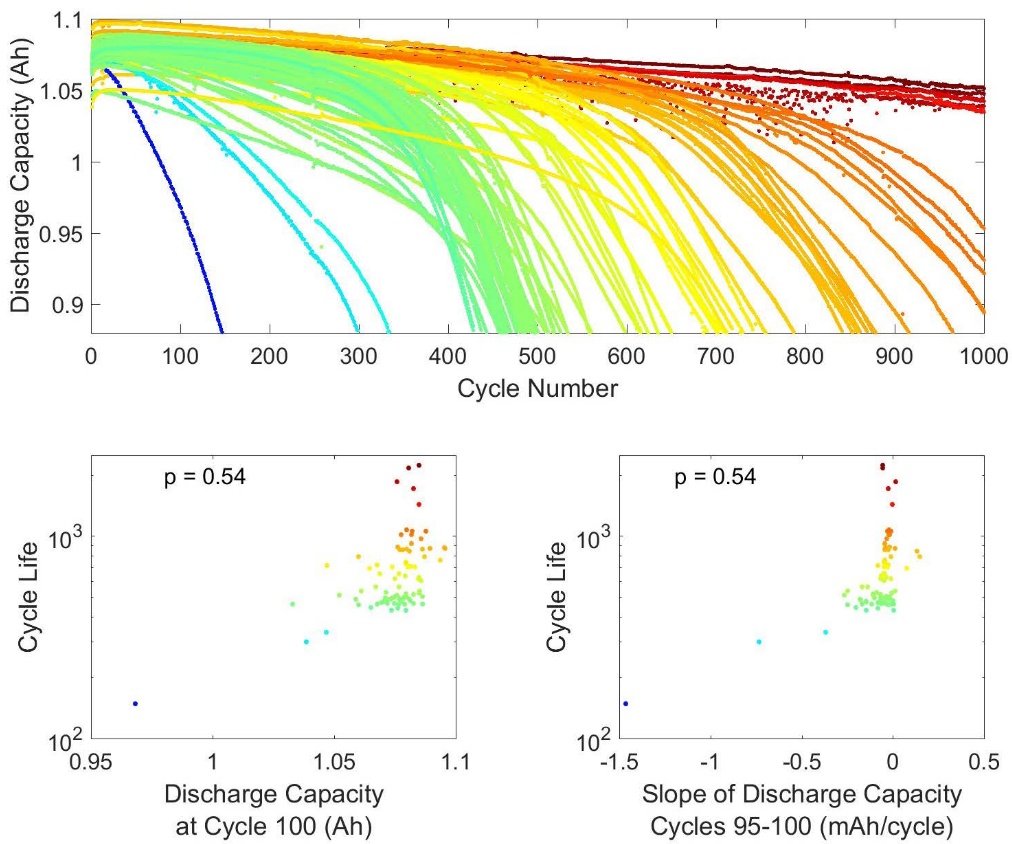

Figure 4. The discharge capacity in the first 100 cycles is a poor predictive of future discharge capacity, as shown for LFP/graphite cells. The color of each curve is scaled by the battery's cycle life.

This year, MIT faculty from Chemical Engineering (Braatz, Bazant), along with colleagues at Stanford University and Toyota Research Institute, developed new machine learning models that accurately predicted the cycle life of commercial lithium iron phosphate (LFP)/graphite cells using early-cycle data, without feeding any prior knowledge of degradation mechanisms to the machine learning algorithms. LFP/graphite was used in this study due to its high specific capacity, low cost, and its low toxicity, which is why LFP/graphite is used commercially in many applications, including electric vehicles, utility-scale stationary applications, and backup power. We generated a dataset of 124 cells with cycle lives ranging from 150 to 2,300 using 72 different fast-charging conditions, with cycle life (or equivalently, end of life) defined as the number of cycles until 80% of nominal capacity (figure 4). For quantitatively predicting cycle life, we developed feature-based machine learning models that can achieve prediction errors of 9.1% using only data from the first 100 cycles, at which point most batteries have yet to exhibit capacity degradation. Furthermore, using data from the first five cycles, we demonstrate classification into low- and high-lifetime groups with a misclassification test error of 4.9% (figure 5). These results illustrate the power of combining data generation machine learning to predict the behavior of lithium-ion batteries far into the future.

