Department of Chemical Engineering

During the academic year 2019–2020, the Department of Chemical Engineering (ChemE) continued its long tradition of global leadership in the discipline. For the 29th 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 sixth straight year and contributed to the record-breaking ninth straight year that MIT was ranked number one among world universities overall. The department has maintained its reputation and record of excellence at a time of increasing competition, investment, and growth among chemical engineering programs at peer institutions.

This year marked the completion of the work of the Task Force on Undergraduate Curriculum Revitalization, headed by Professor Kristala Prather. Over two and a half years, several changes were implemented to increase flexibility and reduce the total number of units required for the two core degrees offered by the department (from 198 to 186 for Course 10, and from 198 to 192 for Course 10B). These include streamlining laboratory and process design requirements, modifying the introductory thermodynamics requirement, and revising the content, structure, or both, of three core courses, 10.213 Chemical and Biological Engineering Thermodynamics; 10.37 Chemical Kinetics and Reactor Design; and 10.32 Separation Processes. The required subject, 5.310 Laboratory Chemistry, was revised this year in partnership with the Department of Chemistry as a communication intensive in the major subject (CI-M). The innovative CI-M proposal was well received by the Subcommittee on the Communication Requirement; of note was the inclusion of a professional communication assignment that asks students to write a brief for an audience with expertise in engineering, chemistry, or policy. The subcommittee intends to revisit this aspect of the course during AY2022, to consider it as a model for future CI-M modules.

In partnership with the Department of Biological Engineering, the department officially launched the Huang-Hobbs BioMaker Space in January under the direction of Justin Buck. 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 connected through the BioMaker Club.

The department continues to show leadership in developing and following best practices to promote equity and inclusion through initiatives and programs geared toward women and people from underrepresented minority groups. Activities have included roundtable discussions with both undergraduate and graduate students, and workshops on diversity and inclusion. The faculty voted this winter to develop lab culture and value statements through a collaborative process within each research group. Many of these statements are now posted to the public sections of the groups' websites. Our graduate students have launched ChAMP (Chemical Engineering Application Mentorship Program), a program that mentors students on applications to our graduate program, and a new graduate group, Diversity in Chemical Engineering, was founded this academic year. Our Graduate Recruiting Weekend program was also modified to include a diversity panel, featuring students and faculty. The department continues to host the ACCESS program, a weekend of educational and informative events introducing talented sophomores, juniors, and seniors to the benefits of a graduate education in chemistry, chemical engineering, and materials science. Three former ACCESS participants are currently matriculated in the doctoral program; a fourth, Sydney Johnson, will arrive in fall 2020. The department also hosted its second Rising Stars in Chemical Engineering Workshop, a program aimed to prepare women for the challenges associated with a career in academia. The third annual workshop is planned as a virtual event for fall 2020.

The department completed its regularly scheduled review with the Accreditation Board for Engineering and Technology (ABET) this year. The on-campus evaluation occurred in September 2019, and included interviews with students, staff, and faculty. The accreditation team noted the department's Communication Lab as a program strength, highlighting the "distinct competitive advantage [afforded to students] when competing for fellowships, seeking admission to professional programs, and presenting the results of their work." The team also identified one weakness in Courses 10 and 10B related to the curriculum. Specifically, the assessors were concerned that there was the potential for fewer than the required 45 credit hours in engineering subjects for graduates, due to ongoing changes being implemented with the laboratory requirements. This was of particular note for the introductory Biology lab, recently changed from a single 7.02/10.702 Introduction to Experimental Biology and Communication subject to a two-subject sequence consisting of 7.002/7.003 Fundamentals of Experimental Molecular Biology and Molecular Biology Laboratory. Since the new curriculum was not yet fully implemented, there was a lack of documentation clearly identifying the engineering content in these subjects. The assessors did note that while the degree charts suggested the possibility of a deficiency in engineering units, no such deficiencies were actually detected. Instead, our students regularly take far more than the minimum required units in engineering subjects. The department will be providing additional information in AY2021 to address this perceived weakness.

The department continues to attract significant research funding at an annual volume of $53.3 million, of which $22.8 million are handled directly through the department; the rest are managed by various other cost centers at MIT. The faculty continue to secure robust funding for their individual research programs, while participating in the creation and direction of larger multi-investigator projects. Chemical Engineering faculty also lead large, multi-institutional research.

Professor Paula T. Hammond completed her fifth year as department head, and Professor Martin Bazant concluded his term of service as executive officer after three and a half years. Professor Bazant is now serving as the inaugural digital learning officer. Kristala Prather stepped into the role of executive officer on February 1, 2020. Professor Patrick Doyle continued to serve as the graduate officer. Professor William Green completed his fifth 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 has claimed two Institute Professors as primary faculty members—Daniel I. C. Wang and Robert S. Langer. Unfortunately, Professor Wang passed away and appropriate memorial recognition of his life is being planned within the department. Professor Robert C. Armstrong is the director of the MIT Energy Initiative.

The COVID-19 pandemic presented a number of challenges during the spring semester. Throughout the ongoing disruption, the department endeavored to conduct impactful research and to educate its students. While all research that could be conducted remotely was moved off campus, most experimental research was halted in mid-March 2020. COVID-related critical research projects that continued included vaccine manufacturing (Professor Chris Love), rapid antigen diagnostics (Professor Hadley Sikes), and testing of filtration properties of masks (Professor Greg Rutledge). Our faculty rapidly transitioned to fully remote teaching, including effectively transitioning the 10.26 Chemical Engineering Projects Laboratory, 10.27 Energy Engineering Projects Laboratory, and 10.29 Biological Engineering Projects Laboratory classes, known as Project Labs to remote mode—to the pleasant surprise of many of the participating students. Students across all years reported broad satisfaction with their Chemical Engineering courses in the spring semester. Professor Karthish Manthiram was selected as a recipient of an MIT Teaching with Digital Technology Award as a result of his innovative approach. Lessons learned from the spring will be applied in the fall semester as the vast majority of our courses are offered in fully remote mode.

Research and Recognition

Many members of the Chemical Engineering faculty received major awards for their research and related teaching achievements. Robert Armstrong received the 2020 American Institute of Chemical Engineers (AIChE) Founders Award and was elected into the American Academy of Arts and Sciences. Richard Braatz won the 2019 AIChE Separations Division Innovation Award. Fikile Brushett won the 2020 National Organization for the Professional Advancement of Black Chemists and Chemical Engineers Lloyd N. Ferguson Young Scientist Award. Paula Hammond received the MRS Turnbull Lectureship Award. Bob Langer received the 2020 Maurice Marie-Janot Award. Karthish Manthiram won a 2020 Department of Energy (DoE) Early Career Research Award and a National Science Foundation CAREER Award. Kristala Prather was named a fellow of the American Institute for Medical and Biological Engineering and earned a 2019 Bose Research Grant. Greg Stephanopoulos earned an honorary doctorate from Technical University of Dortmund, Germany. William Tisdale was named a MacVicar Fellow.

It was an exciting year of research for the department, with many new developments coming out of Chemical Engineering laboratories. Daniel Anderson's so-called living drug factories protect transplanted drug-producing cells from immune system rejection; his lab also developed vaccines packaged in novel nanoparticles that could offer a new way to fight cancer and infectious diseases. Martin Bazant found a new way to remove contaminants from nuclear wastewater. The Doyle Laboratory helped develop a new method for processing fluid droplets to enable researchers to create a unique environment for developing medicine, paving the way for more potent, high-quality drugs. Arup Chakraborty and colleagues published a study that furthered a radically new view of gene control. The Chung Laboratory created the ELAST process to make tissue samples more durable. They also reported that the Alzheimer's plaque emerges early and deep in the brain. Alan Hatton designed an effective carbon capture treatment for both exhaust and ambient air. The Hatton Lab and colleagues developed a new process to make hydrogen peroxide available in remote places; they also worked with other institutions to develop a novel class of ionic liquids that may store more energy than conventional electrolytes with less risk of catching fire. Klavs Jensen and Connor Coley developed a new system guided by artificial intelligence (AI) that automates molecule manufacture. The Kroll Laboratory employed low-cost sensors to detect and track the origins of air pollutants in India. Heather Kulik's neural networks facilitated optimization in the search for new battery materials. Bob Langer developed a specialized dye, delivered along with a vaccine, that could enable on-patient storage of vaccination history. The Langer Laboratory developed a new capsule that can orally deliver drugs that usually have to be injected and a monthly birth control pill that could replace daily doses. The Langer Lab also developed a new strategy for encapsulating nutrients to make it easier to fortify foods with iron and vitamin A. The Love Laboratory is developing a COVID-19 vaccine to potentially reach billions; they also developed a method to isolate and sequence the RNA of T cells that react to a specific target. Karthish Manthiram developed a method to produce a gaseous messenger molecule inside the body on demand, shedding light on nitric oxide's role in the neural, circulatory, and immune systems; his lab also developed a technique that could enable cheaper fertilizer production. Brad Olsen developed BigSMILES, a notation system that allows scientists to communicate polymers more easily. The Prather Laboratory programmed bacteria to switch between different metabolic pathways, boosting their yield of desirable products. The Sikes Laboratory collaborated with 3M to develop rapid COVID-19 tests. Michael Strano developed a nanosensor that can alert a smartphone when plants are stressed. The Swan Laboratory discovered a particle-scale phenomenon in electrical fields that could allow selective separation of suspended nanomaterials. The Tisdale Lab developed hybrid perovskite materials that could help improve the quality of solar cells and light sources.

