Department of Chemical Engineering

The Department of Chemical Engineering continues to be the best chemical engineering program (as ranked by *US News and World Report*) in the world, continuing its streak of more than 20 years in that position, and many of its faculty received major honors and awards. But despite that continuity, this is also a time of transition for the department, with a significant influx of new faculty, changes in the physical space it occupies, and significant engagement of faculty in new research organizations on campus.

Research volume in the department dipped to $44.9 million over the past year, with $25.6 million of these funds handled directly through the department and the rest handled by different cost centers at MIT. These centers include the Koch Institute for Integrative Cancer Research, the MIT Energy Initiative, and the Ragon Institute. The engagement with these interdisciplinary centers continues to provide a strong basis for innovation in the department, and provides our students with experience in solving important and difficult real-world problems.

Professor Klavs Jensen continues as department head, and professor William Green continues as executive officer. Patrick Doyle is graduate officer, Barry Johnston is undergraduate officer, and Karen Gleason is postdoctoral officer. The Department of Chemical Engineering claims two Institute Professors as primary faculty members: Daniel I.C. Wang and Robert Langer. This year, professor Robert Armstrong became the director of the MIT Energy Initiative, and professor Arup Chakraborty became director of MIT's Institute for Medical Engineering and Science (IMES).

New Faculty

This year the department welcomed Fikile Brushett as an assistant professor. Dr. Brushett earned his PhD at the University of Illinois. After doing postdoctoral research at Argonne National Laboratory, he arrived at MIT early in 2013. He is now setting up a research program on electrochemical engineering applied to energy problems.

It was a banner year for faculty recruiting, with three additional assistant professors joining the department in fall 2013: Kwanglun Chung, whose interest is in brain imaging and who holds appointments in IMES and Brain and Cognitive Sciences; Heather Kulik, specializing in computational chemistry; and James Swan, who works on complex fluids.

Space Changes and Renovations

In 2011, five members of the Chemical Engineering faculty moved into the new Koch Institute (Building 76). Early this year, four Chemical Engineering faculty members moved into newly renovated space on the 5th floor of Building E17 and Building E18. These moves significantly improved the department's research capabilities and relieved overcrowding. They also freed up enough space in Building 66 to make it practical to renovate that iconic but aging building. The much-needed renewal is projected to cost $45 million, with MIT providing $25 million toward new infrastructure. The department has begun to raise the remaining $20 million needed to create modern laboratories and offices. The renovations will encompass more than half of the building's total footprint, including every floor and all building operations. The improvements will:

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

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

Research and Recognition

Many senior Chemical Engineering faculty members received major awards for their research achievements. Robert Langer received the Wolf Prize in Chemistry and several honorary degrees this year, and was also elected a charter fellow of the National Academy of Inventors; a more comprehensive list of Professor Langer's recent awards and honors is given below. George Stephanopoulos was inducted into the American Academy of Arts and Sciences and received the Founders' Award for Outstanding Contributions to the Field of Chemical Engineering of the American Institute of Chemical Engineers (AIChE). Dane Wittrup was elected into the National Academy of Engineering, and also was named a fellow of the American Academy of Arts and Sciences. Gregory Stephanopoulos was elected a fellow of the American Academy of Microbiology; he also received the Siegfried Medal from the University of Zurich and the John Fritz Medal from the American Association of Engineering Societies. Michael Strano received the AIChE Nanoscale Science and Engineering Forum Award. Several other faculty members were honored to present named lectureships around the world.

Our junior faculty members have also received significant recognition, with Jesse Kroll receiving the Whitby Young Investigator Award, William Tisdale receiving the US Department of Energy (DOE) Early Career Award, and Bradley Olsen receiving the National Science Foundation Career Award.

Some noteworthy research accomplishments this year include Martin Bazant's theory of chemical kinetics and charge transfer based on nonequilibrium thermodynamics, published in *Accounts of Chemical Research*, and Kristala Prather's report in *Nature* Communications and patent for a biological method for producing hydroxybutyrolactone, an important intermediate in pharmaceuticals.

Undergraduate Education

Current Status of the Undergraduate Program

Since 2004, the Department of Chemical Engineering has offered bachelor of science (SB) degrees in both chemical engineering (Course 10) and chemical-biological engineering (Course 10-B). In fall 2011, the department introduced the 10-ENG flexible SB degree in engineering. Department undergraduate enrollment has been gradually declining since AY2007, but Chemical Engineering continues to have one of the highest student-to-faculty ratios in the School of Engineering. The department advises students about career paths in chemical and chemical-biological engineering through active participation in freshman advising seminars, fall and spring term open houses, parent's weekend, and other activities. Sixty-six SB degrees were conferred in June 2013, 59% 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	03–04	04–05	05–06	06–07	07–08	08–09	09–10	10–11	11–12	12–13
Sophomores	56	95	100	95	96	87	87	80	72	61
Juniors	43	55	83	75	67	77	68	71	73	63
Seniors	41	55	53	83	77	75	73	75	75	69
Total	**140**	**205**	**236**	**253**	**240**	**239**	**228**	**226**	**220**	**193**

The 10-ENG program leading to an engineering bachelor of science degree was introduced in response to demand from our students for a curriculum that would allow specialization in particular topics. The program features some flexibility, in that requirements of the department, the Institute, and the profession may be met in some cases by categories of subjects, rather than particular subjects. We will seek ABET accreditation of 10-ENG as a degree in engineering, not chemical engineering. The initial specialization tracks are energy, materials, biomedical, and environmental. Student response has been cautious (fall 2012 enrollment was eight).