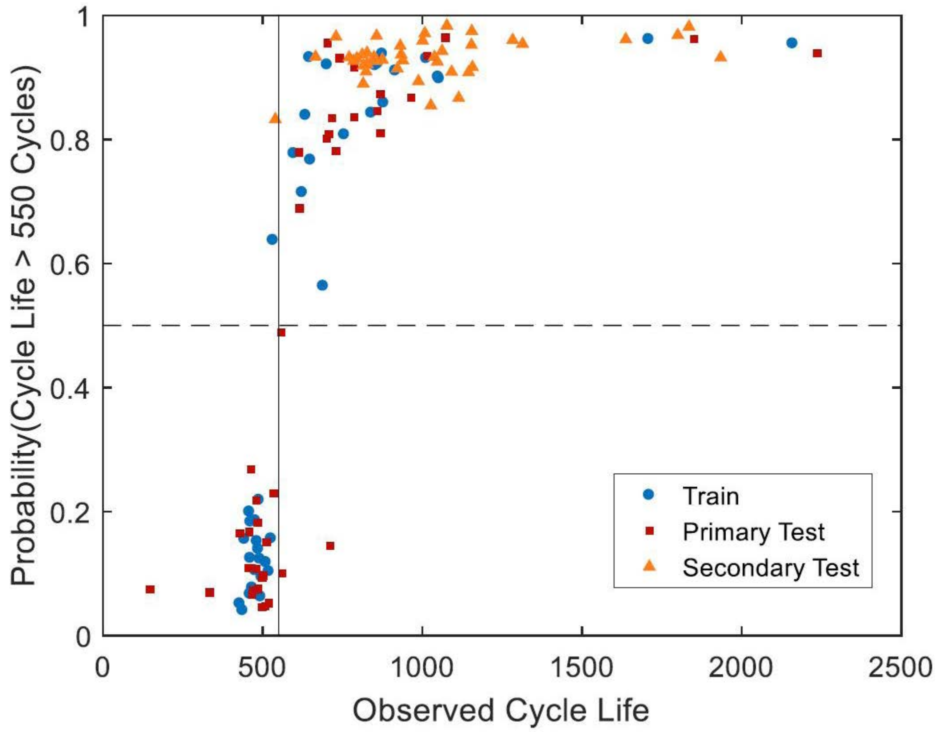

Figure 5. The probability of a battery's lifetime exceeding a lifetime threshold of 550 cycles vs. observed cycle life using the full classifier. The decision boundary is 0.5. Five cycles were used in this classification task.

Our results were published as the cover article of the May 2019 issue of *Nature Energy*. The battery cycling data and associated codes were released via GitHub so that other groups can apply or develop additional machine learning or other approaches for battery lifetime prediction. The article was picked up by a large number of news venues, including Science Daily, Green Car Congress, and AAAS EurekAlert! The journal paper was also discussed in a one-page article in *Nature*.

Cost-Targest Design of Redox Flow Batteries for Grid Storage (Fikile R. Brushett)

Energy is essential to modern society and the abundance, availability, and affordability of liquid fossil fuels has been a key driver of the past century's progress. However, with global energy demand projected to double, there is an increasingly urgent need to decouple carbon emissions from economic activity without stifling economic growth. Electrochemical processes are poised to play a pivotal role in the evolving global power system as the efficient interconversion of electrical and chemical energy can enable the deployment of green technologies that support the decarbonization of the electric grid, power the automotive fleet, and offer new opportunities for chemical manufacturing. Meeting these emerging energy needs requires transformational changes as the stringent performance, cost, and scale requirements cannot be met by many of today's electrochemical technologies. While continued, incremental improvements are expected for present generation systems, market and societal forces require the development of novel chemistries and cell configurations. Designing, controlling, and manipulating charge storage and conversion processes at the molecular level is challenging and continues to be a poorly understood topic. Further, our ability to deconvolute the thermodynamic, kinetic, and transport processes under reaction conditions is still quite limited and is often challenged by the interdependence of multiple processes on the same few variable parameters. Moreover, to be commercially viable, cost-conscious solutions must be developed to overcome major scientific and engineering hurdles. Thus, it is important to pursue target-informed research approaches with an emphasis on developing experimental and modeling tools to elucidate critical materials properties under well-controlled but application-relevant conditions.