Arrivals, Retirements, and Promotions

In FY2020 the department hired three new faculty. Professors Katie Galloway and Ariel Furst began in summer 2019 and Connor Coley will begin in summer 2020. Professor Karen Gleason became a professor post-tenure as of January 2020.

Undergraduate Education

Current Status of the Undergraduate Program

Since 2004, the Department of Chemical Engineering has offered bachelor of science (SB) degrees in both chemical engineering (Course 10) and chemical-biological engineering (Course 10B). In fall 2011, the department introduced the 10-ENG flexible SB degree in engineering. Department undergraduate enrollment has been gradually declining since AY2007, but Chemical Engineering continues to have one of the highest student-to-faculty ratios in the School of Engineering. The department advises students about career paths in chemical and chemical-biological engineering through active participation in first-year advising seminars, fall and spring term open houses, Parent's Weekend, and other activities. Forty-two SB degrees were conferred in February and May 2020, 55% 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

Class	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Sophomores	80	72	61	67	57	56	58	44	41	42
Juniors	71	73	63	63	66	53	51	53	37	44
Seniors	75	75	69	58	64	67	55	50	59	42
Total	**226**	**220**	**193**	**188**	**187**	**176**	**164**	**147**	**137**	**128**

The 10-ENG program leading to the engineering SB 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 curriculum 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, and environmental, as well as 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 year students 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 BioMaker Space, jointly developed with Biological Engineering.

The senior survey indicates that for 2020, 30% 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:

Jenna Ahn	Hannah Loizzo
Juan Aleman	Evelyn Navarro Salazar
Delaney Burns	Ben Nguyen
James Cao	Britney Pham
Jacky Chin	Crystal Pham
Danica Dong	Andison Tran
Sebastian Esquivel	June Yang
Michal Gala	Daiyao Zhang
Kedi Hu	Kara Zhang
Caroline Kenton	Liruonong Zhang

Graduate Education

Current Status of the Graduate Program

The graduate program in the Department of Chemical Engineering offers master of science degrees in chemical engineering (MS) and in chemical engineering practice (MSCEP), the doctor of philosophy (PhD) and doctor of science (ScD) degrees in chemical engineering, and the doctor of philosophy degree in chemical engineering practice (PhDCEP). The PhDCEP track was established in 2000 in collaboration with the MIT Sloan School of Management. The total graduate student enrollment is currently 211, with 197 in the doctoral program and 14 master's level degree candidates. In the doctoral program, 193 students are in the PhD/ScD track and eight are in the PhDCEP track. In the master's program, 10 are in the MSCEP track. Of our graduate students, 32% are women, 4% are from underrepresented minority groups, and 47 were recipients of outside fellowship awards, including those from NSF, National Institutes of Health (NIH), and the Department of Defense (DoD), among others. The distribution of graduate students by degree for the last 10 years is shown in Table 2. During AY2020, 36 doctoral degrees (PhD or ScD, PhDCEP) were awarded, along with 20 master's degrees (17 MSCEP, three MS) for a total of 56 advanced degrees conferred.

The department received 432 applications for admission to the doctoral program, offered admission to 70 individuals, and received 54 acceptances of offers, for an acceptance percentage of 77%. Out of 73 applications for master's level degrees, the department made 13 offers and received 11 acceptances of offers, for a yield of 85%. Among the incoming graduate class for 2020, 25 are women and seven are from underrepresented minority groups.

Table 2. Graduate Enrollment

Degree	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Master's	38	28	20	10	11	15	15	10	12	13	14
Doctoral	203	212	224	212	211	222	218	222	214	224	197
Total	**241**	**240**	**244**	**222**	**222**	**237**	**233**	**232**	**226**	**237**	**211**

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.

Data-Driven Design of Li-ion Batteries

Professors Bazant and Braatz continued their collaboration on data-driven design of li-ion batteries (D3BATT) with researchers at MIT, Stanford, and Purdue 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. Their publications in 2020 included one on the closed-loop optimization of fast-charging protocols for batteries in *Nature*, and another on learning the physics of pattern formation in *Physical Review Letters*.

Smart Data Analytics in Biomanufacturing

Professors Braatz, Anthony Sinskey (Biology), and Retsef Levi (Sloan School of Management) and Stacy Springs (Center for Biomedical Innovation) co-lead a project titled Smart Data Analytics for Risk Based Regulatory Science and Bioprocessing Decisions. This project is funded by the US Food and Drug Administration's 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.

Defense Advanced Research Projects Agency and Machine Learning Industry Consortium

Professor Klavs Jensen continued to lead the Defense Advanced Research Projects Agency (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, composed of colleagues in Computer Science (Professors Regina Barzilay and Tommi Jaakkola) and Chemistry (Professor Timothy Jamison), and Professors Jensen, Green, and Allan Myerson, combined artificial intelligence-driven synthesis planning from historical data and a robotically controlled experimental platform to realize 15 drug or drug-like substances.

With their Computer Science colleagues, Professors Jensen and Green started a new project in accelerated molecular discovery (AMD) that aims to accelerate the pace of chemical innovation through data extraction from the chemical literature—new predictive models based on a combination of literature data, physical knowledge, new high-throughput experiments, and use of these models in autonomous molecular discovery and optimization.

Professors Barzilay, Green, Jaakkola, and Jensen continued to work with members of the MIT-industry consortium on Machine Learning for Pharmaceutical Discovery and Synthesis (MLPDS) (Amgen, AstraZeneca, BASF, Bayer, GSK, Janssen, Leo Pharm, Lilly, Merck, Novartis, Pfizer, Sunovion, Syngenta, and WuXi). The consortium brings together scientists and engineers from member companies and MIT to create new data science and artificial intelligence algorithms along with tools to facilitate the discovery and synthesis of new therapeutics. MLPDS educates scientists and engineers to work effectively at the data science/chemistry interface and provides opportunities for member companies and MIT to create, discuss, and evaluate new advances in data science for chemical and pharmaceutical discovery, development, and manufacturing.

Disruptive and Sustainable Technology for Agricultural Precision

The Disruptive and Sustainable Technology for Agricultural Precision (DiSTAP) integrated research group (IRG) in the MIT-Singapore SMART program completed a highly successful second year in partnership with the Temasek Life Sciences Laboratory in Singapore. 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. Lead by Professor Michael S. Strano, the DiSTAP team includes other Course 10 faculty, such as Greg Stephanoplous and Kristala Prather, as well as Rajeev Ram (Electrical Engineering and Computer Science) and Anthony Sinskey (Biolgoy). This year, DiSTAP produced several new technologies that considerably advance precision agriculture. A field-portable Raman Spectrometer has also been demonstrated that is capable of profiling drought, nutrient, and other stresses at stand-off distances from living plants. This year DiSTAP demonstrated a new nanosensor interface that can transmit, in real time, the internal immunological signaling of a living plant to a user's smartphone. In a paper published in *Nature Plants*, the team showed how the technology can indicate the type and magnitude of specific stresses experienced by living plants at a speed sufficient for feedback control. DiSTAP and its work have been highlighted in major media outlets, including CNBC, *Straits Times*, and the *Economist*. The team has also successfully applied its powerful analytical technology to the COVID-19 crisis in a rapid development project initiated during the spring 2020 shutdown.

The Center for Enhanced Nanofluidic Transport

The Center for Enhanced Nanofluidic Transport (CENT), a $11 million Energy Frontier Research Center funded by the US Department of Energy, has completed a successful second year with founder and scientific director Professor Strano, along with Professors Kulik, Daniel Blankschtein, and 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-sized 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 is producing fundamental insights into geologic transport, and led to new membrane and other separation technologies for energy efficiency and chemical process intensification. CENT has seen the nanofluidics field adopt several of its conceptual innovations as well as the identification of knowledge gaps as high opportunity research targets (as described in several impactful publications). CENT completed a highly successful two-day symposium at Yale University in fall 2019. It completed a major midterm review from the Department of Energy in spring 2020 with high praise and accolades from both the DoE and its peer review panel of experts.

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 Dane Wittrup. The KI brings together scientists and engineers with appointments spanning the campus to collaborate on research aimed at new cancer therapies. Dane Wittrup serves as the associate director of the Koch Institute. A particular strength of the KI is cutting-edge research on drug delivery, anchored by the efforts of Anderson, Hammond, and Langer. Another strength is the engineering of new protein-based interventions for use in treating cancer and infectious diseases.

Faculty Notes

Professor Robert C. Armstrong serves as director of the MIT Energy Initiative (MITEI). MITEI continues to grow rapidly in its research, educational, and outreach components. Ten companies sponsor research as founding, sustaining, and startup members. All together, the Energy Initiative is engaged with more than 80 industrial and public partners and individual members across five continents. MITEI has helped to bring in approximately $850 million in support over the past 10 years, along with 400 energy named 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 launched the Energy at Scale and Energy in the Developing World Centers aimed at two of the biggest challenges we face in energy transition. The Future of Storage Study continues and 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 Matteo Foundation, the editorial board of *World Energy Magazine*, the external scientific advisory committee of Argonne National Laboratory, and the board of directors of the National Renewal Energy Laboratory.