In pursuit of these goals, the Brushett group seeks to understand and control the fundamental processes that govern the performance, cost, and lifetime of present day and next-generation electrochemical systems for energy storage and conversion. Our approach combines synthesis and characterization of redox active materials, design and engineering of electrochemical reactors, and techno-economic modeling of electrochemical systems. The group places a strong emphasis on connecting system-level performance and cost goals to materials-level property requirements and on leveraging this knowledge to guide exploration of new chemistries and reactor designs. Ultimately, the group aims to develop robust and portable guiding principles for the design of materials, processes, and devices that harness electrochemical phenomena to address important challenges in grid energy storage, environmental stewardship, and chemical manufacturing.

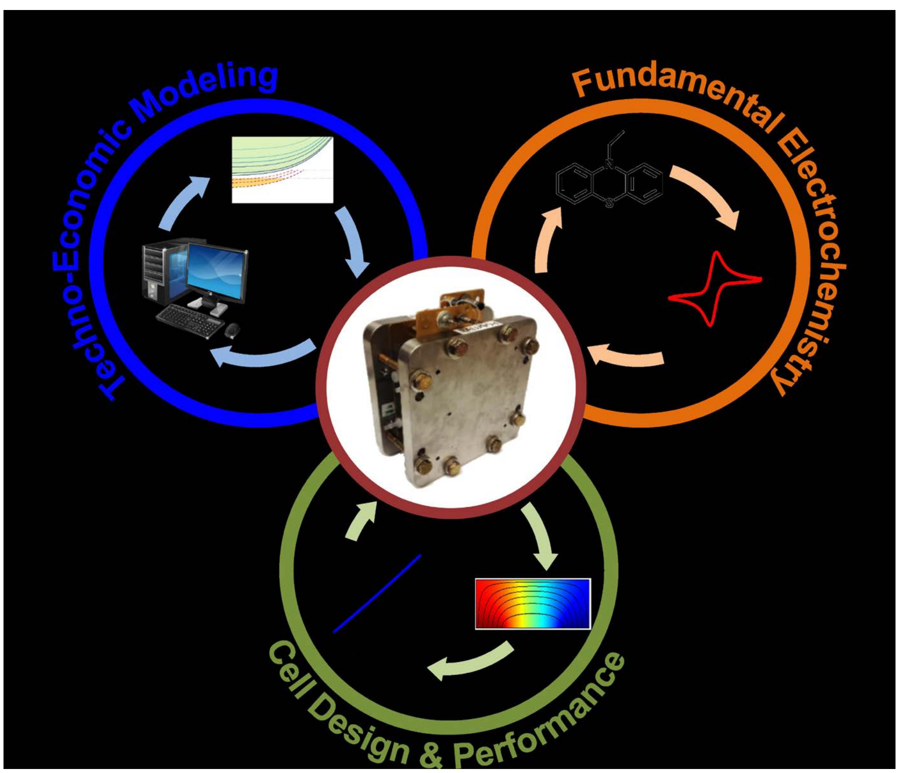

Figure 6. The Brushett group's approach integrates fundamental electrochemistry, cell design and performance analysis, and technoeconomic modeling to accelerate the development of new electrochemical systems for grid storage, environmental remediation, and chemical manufacturing.

Wind and solar generation can displace carbon-intensive electricity if their intermittent output is cost-effectively reshaped using electrical storage to meet user demand. Reductions in the cost of storage have lagged those for a generation, with pumped-storage hydropower (PSH) remaining today as the lowest-costing and only form of electrical storage deployed at multi-gigawatt hour scale (typically 6–10 hour discharge daily). A key feature of PSH is the combination of an inexpensive storage media (water transferred between reservoirs at different elevations) with power-converting turbines. Consequently, at long storage durations, the cost contribution of the turbines is minimized and system cost asymptotically approaches the cost of the working fluid. Over the past 25 years, there have been few new PSH installations due to the difficulty of permitting new sites and financing large projects. Redox flow batteries (RFBs) represent an appealing electrochemical alternative to PSH. In a typical RFB, two redox species, operating at different electrode potentials, are dissolved in liquid electrolytes, which are stored in tanks and pumped to a power-converting reactor where they are oxidized and reduced to alternately charge and discharge the battery. The decoupling of power and energy enabled by the RFB architecture offers a pathway to extremely low capital costs and long operational lifetimes at significantly higher energy densities (a smaller system footprint) and relaxed siting constraints as compared to PSH. Despite this promise, the RFB is a nascent technology platform and current state-of-the-art systems, based on vanadium salts dissolved in acidic aqueous electrolytes, are too expensive (approximately three to four times) for broad deployment inspiring research efforts on new redox chemistries, electrolyte formulations, and reactor designs.