Professor Daniel Blankschtein's group conducts modeling, simulation, and experimental research in the area of colloid and interface science with an 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 and seminars, and presented posters at various scientific meetings in the United States and abroad. He is a member of the DoE Center for Nanofluidic Transport, which involves seven universities and the Lawrence Livermore National Laboratory. As part of this center, Professor Blankschtein's group is investigating how fluids—particularly water and aqueous electrolytes—behave under extreme confinement, including developing novel polarizable force fields to model the relevant interactions at the nanoscale. New, intriguing equilibrium and transport phenomena have been observed, for example, inside very narrow carbon nanotubes water freezes at a temperature of about 100 degrees Celsius, a temperature at which bulk water normally boils. In addition, Professor Blankschtein's group is investigating, both theoretically and experimentally, nanoporous graphene membranes for gas separation. Professor Blankschtein continues to serve on the editorial board of Marcel Dekker's Surfactant Science book series, published by CRC Press.

Professor Richard D. Braatz served as past president of the American Automatic Control Council, which is a federation of nine professional societies (AIChE, American Institute of Aeronautics and Astronautics, American Society of Civil Engineers, American Society of Mechanical Engineers, Institute of Electrical and Electronics Engineers, International Society of Automation, Society for Modeling and Simulation, Society for Industrial and Applied Mathematics, and Applied Probability Society). As research officer for Chemical Engineering, he coordinated with other faculty to propose research areas for faculty cluster hires for the College of Computing. He led the data analytics and control research in several large advanced manufacturing projects, including approximately $9 million from US Health and Human Services to validate his methodologies in fully automated experimental platforms for biopharmaceutical manufacturing. His publications included an article in *Nature* on machine learning–based optimization of fast-charging protocols for lithium-ion batteries. He gave numerous invited talks, including plenaries and keynotes, and the opening presentation on data analytics at the National Academies Workshop on Innovations in Pharmaceutical Manufacturing in February 2020. He served on the scientific advisory boards for a local biotech company and for a NASA Science and Technology Research Institute developing biological and energy technologies for the survival of humans in outer space. He received the AIChE Separations Division Innovation Award for "the development and implementation of semi-automated technologies for the robust and reliable production of pharmaceutical crystals of desired polymorphic/solvatomorphic form."

Professor Fikile R. Brushett, Cecil and Ida Green Career Development Chair, was promoted to the rank of associate professor with tenure. He continued to lead his team in advancing the science and engineering of electrochemical systems needed for a sustainable energy economy. This past year, his group's original research contributions focused on the synthesis and characterization of new electroactive materials, the design and engineering of electrochemical reactors, and the techno-economic modeling of electrochemical systems for energy storage and conversion. Much of this work was performed in collaboration with a range of academic, national laboratory, and industrial partners. This past year, Professor Brushett's service to his community was highlighted by co-organizing a topical session at the 257th National Meeting of the American Chemical Society, contributing to the impending MIT Energy Initiative Future of Storage study group, and serving as the research integration co-lead for the Joint Center for Energy Storage Research, a DoE-funded energy innovation hub.

Professor Arup K. Chakraborty continued efforts to understand the mechanistic bases of how a systemic immune response to pathogens arises, and how its aberrant regulation leads to disease. Research aimed at understanding how this knowledge can be harnessed for the rational design of vaccines and therapies is also an important facet. Chakraborty, in collaboration with Professors Philip 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. Chakraborty researched COVID-19 in 2020, and his HIV work has led to an immunogenic vaccine in monkeys. Chakraborty and co-author Andrey S. Shaw submitted their manuscript to MIT Press—the book, *Viruses, Pandemics, and Immunity* is written for a general audience and will be published in 2021. He is also working on a book for physical scientists who want to enter (or have already entered), the field of immunology. Chakraborty was awarded the Outstanding Graduate Faculty Award for his classroom teaching in 2019, based on student votes. Chakraborty continues to serve as a member of the US Defense Science Board.

Professor Kwanghun Chung continued to lead an interdisciplinary research team to develop and apply novel technologies for holistic understanding of large-scale complex biological systems. Recent research advances by the Chung Lab include the development of ELAST technology that transforms human brain tissues into elastic hydrogels to enhance macromolecular accessibility and mechanical stability simultaneously. He led several large multi-PI projects, including a $9 million NIH human brain mapping project and a $5 million NIH reusable antibody development project to apply his technologies for mapping and studying the human brain. In addition, his group has active collaborations with many researchers at MIT, the Broad Institute, Massachusetts General Hospital, and Harvard University to study various neurological disorders such as autism spectrum disorder and Alzheimer's disease. He has traveled extensively, including visits to the California Institute of Technology (Caltech), Johns Hopkins University, and Georgia Institute of Technology (Georgia Tech) to speak about his group's technologies and their applications.

Professor Chung received the Presidential Early Career Award for Scientists and Engineers. Several group members received awards, including a Simons Center for the Social Brain Postdoctoral Fellowship and Picower Fellowship. Professor Chung taught 10.302 Transport Processes, and HST.562 Pioneering Technologies in Biology and Medicine. He also served on the Institute for Medical Engineering and Science Committee for Academic Programs, as well as the ChemE graduate admission committee. Professor Chung also continued serving as a chief scientist to a startup, LifeCanvas Technologies, which aims to advance the adoption and usage of the technologies developed by the Chung Lab at MIT.

Charles L. Cooney, Robert T. Haslam (1911) Professor of Chemical and Biochemical Engineering, emeritus, teaches the capstone subject 10.490 Integrated Chemical Engineering, introducing chemical engineering seniors to batch processes through 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 2035, complete a process design along with a roadmap for the project and facilities costing. Cooney also teaches the MIT Open Courseware subject, 10.547 Principles and Practice of Drug Development. Professor Cooney continues as an advisor to the SMART Innovation Center in Singapore and is 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 Education program. Professor Cooney is also on the advisory boards of the National Institute of Biotechnology Research and Technology and the Biopharmaceutical Analysis Training Laboratory at Northeastern University.

Professor Patrick S. Doyle, 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 published 18 articles this past year. Major accomplishments include publishing the first single molecule study of a two-dimensional DNA system in the journal *PNAS* and the development of a new way to print droplets in yield stress fluids (also published in *PNAS*). He continues to lead two major efforts in Singapore, which focus on new methods for formulating small molecule drugs. In a collaboration with Frank Slack at Beth Israel Deaconess Medical Center, he received a Deshpande Ignition grant to commercialize his technologies to spatially profile miRNA in tissues. He delivered several invited lectures at companies, conferences, and universities. Professor Doyle currently serves on the scientific advisory board at Withings and Achira Labs, and is on the National University of Singapore Chemical Engineering Department visiting committee.

Assistant Professor Ariel Furst leads a research group that combines electrochemistry with biochemical engineering to improve healthcare and clean energy technologies. The current group members (two graduate students, one postdoc, one visiting student, and two undergraduate students) are working on electrochemical strategies to detect and combat antibiotic resistance in bacteria, diagnose COVID-19, and detect harmful pesticides. Her research is currently supported by MITEI and the Royal Society for Chemistry. Professor Furst spoke at the Harvard Microbial Sciences Initiative Annual Symposium and published an invited viewpoint in *ACS Infectious Diseases*. She is working to increase active learning and practical skills in courses, developing the graduate-level subject 10.S96 Special Problems in Chemical Engineering, and revamping the chemistry subject for nonmajors, 5.310 Laboratory Chemistry. She is currently working with Sarah Hewett to incorporate active learning and engineering content into 5.310, which will be supported by alumni funds.

Professor Katie Galloway started as assistant professor at MIT in the Department of Chemical Engineering in 2019. Her research has been featured in *Science* and *Cell Stem Cell*. She has won multiple fellowships and awards, including the NIH F32 and Caltech's Everhart Award. As a chemical engineer working in molecular systems biology, Professor Galloway has her group focus on elucidating the fundamental principles of integrating synthetic circuitry to drive cellular behaviors. The current members of the lab (three graduate students, one technician, and four undergraduates) have begun constructing sensors for tracking diverse processes during reprogramming and expanded computational modeling to predict the impact of systems-level perturbations. In 2020, her lab was featured as emerging stem cell researchers in *Cell Stem Cell*. At the 2020 International Society for Stem Cell Research, she presented new work elucidating the functional relationship between p53 and reprogramming. Professor Galloway was invited to speak at the mammalian Synthetic Biology Workshop in Scotland, the Boston Gene Expression and RNA Series, and to serve as an instructor for the Cold Spring Harbor Laboratory summer course on synthetic biology. Due to COVID-19, these engagements were postponed. Professor Galloway continues to develop new methods of engaging students in 10.10 Introduction to Chemical Engineering. In spring 2020, she facilitated the transition to online learning and will continue to support the development of online resources and best practices for 10.10 in the fall.

Professor William H. Green received the R. H. Wilhelm Award, AIChE's top award in chemical reaction engineering. He co-directs the new Mobility Systems Center. He co-founded Thiozen, a startup commercializing a new process he co-invented for converting waste H_2S into low-carbon hydrogen.

Professor Paula Hammond was the 2019 Materials Research Society David Turnbull Lecturer, and she was recognized with the ETH Zurich Chemical Engineering Medal. She delivered the Richard H. Wilhelm Lecture in Chemical Engineering at Princeton in October 2019. She also received the 2019 UCLA Founder's Lectureship. She was elected to the National Academy of Medicine Council in 2020, and also became a member of the board for the Burroughs-Wellcome Fund. In March 2020, she joined the board of directors of Alector, a San Francisco company focused on immuno-neurology to treat degenerative disorders. 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 focuses on the areas of targeted cancer nanotherapies and immuno-oncology, wound healing, and tissue regeneration, with new technologies also directed toward 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. The past year has been particularly focused on increasing enrollment of a more diverse graduate program, and working with the chemical engineering community to establish a more welcoming and inclusive environment.

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 MITEI workshops and meetings. Invited keynote and plenary lectures have been delivered at meetings in the United States; University of Auckland, University College of Dublin, and the MIT-Japan Conference in Tokyo, among others. A number of invited talks at Gordon Research Conference, Cornell University, ESEE Leeuwarden Netherlands, and others, were postponed due to the pandemic. He received a Distinguished Visitor Award from the University of Auckland, and is co-founder of Verdox, for the development of sustainable environmental solutions based on technology developed in his laboratory. Hatton continues to develop new directions for mitigation of environmental problems, primarily electrochemical approaches for carbon capture and microcontaminant removal from aqueous sources.

Professor Klavs F. Jensen led research with colleagues in Chemical Engineering, Chemistry, and Computer Science 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, which was published in *Science*. With Computer Science colleagues, Professors Jensen and Green started a new DARPA-sponsored project in accelerated molecular discovery that aims to accelerate the pace of chemical innovation through autonomous molecular discovery and optimization. The laboratory also continued its efforts to use automated platforms to explore chemical transformations, to optimize chemical reactions, and to extract chemical kinetics. With Professor Barzilay in Computer Science, Jensen continued to co-direct the MIT-industry consortium on Machine Learning for Pharmaceutical Discovery and Synthesis. The consortium now includes 14 major chemical and pharmaceutical industry partners. During the past academic year, he gave plenary lectures on microfluidics, flow chemistry, and machine learning technology at international conferences and at universities, including the P. V. Danckwerts Memorial Lecture for European Federation of Chemical Engineering. He continued to serve on scientific advisory boards to chemical engineering departments, research institutes, and companies.

Professor Jesse H. Kroll and his research group continued their research on the organic chemistry of the atmosphere, the formation and evolution of atmospheric particulate matter, and air quality measurements using low-cost sensors. Their recent focus has been on comprehensively measuring the chemistry of atmospheric organic carbon, using data from multiple time-of-flight mass spectrometers to track how compounds emitted into the atmosphere evolve over timescales of hours to weeks. This approach is being applied to a wide range of atmospheric chemical systems, including aromatic hydrocarbons from fossil fuel use, terpenoids from plants, N- and S-containing organic species formed from photochemical reactions in the air, and wildfire smoke. Kroll is director of the R. M. Parsons Laboratory for Environmental Science and Engineering, and serves on the board of directors for the American Association of Aerosol Research.

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 accelerated discovery of new functional materials from over three million candidates and new models that detect when electronic structure methods will fail. This past year, she received the DARPA Director's Fellowship and presented the Saville Lecture at Princeton University. She has traveled extensively, presenting over 40 talks in the past year, both at national and international conferences and universities. This past year, she published over a dozen peer-reviewed papers, including profiled articles in *ACS Central Science* and *Chemical Science*. Her group's research is supported by the 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 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 six postdoctoral researchers, nine graduate students, and several visiting and undergraduate researchers.

In 2019, Professor Robert Langer published 48 papers and delivered 58 lectures and talks across the world. He also filed 11 patents, served on seven Institute boards and 45 industry boards. Professor Langer serves as consultant to the following government agencies: Science Envoy (US State Department), National Academy of Science, National Academy of Engineering, National Academy of Inventors, National Academy of Medicine, and the US Food and Drug Administration. He received the following awards and honors in 2019: Dreyfus Prize in the Chemical Sciences, an honorary degree from Columbia University, National Library of Medicine (Friends) Distinguished Medical Science Award, and Hope Funds for Cancer Award of Excellence in Basic Sciences.

Assistant Professor Karthish Manthiram was awarded the Institute-wide Theodore T. Miller Career Development Chair. He leads a research group that develops methods by which carbon dioxide, nitrogen, and water can be converted into diverse chemicals using renewable electricity. In the past year, Professor Manthiram received the NSF CAREER Award and DoE Early Career Award. As a part of shaping policy and research initiatives for the United States, he was invited to give a talk at the National Academies' Chemical Sciences Roundtable titled "Electrification and Decarbonization of Chemical Synthesis." His lab has made key discoveries that have led to the highest performing prototype for converting nitrogen and water into ammonia using electricity at ambient conditions, which is critical for sustainably producing fertilizers and disinfectants. This work was published in *Nature Catalysis* and covered widely in the press, including in *Science*. His lab, working in collaboration with Professor Polina Anikeeva, has also shown how chemical messengers can be created in situ in the brain using electrically driven chemical reactions, which was published in *Nature Nanotechnology*. Professor Manthiram was named to the early career advisory board for *ACS Catalysis* and to the advisory board of the student-run *MIT Science Policy Review*. Professor Manthiram continues to innovate in teaching through the use of Socratic dialogue, as reflected in his winning the MIT Teaching with Digital Technology Award and the C. Michael Mohr Outstanding Undergraduate Teaching Award in 2020.

Professor Allan S. Myerson continued his research on fundamental and applied problems in crystallization and pharmaceutical manufacturing. He is a principal investigator on projects related to the use of image analysis and machine learning for the control of pharmaceutical unit operations (sponsored by Takeda) as well as an

NIH–sponsored project involving novel plug flow crystallization methods. He serves as a scientific advisor to BlueSpark, a company that develops novel flexible batteries, continuous pharmaceuticals, and on-demand pharmaceuticals.

Professor Bradley D. Olsen was recognized this year with the AIChE Owens-Corning Award and as a fellow of the American Chemical (ACS). 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 and informatics and automation. The group published 14 papers. Major accomplishments included publishing a new chemoinformatics language for polymer science and the development of a graph-based schema for organizing materials synthesis data across reaction networks, a new theory for predicting the effect of defects on polymer network fracture, engineering new materials from biomass that could provide a sustainable replacement for polyurethanes, and development of new biosensor technologies from protein-based materials. Starting this spring, his group has also been applying their biomimetic polymer technologies to develop new strategies for preventing SARS-CoV-2 infection. Olsen served as an instructor for MIT OpenCourseWare's 10.40 Chemical Engineering Thermodynamics, as well as serving as faculty co-director of the MIT International Science and Technology Initiatives Brazil program and co-chair of the Chemical Engineering admissions committee.

As the Arthur D. Little Professor of Chemical Engineering and a member of the Synthetic Biology Center at MIT, Professor Kristala L. J. Prather continues to focus her research on microbial synthesis of chemical compounds. Prather plays an active role in service to the scientific community through several scientific advisory and editorial boards, including as an associate editor of *ACS Synthetic Biology* and *Metabolic Engineering Communications* and as vice president (president-designate) of the International Metabolic Engineering Society. Prather's appointment as a member of the DoE Biological and Environmental Research Advisory Committee was renewed for an additional two-year term. She was inducted as a fellow of the American Institute for Medical and Biological Engineering in June. Within MIT, Prather continues to serve as lead instructor of the long-running subject Fermentation Technology (popularized by Professor Daniel I. C. Wang and offered through the MIT Professional Education Program), She is also 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 one-year term of service as chair of the Committee on Academic Performance, which required particular attention due to the significant disruption caused by the COVID-19 pandemic. Within the department, Prather led the conclusion of the work of the Task Force on the Undergraduate Curriculum, which has shepherded significant changes to the SB degree requirements. On February 1, 2020 she became executive officer of Chemical Engineering.

Professor Gregory C. Rutledge and his research group study fundamental relationships in processing and crystallization of macromolecules, fiber-forming polymers, and the applications of polymeric nanofibers. They developed the first molecular simulations to study nucleation and growth of crystals in simple polymers, homogeneously, heterogeneously, and in flow. Most recently, they coupled atomistic and mesoscale methods to construct a constitutive model that accounts for the reciprocal effects of crystallization kinetics and rheology. Their work continues on nanofiber membranes for the separation of emulsions and aerosols. Based on the latter, the group pivoted rapidly in March 2020 to the screening of filtration materials for personal protective equipment (PPE), in particular N95 masks, providing critically needed data for decisions makers and frontline workers dealing with the COVID-19 pandemic. This work was done in collaboration with Advanced Functional Fabrics of America (AFFOA) and the Manufacturing Emergency Response Team of Massachusetts. Rutledge continues to promote the community of researchers at MIT in advanced fibers and fabrics, and organized the summit Ideas on the Future of Fabric in November 2019. Over the past year, Professor Rutledge delivered numerous keynote or invited lectures, both domestically and internationally. He continues to serve as editor for the *Journal of Materials Science*.