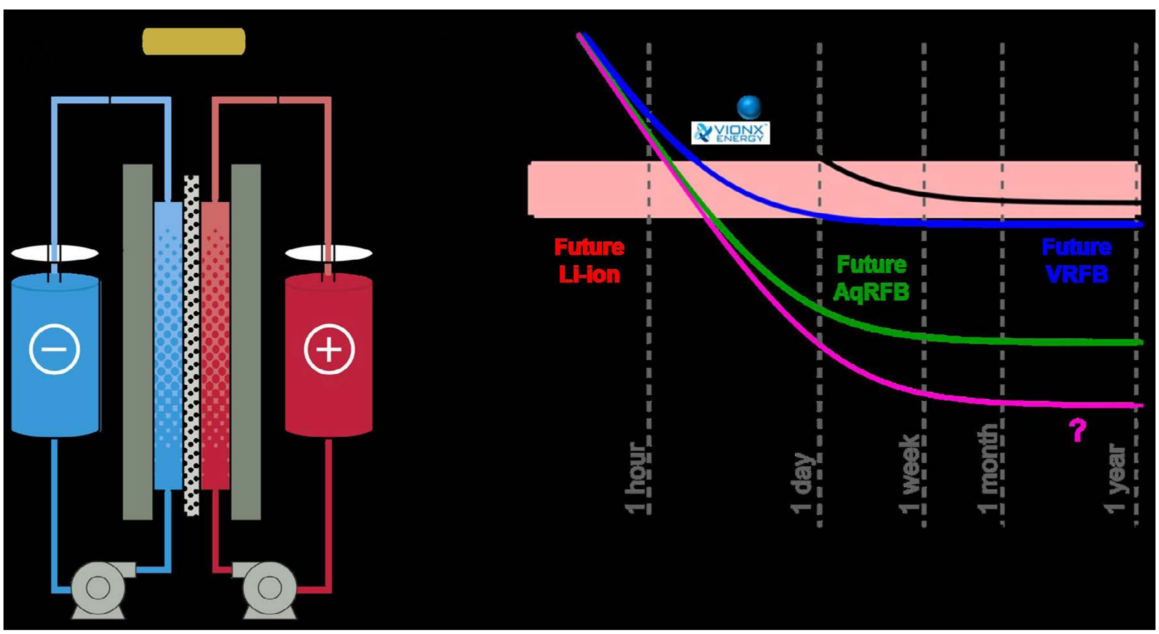

Figure 7. Generic schematic of a redox flow battery and a representation of the value of decoupled power (P) and energy (E) scaling via model outputs of battery capital cost as a function of discharge duration (E/P) for a range of present and future RFBs as compared to lithium-ion batteries where VRFB is vanadium RFB and AqRFB is aqueous RFB. The present VRFB and future lithium-ion costs are validated with other literature models, Vionx Energy cost estimates, and the Lazard energy storage report. Future VRFB cost reductions assume economies of scale, cheaper stack components, and reduced chemical costs. Future AqRFBs cost reductions anticipate a slight performance boost and significantly cheaper chemicals.

While the breadth and diversity of research campaigns undertaken to lower the cost of RFBs is promising, ultimately economic considerations remain a primary driver to technology adoption, thus, even at an early stage, there is a need to establish performance benchmarks, identify technical hurdles, and guide research focus. Along with colleagues in the Joint Center for Energy Storage Research, a US Department of Energy-funded energy innovation hub, we developed techno-economic models to quantify and compare the performance and economic potential of a diverse set of existing and conceptual grid batteries for a range of applications. The open-source and flexible modeling framework can be used to "back-translate" from system-level performance and cost goals to materials and component-level targets, to "forward evaluate" the challenges, costs, and ultimate performance of different technology approaches, and to chart progress and allocate limited resources most effectively. Through TE modeling, we were the first to determine that both aqueous and nonaqueous RFBs are viable technology platforms for meeting the DOE's recommended capital cost targets (for 5–10 hour storage) and established preliminary criteria for meeting these targets. Further, this work highlighted an emerging opportunity for non-vanadium aqueous RFB chemistries (e.g., redox active organics, commodity-scale inorganics). We then developed detailed selection criteria for nonaqueous and aqueous RFB electrolytes including explicit design maps that illustrate pathways to battery systems below DOE targets.

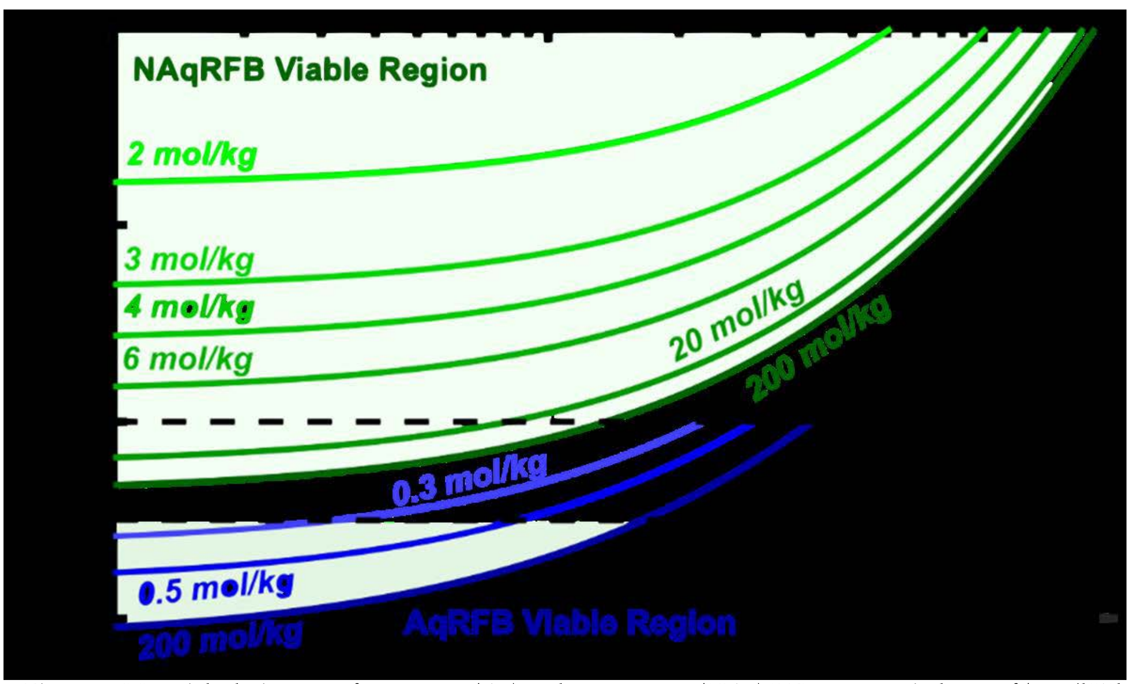

Figure 8. Materials design map for aqueous (Aq) and nonaqueous (NAq) RFBs at a capital cost of $100/kWh. The shaded regions represent viable design spaces for AqRFBs and NAqRFBs as a function of cell voltage, area-specific resistance, and active species concentration. Key property sets and tradeoffs can be extracted from these plots.

Knowledge of the critical sets of interdependent, cost-constraining variables motivates new innovative target-informed science. For example, as fluorinated supporting salts are the most expensive component in nonaqueous RFBs, we demonstrated, for the first time, supporting salt free flow cells enabled by the incorporation of ionic pendants onto the active species to enable permanent charge across all redox states. Recently, as many emerging inexpensive aqueous redox couples are incompatible with conventional acidic electrolytes, we assessed the impact of neutral to alkaline electrolytes and membranes on overall RFB performance and cost finding and discovered that the combination of size-exclusion separators and larger molecules hold particular promise for low-cost storage in the near-term future. Most recently, we have used the modeling toolkit to assess the design space for longer duration energy storage systems (10–100 hour) whose requirements of exceptionally low lifetime costs but reduced power performance challenge incumbent technologies. Using alkaline polysulfides as an inexpensive and abundant negative material, we are investigating different positive redox couples (e.g., polyiodide, oxygen, permanganate), cell formats, and operating strategies (crossover-recovery) guided by TE analyses and enabled by application specifications.

Our results represent the first comprehensive and general TE analysis of incipient battery technologies and have been widely adopted by the broader research community as the work provides guidance in materials selection, development, and assessment. Notably, the key technical targets used in the recent ARPA-E IONICS and DAYS programs were based on our modeling work. Moreover, our modeling efforts were one of the drivers for the formation of Form Energy, an MIT startup focused on ultra-long duration energy storage. We are extending our modeling framework to assess other electrochemical systems including carbon dioxide, organic, and water electrolyzers (successfully benchmarked against the DOE's H2A production model), as well as inspiring new technology platforms such as convection-enhanced intercalation batteries that may enable fast charging in vehicles or the use of thick electrodes for stationary storage.