Professor Zachary P. Smith joined the Department of Chemical Engineering in January 2017. He is a recipient of the DoE Early Career Award, the ACS 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. He serves on the board of directors for the North American Membrane Society and is on the editorial advisory board for *Polymer*. His research focuses on the development of polymers and porous materials for applications in energy-efficient separations. In 2020, the Smith Lab grew to nine PhD students, six postdoctoral scholars, and four undergraduate researchers. Invited seminar presentations have been presented at Auburn University, the University of Connecticut, Georgia Tech, and Stanford University. To date, multiple papers have been published, including publications in *Advanced Materials*, *ChemSusChem*, *AIChE Journal*, *Macromolecules*, *ACS Applied Materials and Interfaces*, *Chemical Reviews*, and *Industrial & Engineering Chemistry Research*. Two patent applications have also been filed from work at MIT, and pre-seed funding through the Deshpande Center has been awarded to consider creating a spin-off company in the near future. Professor Smith taught MIT OpenCourseWare's 10.569 Synthesis of Polymers in the spring term and anticipates teaching OpenCourseWare's 10.467 Polymer Science Lab in the fall.

Professor Gregory Stephanopoulos, the W. H. Dow Professor of Biotechnology and Chemical Engineering and director of the Metabolic Engineering Laboratory, continued his research on engineering microbes for the production of chemicals and fuels. Two focus areas were the production of natural products, such as carotenoids, flavors, and fragrances, and the fixation of CO_2 by acetogenic bacteria using hydrogen as reducing gas. Notable advances include the construction of overproducing strains for the production of beta carotene and lycopene and drastic improvement of the rates of CO_2 fixation through co-feeding strategies. Products of fixed CO_2 are converted into oil; another new development was the engineering of microbes for the conversion of CO_2 fixation products to alkanes and alkenes. The ultimate goal of this work is the replacement of fossil feedstocks and advancing the vision of a biobased economy. Professor Stephanopoulos graduated two doctoral students and one postdoc, He serves on the advisory boards of four academic institutions and the managing board of the Society for Biological Engineering. 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. In addition to numerous research presentations at meetings of professional societies (AIChE, ACS, ASM, and the Society for Industrial Microbiology), he also delivered the opening plenary at the Asian Pacific Conference of Chemical Engineering and Annual Conference of the Society for Chemical Engineering of Japan, and the Advanced Research Projects Agency–Energy workshop on carbon use in September. In 2019, Professor Stephanopoulos was honored with the Gaden Award of the American Chemical Society's Biochemical Technology Division.

Professor Michael S. Strano, the Carbon P. Dubbs Professor, has continued his research at the interface of nanotechnology and chemical engineering. This year he was awarded AIChE's Andreas Acrivos Award for Professional Progress in Chemical Engineering. In the past year, his laboratory has developed a nanosensor that can transmit (in real time) the internal immunological signaling response from any living plant to a user's smartphone. His team used this sensor to decode a wealth of new signaling waveforms that encode specific plant stresses in real time, as described in the journal *Nature Plants*. The Strano laboratory also developed a mathematical model of the human endocrine system and human physiology that can predict a patient's response to glucose, insulin, and glucagon. Originally developed to guide nanosensor research, the team has shown that it can aid in the design of glucose responsive insulins as a new class of pharmaceutical treatment. Professor Strano continues his work as lead principal investigator of the Disruptive and Sustainable Technology for Agricultural Precision IRG in the MIT-Singapore SMART program. Professor Strano is also the founder and scientific director of the Center for Enhanced Nanofluidic Transport. This $11 million DoE Energy Frontier Research includes three other Course 10 PIs at MIT, and 12 other national academics. 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 mesoscale, and application of those methods to materials of industrial and societal interest, including food and consumer care products and biopharmaceuticals. His work appeared in 14 peer-reviewed publications, including a feature on the cover of *ACS Materials Letters* and a feature article in *Physics* magazine covering research published in the *Physical Review Letters* on the discovery of a new mode of electrokinetic particle motion. This year, the Swan group branched out in a new direction, examining high-throughput experimentation for the measurement of nonlinear mechanical response functions in soft materials and non-Newtonian fluids. These datasets will enable new sensors for industrial processes and new material design processes that can be integrated robustly with machine learning methods. The Swan group has graduated five PhDs over the last six years and currently hosts seven graduate students and one postdoctoral associate.

Professor William A. Tisdale is the ARCO Career Development Professor in Energy Studies and an associate professor of chemical engineering. In 2020, he was named to the newest class of MacVicar Faculty Fellows. 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 discovering the effect of free ligands on the self-assembly of colloidal nanocrystals (published in *JACS*) and their role in facilitating charge transport in perovskite solar cells (published in *Nature Materials*). 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 the past year, Professor Tisdale delivered plenary lectures at the AIChE annual meeting and the nanoGE conference in Berlin, Germany. Professor Tisdale is also faculty lead for the NEET Renewable Energy Machines Thread, serves as the Course 10 representative at Institute faculty meetings, and is a faculty advisor to the student-led Baker Foundation Advisory Committee.

Professor Bernhardt L. Trout developed and continues to teach with colleagues the germinal subject, 10.01 Ethics for Engineers, 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. He recently introduced a version focusing on the ethics of artificial intelligence, a perfect flagship course for the new MIT Schwarzman College of Computing. 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 continues to be co-chair of the International Symposium on Continuous Manufacturing of Pharmaceuticals, which is proving to be critical in promoting advanced manufacturing technologies for supply chain security and future pandemic response. 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

Nanofiber Filter Media for Fine Separations Applications (Gregory C. Rutledge)

Large quantities of oil-contaminated water are generated daily by the petrochemical, metallurgical, pharmaceutical, food, and beverage industries. In the petrochemical sector alone, over 12,000 barrels of crude oil are produced every day in the United States, which on average generates three to five times as much oil-contaminated water. Unintentional release into the environment without appropriate treatment can have significant negative impact on aquatic plants and animals. The reclamation of oily wastewater, however, faces a number of challenges, due to the volume and the variety of the discharged mixtures. Conventional techniques to separate oil and water, such as gravity-based or centrifugal separations, become inefficient when the oil is present as a surfactant-stabilized emulsion, with droplets of oil below 20 μm in diameter that remain suspended indefinitely. The conventional approach to remove such emulsified oil involves the addition of chemical de-emulsifiers. However, this method is expensive, environmentally unattractive, and susceptible to changes in the influent quality.

Ultrafiltration and microfiltration offer alternative processes for removing emulsified liquids and particles from fluid streams. Compared to conventional approaches, these technologies can be attractive because of their high throughput, good rejection of emulsified droplets, compact modular design and low energy consumption. Performance is highly dependent on the type of filter or membrane material used. The primary difficulty is that such membranes are prone to rapid fouling—the process by which rejected droplets accumulate on the surface of or within the membrane—which leads in turn to flux decline, inefficient separation, and increased material and energy costs. Typical foulant removal processes include backflushing and the use of harsh chemicals, which result in higher cost, environmental concerns, and usually shortens the lifetime of filtration membranes, especially for polymeric membranes.

The Rutledge Laboratory in Chemical Engineering has been exploring the use of alternative filtration media based on nanofibers produced by a technology called electrospinning. Compared to other nanofiber-forming technologies, electrospinning allows formation of fibers from a broad range of chemical compositions with good uniformity and relatively narrow polydispersity. As illustrated in figure 1, these fibers are remarkable for their small fiber diameters, typically on the order of 50 to 500 nm. When assembled into nonwoven fabrics, they exhibit high porosity (approximately 90%), and a highly interconnected pore structure that allows fluids to find alternative paths through the filter even when some channels are blocked by foulants, thus resulting in improved performance over time. We showed that electrospun fiber membranes can exhibit higher flux than commercial microfiltration membranes with comparable mean pore sizes, while maintaining comparable levels of rejection, and that fouling is reduced. Subsequently, by varying their composition and surface functionality, different degrees of hydrophobicity/philicity and electrostatic charge could be designed into the membrane. In the latter case, this capability led to a strategy for membrane design to resist fouling based on the tuning of electrostatic interactions between the membrane and the emulsion, as illustrated in figure 1c.

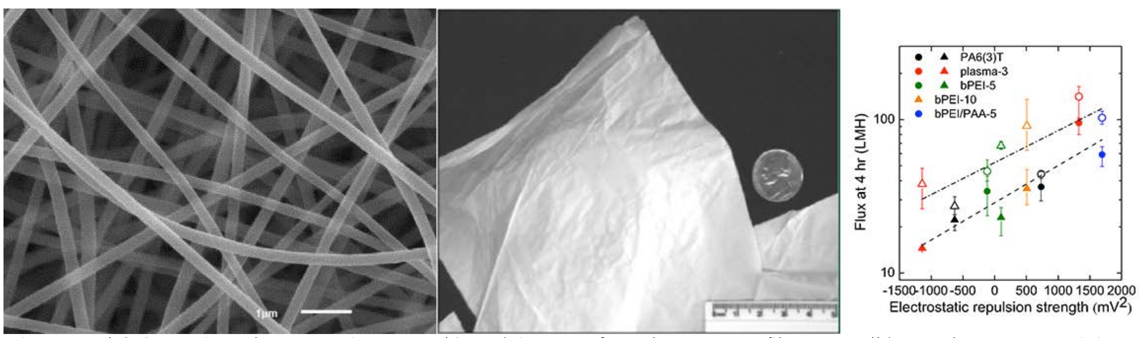

Figure 1. (a) Scanning electron microscope(SEM) image of an electrospun fiber mat; (b) membrane comprising nanofibers; and (c) illustration of flux dependence on electrostatic repulsion strength for both negatively and positively charged emulsions and membranes.