Annual Lectures and Seminars

During AY2019, the Chemical Engineering Department hosted a distinguished group of academic and industry leaders, speaking on topics highlighting cutting-edge research addressing today's energy and health-related challenges.

16th Daniel I. C. Wang Lecture on the Frontiers of Biotechnology (December 7, 2018): "Building T Cell Immunity with Biomaterials"

Professor David J. Mooney, Pinkas Family Professor of Bioengineering at the Harvard School of Engineering and Applied Sciences, and a core faculty member of the Wyss Institute, discussed his work. Mooney's laboratory designs biomaterials to make cell and protein therapies effective and practical approaches for treating disease. He is a member of the National Academy of Engineering, the National Academy of Medicine, and the National Academy of Inventors. He has won numerous awards, including the Clemson Award from the Society for Biomaterials, MERIT Award from the National Institutes of Health, Distinguished Scientist Award from the International Association for Dental Research, Phi Beta Kappa Prize for Excellence in Undergraduate Teaching, and the Everett Mendelsohn Excellence in Mentoring Award from Harvard College. His inventions have been licensed by numerous companies, leading to commercialized products, and he is active on industrial scientific advisory boards.

33rd Hoyt C. Hottel Lecture (October 26, 2018): " Climate Change and How We Can Shift to a Sustainable Future"

Steven Chu, William R. Kenan Jr. Professor and Professor of Molecular and Cellular Physiology at the Medical School Stanford University, presented his thoughts on today's sustainability challenges. He has published over 280 papers in atomic physics, polymer physics, biophysics, biology, biomedical imaging, nanoparticle materials synthesis, batteries, and other energy technologies. He holds 10 patents, and has 11 more patent filings since 2015. Chu was the 12th US Secretary of Energy from January 2009 until the end of April 2013. As the first scientist to hold a cabinet position and the longest serving energy secretary, he recruited outstanding scientists and engineers into the Department of Energy. He began several initiatives, including Advanced Research Projects Agency—Energy, the Energy Innovation Hubs, the annual Clean Energy Ministerial meetings in 2009, and was personally tasked by President Barack Obama to assist BP in stopping the Deepwater Horizon oil leak. Chu is the co-recipient of the 1997 Nobel Prize in Physics for his contributions to laser cooling and atom trapping, and has received numerous other awards.

25th Alan S. Michaels Lecture (April 19, 2019): "Engineering the Genome: How CRISPR Systems Work"

Jennifer Doudna, Professor of chemistry and molecular and cell biology at University of California at Berkeley, discussed her work. Doudna and her colleagues rocked the research world in 2012 by describing a simple way of editing the DNA of any organism using an RNA-guided protein found in bacteria. This technology, called CRISPR-Cas9, has opened the floodgates of possibility for human and non-human applications of gene editing, including assisting researchers in the fight against HIV, sickle cell disease, and muscular dystrophy. Doudna is an investigator with the Howard Hughes Medical Institute and a member of the National Academy of Sciences, the National Academy of Medicine, the National Academy of Inventors, and the American Academy of Arts and Sciences. She is also a foreign member of the Royal Society, and has received many other honors, including the Breakthrough Prize in Life Sciences, the Heineken Prize, the BBVA Foundation Frontiers of Knowledge Award and the Japan Prize. She is the co-author, with Samuel Sternberg, of *A Crack in Creation: Gene Editing and the Unthinkable Power to Control Evolution*, a personal account of her research and the societal and ethical implications of gene editing.

41st Warren K. Lewis Lecture (April 5, 2019): "Bringing Pharmaceutical Manufacturing into the Digital Age"

Mauricio Futran, vice president of Advanced Technology in the Global Tech Services group of Janssen Supply Chain, Johnson & Johnson, lectured on his current research. Futran's work focuses on the understanding and reliability of manufacturing processes. This is done by incorporating predictive modeling, in-line measurements, data analytics, and other technologies into the full range of activities, from research and development through scale-up, technology transfer, and lifecycle management. The ultimate goal is model predictive control and real-time release. Before joining Johnson & Johnson, Futran was professor and chair of chemical and biochemical engineering at Rutgers University, after working for 28 years in various positions in pharmaceutical product and process development at Merck and Bristol-Myers Squibb, where he was vice president of

Process R&D. His areas of expertise include process development, technology transfer, validation, regulatory compliance, new product registration, external manufacturing, and partnership development. Futran is a member of the National Academy of Engineering, where he has been chair of its Chemical Engineering section, and has served on its peer committee; the board of Chemical Sciences and Technology; and an NRC panel. As an AIChE member he has served on the awards committee. He has been a member and chair of the Princeton Chemical and Biological Engineering external board, and has been a member of the external boards for the University of Illinois at Urbana-Champaign, Georgia Tech, and Rutgers.