The conventional analysis of fouling in ultra- and microfiltration media relies on so-called blocking models, wherein the fouling mechanism is inferred from a power law dependence between the flux and its time derivative, a relationship that is never precise. In order to examine the fouling process directly, the Rutledge Lab pioneered the use of confocal laser scanning microscopy (CLSM), an optical imaging technique that enables 3D internal structure reconstruction. The method is simple, efficient, and nondestructive. By embedding a fluorescent dye in either the fibers of the membrane (at time of fabrication) or in the fluid itself and subsequently imaging, one can acquire entire 3D datasets for a porous medium. Greater depth and resolution of profiling can be obtained using index matching fluids. Image analysis techniques developed in-house were then employed to extract important morphological characteristics, such as porosity, specific surface area, distributions of fiber diameter and pore diameter, fiber orientation, and measures of the connectivity of pore space within the membrane. Accurate description of the pore space connectivity, in particular, is essential to understanding how fouling alters the flow through a fibrous membrane. By labeling both the fibers and the emulsified oil droplets with different markers and imaging though multiple channels, direct observation of the distribution of foulant (oil) atop and within a membrane was obtained for the first time, as demonstrated in figure 2. By imaging membranes exposed for different durations of oil/water separation or following subsequent cleaning protocols, one obtains the unprecedented capability of revealing the nature and development of fouling through direct visualization and quantitative geometric analysis.

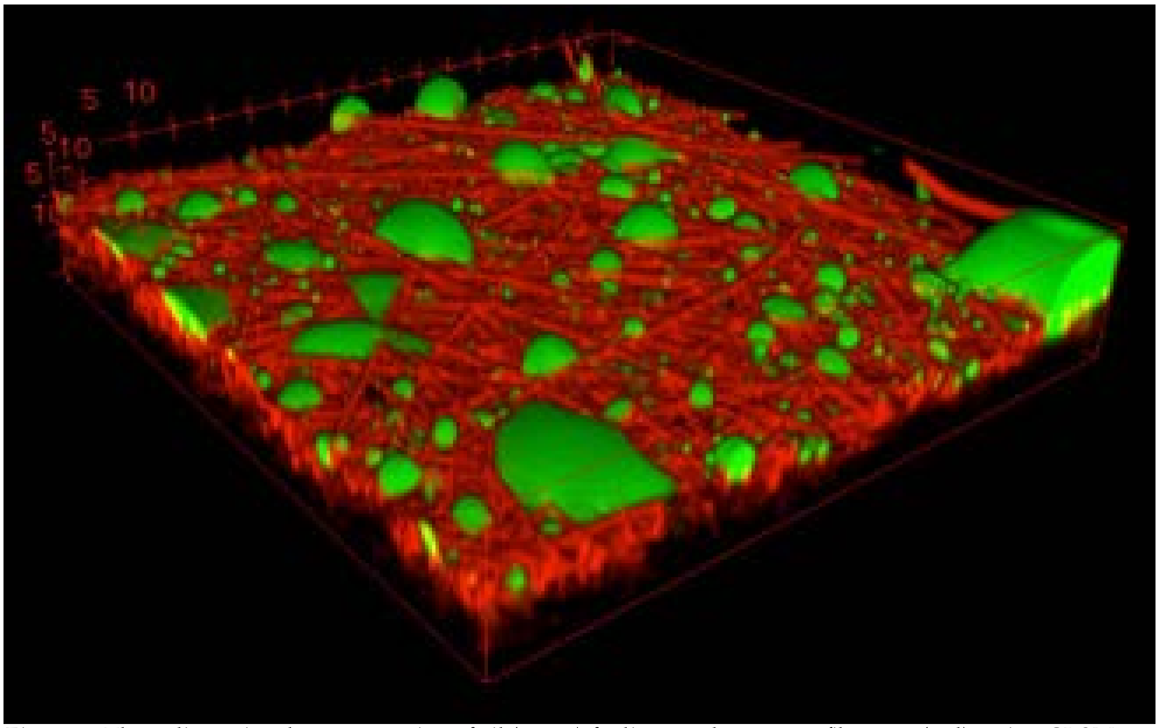

Figure 2. Three-dimensional reconstruction of oil (green) fouling an electrospun fiber mat (red), using CLSM. 3D data was collected using a Zeiss LSM 700 with an oil-immersion objective and a magnification of 63´. Two fluorescent dyes—perylene and Nile Red—were used as markers for the oil (dodecane) and nylon (fiber-forming) solution, respectively.

The methods described above can be applied not only to oil-in-water emulsions, but also to fine particulate aerosols. Originally demonstrated by the Rutledge Lab in 2016, solid and liquid aerosols with mean mobility diameters ranging from 100 to 300 nm can be efficiently separated from air using electrospun nanofiber filters, resulting in low penetration values and a shift of the most penetrating particle size to droplets as small as 40 to 50 nm. The ability to filter particles in this size range selectively opens up the possibility to perform chemical separation based on size-dependent variations in particle composition. The experience of the Rutledge Lab with materials and methods of evaluation for the removal of such fine aerosols found new importance with the onset of the COVID-19 pandemic in spring 2020, when the supply chains for personal protective equipment, in particular face masks and N95 respirators, rapidly became overwhelmed in the United States. While the (US Food and Drug Administration (FDA) was issuing emergency use authorizations to address the crisis, poor quality products were flooding the market from overseas, resulting in confusion and a crisis of confidence on the frontlines of the pandemic. By donating its time and expertise in aerosol filtration materials and characterization to hospitals, first responders, the Massachusetts Emergency Management Agency (MEMA), and companies pivoting their own production capacity to address the immediate need for PPE, the lab provided critically needed data for decision makers and frontline workers dealing with the COVID-19 pandemic. Over a hundred different types of respirators from the MEMA stockpile alone were screened for filtration performance, resulting in a database that has served users across the nation in a time of urgent need. This work was done in collaboration with AFFOA and the Manufacturing Emergency Response Team of Massachusetts.

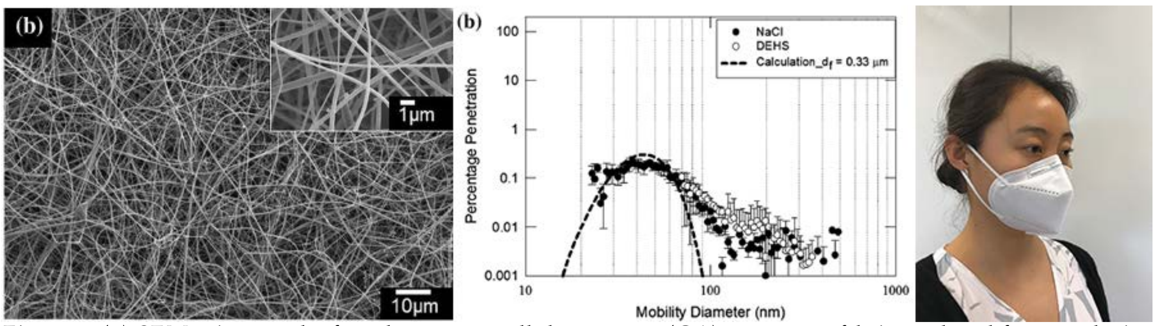

Figure 3. (a) SEM micrograph of an electrospun cellulose acetate (CA) nonwoven fabric produced from a solution of 15 wt% CA in a solvent comprising 3:1 acetone: N,N-dimethyl acetamide; (b) percentage penetration (the complement of filtration efficiency) for the CA nonwoven fabric, including data for solid aerosol (NaCl), liquid aerosol (diethylhexylsebacate, DEHS), and theory; and (c) example of a typical KN95 respirator, illustrating quality of fit with the ear loop design, and stringent requirement for both filtration efficiency and breathability over long periods of time.

Understanding the Brain Function and Dysfunction through Holistic Molecular Imaging (Kwanghun Chung)

Human organs such as the brain are stunningly complex. They consist of hundreds to thousands of separate functional areas, each containing a comparable number of distinct cell types and innumerable molecules. Understanding how these multi-scale components work together to generate system-level responses is essential for many fields of biology, but advancement in this area is hampered by the prevalent methodology of dividing biological systems into known cell types followed by a separate study of each population. Although powerful, this reductionistic approach makes it difficult to interrogate complex interactions at multiple levels—molecular (e.g., proteins), cellular, and area. Moreover, this approach could obscure many potentially important but unidentified functional networks. Our inability to thoroughly identify multi-scale functional networks and interrogate their multi-factorial interactions has limited our ability to understand the function and dysfunction of complex biological systems. We aim to fundamentally transform our approach from a reductionistic to a holistic one by developing a host of technologies that enable rapid, high-dimensional, quantitative phenotyping of organ-scale tissues.