Department Awards Ceremony

The Department Awards Ceremony took place on May 14, 2018, in the Gilliland Auditorium of the Landau Building (Building 66). We were pleased to recognize this year's recipients of the Outstanding Faculty Awards: James Swan and Karthish Manthiram were the graduate students' choice and Professor William Tisdale was selected by the undergraduate students.

Edward W. Merrill Outstanding Teaching Assistant Award

The Edward W. Merrill Outstanding Teaching Assistant Award was presented to graduate students Mark Payne, Yoshine Sato, and Ryan Shaw for their work during the fall 2018 and spring 2019 terms. The Outstanding Graduate Teaching Assistant Award was presented to PhD student Albert Liu for his work in 10.65 Chemical Reactor Engineering during spring 2019. 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 Michael McEldrew and Katharine Greco.

Chemical Engineering Special Service Awards

Chemical Engineering Special Service Awards were conferred to the members of the Graduate Student Council, the recipients are as follows:

- Patrick Asinger
- Andrew Biedermann
- Sarah Cowles
- Madeline Dery
- Hamid Doost Hosseini
- Natalie Eyke
- Cameron Halliday
- Nidhi Juthani
- Jennifer Kaczmarek
- Joseph Maalouf
- Duncan Morgan
- Tam Nguyen
- Joseph Palmeri
- Lagnajit Pattanaik
- Chen Song
- Thejas Wesley
- Joy Zeng

Members of the Graduate Student Advisory Board were also recognized:

Chun Man Chow
Conor Coley
Supratim Das
Kimberly Dinh
Brook Eyob
McLain Leonard
Bertrand Neyhouse
Kara Rodby
Sarah Shapiro
Kindle Williams

Members of the Graduate Women in Chemical Engineering group were recognized:

Madeline Dery
Katharine Greco
Junli Hao
Yining Hao
Jennifer Kaczmarek
Stephanie Kong
Tam Nguyen
Kelsey Reed
Kara Rodby
Lisa Volpatti
Yen-Ting Wang

Awards were also given to the members of the Resources for Easing Friction and Stress group:

Neil Dalvie
Michael Lee
Natasha Seelam
Kevin Silmore
Jennifer Kaczmarek
Lisa Volpatti

In addition, Michael McEldrew 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:

Andrea Blankenship
Marjorie Buss
Sarah Coleman
Natalie Delumpa-Alexander
Erika Ding
Anjolaoluwa Fayemi
Michelle Huang
Morgan Matranga
Rafid Mollah
Linh Nguyen
Luis Sandoval
Zach Schmitz
Amy Wang
Nancy Wang
Emily Yan
Brian Zhong

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 Rodriguez. 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 Sierra Brooks. 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 was awarded to Nancy Wang and Michelle Huang. Additionally, the 2019 Phi Beta Kappa electees were:

- Saleem Aldajani
- Sierra Brooks
- Angela Cai
- Erika Ding
- Michelle Huang
- Jenny Kang
- Janice Ong
- Chloe Thacker
- Nancy Wang

The department is quite pleased to recognize Sharece Corner and Eileen Demarkles as the department's Outstanding Employees of the Year for their dedication and exceptional service to faculty, staff, and students. Sharece Corner and Eileen Demarkles received the School of Engineering's Infinite Mile Award, which was presented at the Infinite Mile Awards Ceremony. In addition, eight Chemical Engineering Individual Accomplishments awards were given out to:

- Adrienne Bruno
- Sarah Coleman
- Supratim Das
- Nicholas Gibson
- Albert Liu
- Crystal Pham
- Kara Rodby
- Cindy Welch

The Department of Chemical Engineering at MIT has certainly had a very fruitful and rewarding year and is poised for even bigger and greater successes for the upcoming year.

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

Martin Z. Bazant
Executive Officer
E. G. Roos (1944) Professor of Chemical Engineering