To enable rapid and holistic phenotyping of organ-scale tissues, we have developed technologies that engineer transport of chemicals to enable rapid interrogation of organ-scale tissues, interactions between endogenous biomolecules and exogenous chemicals to enable scalable tissue processing, and physicochemical properties of biological samples to preserve biomolecules and their key features while allowing multiscale interrogation of intact organs.

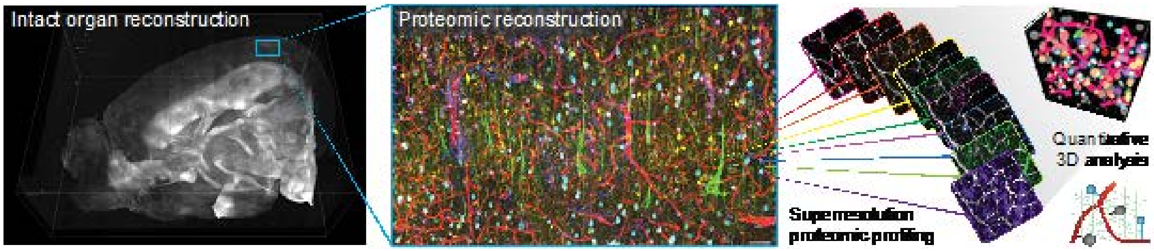

Figure 4. Proteome-driven holistic phenotyping of the brain. We develop novel technologies for proteome-driven holistic reconstruction of organ-wide, multi-scale networks. This new paradigm enables us to identify functional networks at multiple scales (from molecules to cells to tissue areas) and investigate their system-wide interactions.

To enable simple, scalable, and generalizable tissue-processing and molecular labeling, we developed SWITCH (System-Wide control of Interaction Time and kinetics of CHemicals), which tightly controls a broad range of chemical reactions in tissue processing simply via a set of buffers. Chemical reaction kinetics are governed by a multiplicity of non-covalent bonds such as hydrogen bonds, electrostatic forces, van der Waals bonds, and hydrophobic interactions. These weak forces can be effectively controlled by changing the surrounding chemical environment. We have developed a set of SWITCH-Off buffers that can effectively inhibit key reactions in tissue processing. First, we use the SWITCH-Off buffer to disperse inactivated exogenous chemicals throughout a sample. Once the chemicals are uniformly dispersed, we move the sample to the SWITCH-On buffer to switch the reaction sample-wide in a synchronized manner. Using this simple approach, we achieved both uniform preservation of large-scale clinical samples using multi-functional fixatives and uniform labeling with various molecular markers. We also demonstrated combinatorial protein expression profiling of the human cortex and interrogated the geometric structure of the fiber pathways in mouse brains.

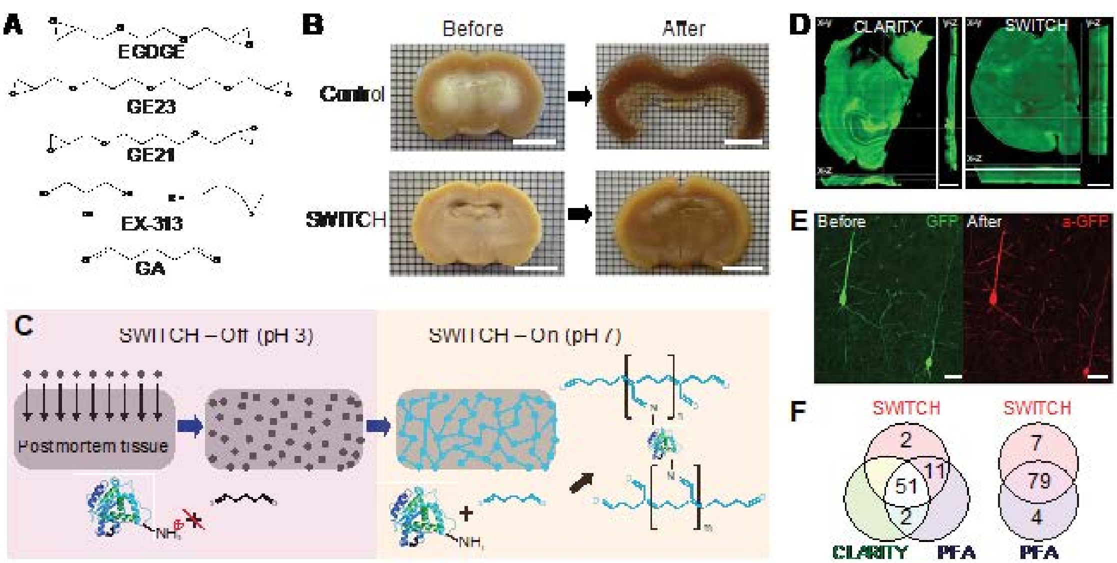

Figure 5. SWITCH-mediated tissue-gel formation renders tissues heat- and chemical-resistant while maximally preserving antigenicities: (a) multifunctional crosslinkers; (b) rat brain tissues showing that SWITCH-mediated fixation enables uniform preservation of large-scale tissues; (c) SWITCH-mediated tissue-gel formation; (d and e) SWITCH preserves macroscopic and microscopic structures against a harsh destaining condition; and (f) antigenicity of proteins is well preserved in SWITCH.

To characterize the multi-scale organization of intact tissues, we developed SHIELD (Stabilization to Harsh conditions via Intramolecular Epoxide Linkages to prevent Degradation), a versatile, tissue-processing method that simultaneously preserves key molecular information—nucleic acids, protein fluorescence, and protein immunoreactivity—in cleared intact tissues by using a polyfunctional flexible epoxide crosslinker. This chemical modifier renders individual biomolecules highly resistant to denaturation, protects their physicochemical properties (such as protein fluorescence) while minimally altering interactions with molecular probes (including antibodies), and secures biomolecules to their physiological location. We demonstrated that SHIELD enables ultrafast 3D processing of whole needle biopsies within only four hours, a process that takes days to weeks with other technologies. In addition, SHIELD combined with MAP allowed us to map neural projection patterns and their downstream targets at single cell resolution. SHIELD is a highly versatile platform built on a rationally designed crosslinker with controllable molecular interactions, and it should find wide application in the study of complex biological systems.

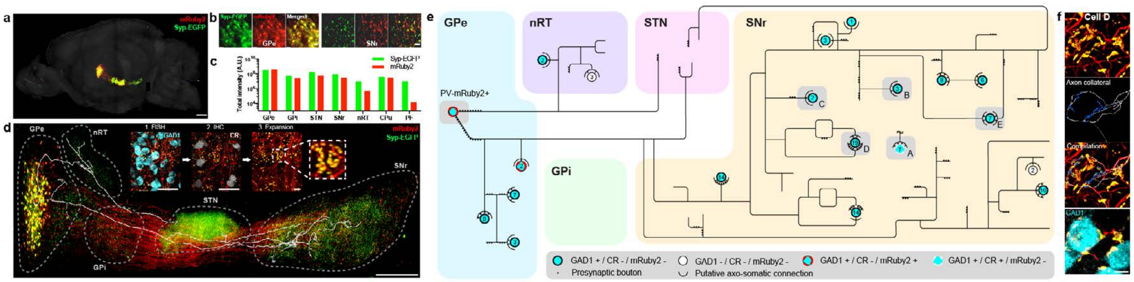

Figure 6. Integrated multi-dimensional cell-type mapping enabled by SHIELD and MAP: (a) 3D rendering of the intact mouse hemisphere showing brain-wide projection patterns of labeled GPe-PV+ neurons; (b) representative images of labeled neurons and their presynaptic terminals in GPe and SNr; (c) total pixel intensity of mRuby2 and EGFP in seven brain regions to which the labeled GPe-PV+ neurons project; (d) 3D rendering of GPe-PV+ neuronal circuitry with the overlaid axon trace of a single labeled neuron. The inset shows example images from multiround staining and multiscale imaging. Main scale bar, 1mm; insets, 50 μm. (e) Reconstructed axon arborization of the neuron and its downstream targets. Each circle represents a neuron. The number of putative axosomatic boutons is marked inside each circle. (f) Images of Cell D Scale bars, 20 μm.

To interrogate large-scale tissues (particularly human brain tissues), we developed Entangled Link-Augmented Stretchable Tissue-hydrogel (ELAST), a technology that transforms tissues into elastic hydrogels to enhance macromolecular accessibility and mechanical stability simultaneously. We discovered that ultrahigh concentrations of acrylamide (AAm) alone can polymerize to form an elastic hydrogel in a single synthesis step if extremely low concentrations of thermal initiator and crosslinker are used to synthesize long polymer chains that naturally undergo entanglement with each other under a densely packed environment. Compared to typical pAAm gels covalently linked by high concentrations of crosslinker, entangled pAAm gels are formed via physical slippery tangles between growing polymer chains. Such slip-links offer entangled gels great flexibility and elasticity. Our entangled pAAm gels showed exceptional stability against physical stresses, such as nine-fold compression and 10-fold stretching. ELASTicized tissues are highly stretchable and compressible, which enables completely reversible shape transformation while keeping subcellular architectures intact. By compressing and thinning the ELASTicized tissues, we achieved orders of magnitude faster delivery of probes into intact tissue specimens. We envision that ELAST will facilitate rapid and scalable molecular phenotyping of large-scale biological systems, such as human organs.

We have been collaborating with many groups to apply these technologies for studying various biological systems and questions. To highlight one of the studies, in collaboration with the Tsai lab, we applied SWITCH to the creation of a spatiotemporal map of beta-amyloid deposition in Alzheimer's disease (AD) mouse models. We discovered that brain structures connected by the fornix show primary susceptibility to beta-amyloid accumulation. We also discovered that the densest early beta amyloid aggregates occur in the mammillary body, coincident with electrophysiological alterations. We confirmed the presence of beta-amyloid aggregates in the mammillary body of postmortem patient specimens. This data suggests that subcortical memory structures are particularly vulnerable to beta amyloid deposition and that functional alterations within and physical propagation from these regions may underlie the progress of AD in increasingly complex networks. In addition, we applied SHIELD, SWITCH, and SE to study how multi-sensory stimulation decreases the beta-amyloid burden in AD mouse models. In an earlier study, the Tsai group reported that inducing gamma oscillations with a non-invasive light flicker influenced pathology in the visual cortex of AD mouse models. In the joint study, we applied our technologies to characterizing the effect of simultaneous auditory and visual stimulation on brain-wide amyloid plaque distribution. We discovered widespread reduction of amyloid plaques throughout the neocortex after multi-sensory stimulation. These findings indicate that noninvasive, multi-sensory stimulation drives circuit-wide attenuation of AD-related pathology, which is correlated with cognitive improvement.

Moving forward, the Chung Lab will continue to develop new technologies and apply them for interrogating abnormal neuronal circuits, cells, and molecules in diseased brains using animal models, postmortem human brain tissues, and organoid systems. We envision that a successful outcome for this research will fundamentally advance our understanding of brain function and dysfunction.

Annual Lectures and Seminars

During AY2020, the Department of Chemical Engineering hosted a distinguished group of academic and industry leaders, speaking on topics highlighting cutting-edge research addressing today's energy and health-related challenges.

17th Daniel I. C. Wang Lecture on the Frontiers of Biotechnology (October 25, 2019): "A Tale of Two Cities: What It Takes to Manufacture for Two Frontiers in the War on Cancer."

Michael P. Thien, ScD '88, senior vice president of global science, technology, and commercialization at Merck, discussed the ongoing fight against cancer and its battle on at least two new fronts. Vaccination, the first front, seeks to prevent cancer, while the second front includes launching and commercializing an immune-oncology product under breakthrough therapy designation. Thien has worked in new product and process development at Merck for over 30 years. He currently leads the Manufacturing Systems Design and Commercialization group, which is responsible for the introduction of new processes and methods for new vaccine and biological products, new product technology transfer, deep scientific and engineering support for in-line products, new facility introduction and startup, and development of the next and best practices for new facilities.

34th Hoyt C. Hottel Lecture (November 8, 2019): "Catalytic Conversion of Lignocellulosic Biomass to Biofuels and Bioproducts."

James A. Dumesic, Micek distinguished professor in the College of Engineering and the Michel Boudart Professor of Chemical and Biological Engineering at the University of Wisconsin at Madison, presented his thoughts on the potential of developing a bio-based economy for the production of fuels and chemicals from renewable biomass resources. Dumesic has co-founded two companies (Virent and Glucan Biorenewables) and pioneered new processes for creating bio-derived fuels and chemicals. He and his colleagues at the Wisconsin Energy Institute created an organosolv-type process for fractionation of lignocellulosic biomass for production of sugars and lignin that can be converted into biofuels and bioproducts. Professor Dumesic pioneered the field of microkinetic analysis, in which diverse information from experimental and theoretical studies is combined to elucidate the essential surface chemistry that controls catalyst performance.

26th Alan S. Michaels Lecture (February 21, 2020): "Translation of Discoveries into Products—An Industrial Perspective."

Hongming Chen ScD '97, chief science officer at Kala Pharmaceuticals, discussed Kala's journey of translating a novel technology from its early discovery through preclinical validation and clinical trials to ultimate FDA approval. Chen helped start Kala Pharmaceuticals in 2010. At Kala, she successfully translated a novel nanoparticle technology from bench discovery through phase three clinical trials and FDA approval, and has helped to attract over $250 million in investments to the company, including a $104 million initial public offering in 2017. Chen is a member of the National Academy of Engineering, a fellow of the American Institute for Medical and Biological Engineering, a fellow of the Controlled Release Society, and a member of the Academy of Distinguished Chemical Engineers at the University of Texas at Austin. In 2014, she was named by the Mass High Tech as one of the Women to Watch.

42nd Warren K. Lewis Lecture

Due to the COVID-19 pandemic, the Lewis Lecture, originally scheduled for April 17, 2020, has been rescheduled to spring 2021. Howard A. Stone, the Donald R. Dixon '69 and Elizabeth W. Dixon Professor in Mechanical and Aerospace Engineering at Princeton University, will be the speaker.

Departmental Awards

The Department Awards Ceremony took place virtually on May 29, 2020, in conjunction with our online commencement celebration. We are pleased to recognize this year's recipients of the Outstanding Faculty Awards: Arup Chakraborty was the graduate students' choice and Karthish Manthiram 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 student Jennifer Kaczmarek for her work in 10.10 Introduction to Chemical Engineering. The Outstanding Graduate Teaching Assistant Award was presented to PhD student Kevin Silmore for his work in 10.34 Numerical Methods Applied to

Chemical Engineering. 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 Pedro de Souza and Kevin Silmore.

Chemical Engineering Special Service Awards

Chemical Engineering Special Service Awards were conferred to the following members of the Graduate Student Council: Amber Phillips, Haley Beech, Brianna Lax, Kyle Lennon, Daniel Lundberg, Aditya Limaye, Matthew Van Beek, Alexi Khechfe, Keith Cheah, and Kaylee McCormack.

The following members of the Graduate Student Advisory Board were also recognized: McLain Leonard, Kimberly Dinh, Helen Yao, Supratim Das, Kindle Williams, Thejas Wesley, Kara Rodby, Bertrand Neyhouse, Alexi Khechfe, Mary Joens, and Zayla Schaeffer.

The following members of the Graduate Women in Chemical Engineering group were recognized: Kara Rodby, Lisa Volpatti, Junli Has, Jennifer Kaczmarek, Kelsey Reed, Narumi Wong, Maddie Dery, Katharine Greco, Yining (Lynn) Hao, Tam Nguyen, Stephanie Kong, Katherine Steinberg, Sarah Cowles, MayLin Howard, Kaylee McCormack, and Haley Beech.

Awards were also given to the members of the REFS (Resources for Easing Friction and Stress) group: Emily Krucker-Velasquez, Cynthia Ni, Kevin Silmore, MayLin Howard, Joy Zeng, Jennifer Kaczmarek, Chun Man Chow, and Cindy Jin.

The Michael Johnson Award went to Abdulrahman Al Mashaan and Aristotle Grosz. Mike Orella and Kindle Williams were awarded the Chemical Engineering Rock Award for their contributions to athletic achievement within the department.

The following undergraduate students were also recognized for their service to the student chapter of AIChE: Crystal Pham, Jenna Ahn, Taotao Zhang, Caroline Kenton, Delaney Burns, Evelyn Navarro Salazar , Hannah Loizzo, June Yan, Britney Pham, Kara Zhang, Jacky Chin, Daiyao Zhang, Kedi Hu, Michal Gala, Andison Tran, Ben Nguyen, Danica Dong, Juan Aleman, Sebastian Esquivel, and James Cao. Also recognized were the officers of the student chapter of NOBCChE: Jordan Alford and Ashton Dacon.

Other service awards went to the following officers of the Undergraduate Student Advisory Board: Johan Villanueva, Hannah Loizzo, Zachary Villaverde, Nicole Munne, Julie Tung, Andrea Orji, Michal Gala, and Daiyao Zhang.

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 Kaitlyn Hennacy. 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 Delaney Burns. The Lourdes C. and Wing S. Fong Memorial 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 Kedi Hu. Additionally, the 2020 Phi Beta Kappa electees were Delaney Burns, Kedi Hu, and Kaleigh Hunt. Daiyoa Zhang earned a Goldwater Scholarship and Michal Gala won the Henry Ford Scholar Award.

The department is pleased to recognize Gwen Wilcox as Outstanding Employee of the Year for her dedication and exceptional service to faculty, staff, and students. Eight Chemical Engineering Individual Accomplishments awards were given out to Britney Pham, Kara Zhang, Delaney Burns, Kindle Williams, Thejas Wesley, Caitlin Stier, Brian Smith, and Joey Gu. The Chemical Engineering Finance Team (Catherine Gyewu, Theresa Peterson, Kristal Kilmain, Brandon LaPorte, Liona Delva, and Nicholas Gibson) and Adrienne Bruno (assistant to the executive officer) received the School of Engineering's Infinite Mile Awards, which were presented at the Infinite Mile awards ceremony.

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

Kristala L. J. Prather
Executive Officer
Arthur D. Little Professor of Chemical Engineering