The average starting salary for graduates of the Department of Chemical Engineering is $71,500 (2013 senior survey), which is among the highest in the School of Engineering. This attests to the success of the graduates of the 10 and 10-B programs and to the continued high demand for our students. The senior survey indicates that, for 2013, 54% 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 Mark Kalinich and Ksenia Timashova, co-presidents; Jean Fang vice president; Alan Miranda secretary; Khizar Qureshi, treasurer; Kim Aziz, social chair;

Michelle Teplensky, publicity chair; Tejas Navaratna, webmaster; Sam Hagerman, recruitment chair; David Hou, class of 2015 representative; Paige Finkelstein, class of 2014 representative; Mark Kalinich and Ksenia Timashova, class of 2013 representatives.

Graduate Education

Current Status of the Graduate Program

The graduate program in the Department of Chemical Engineering offers masters 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 222, with 212 in the doctoral program and 10 master's degree candidates. In the doctoral program, 202 students are in the PhD/ScD track and 10 are in the PhDCEP track. In the master's level program, seven are in the MSCEP track. Thirty-two percent of our graduate students are women. Four percent are underrepresented minority students. Forty-five of our graduate students were recipients of outside fellowship awards, including those from the National Science Foundation, National Institutes of Health, US Department of Defense, and others. The distribution of graduate students by degree is shown in Table 2 for the last 10 years. During the 2012–2013 academic year, 39 doctoral degrees (35 PhD or ScD, four PhDCEP) were awarded, along with 41 master's degrees (38 MSCEP, three MS) for a total of 80 advanced degrees conferred. Thirty-three students passed the written portion of the doctoral qualifying exams and are one step closer to being promoted to candidacy for the PhD/ScD or PhDCEP. The department received 357 applications for admission to the doctoral program, offered admission to 75 individuals, and received 55 acceptances, for a 73% acceptance percentage. Out of 67 applications for master's degrees, the department made nine offers and received eight acceptances of offers, for a 90% yield. Among the incoming graduate class for 2013, 22 are women and three are members of an underrepresented minority. On average, the incoming graduate class held an undergraduate GPA of 4.95 (out of 5.0).

Table 2. Graduate Enrollment over the Last 10 Years

Degree Level	03–04	04–05	05–06	06–07	07–08	08–09	09–10	10–11	11–12	12–13
Master's	26	19	16	18	26	32	38	28	20	10
Doctoral	232	216	203	217	212	228	203	212	224	212
Total	**258**	**235**	**219**	**235**	**238**	**260**	**241**	**240**	**244**	**222**

Research Centers

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

Novartis–MIT Center for Continuous Manufacturing

The Center for Continuous Manufacturing, now in the second phase (2012–2017) of a 10-year collaboration between Novartis and MIT, was formed with the vision of transforming pharmaceutical manufacturing from batch to fully integrated continuous manufacturing. The goal, represented by the "wind-pipe" vision (Figure 1), means end-to-end integration of the entire process, from synthesis of the active ingredient to production of the finished dosage form; a continuous flow of material; and 24 hour-a-day operations.

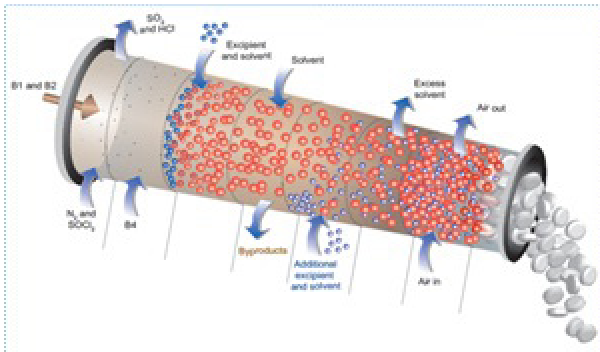

Figure 1. The goal, represented by the "wind-pipe" vision.

The vision within the center is transformational: rather than considering each process step as a separate entity, it takes a holistic view of the entire value stream, from chemical raw materials to the finished dosage form. All processes are intimately interlinked, and the need for corrective processing steps eliminated. This vision offers the potential for leaner processing, higher quality, more flexibility, and—in the end—cost savings.

To date, researchers have published 242 publications and presented findings at numerous international and national meetings. The center has filed patent applications for 10 breakthrough technologies in the past year alone. In addition to this, a core team of researchers successfully demonstrated fully integrated continuous manufacturing operation of an existing Novartis medicine using a pilot plant designed and built by MIT. This plant has been a very useful tool for understanding the complexities of integrated continuous manufacturing.

The second phase of the collaboration focuses on continued research and translation of novel technologies into integrated manufacturing tools. These new technologies will be developed by a team of approximately 50–60 researchers who are being led by 11 faculty members from three departments (Chemical Engineering, Mechanical Engineering, and Chemistry). Research areas cover the entire spectrum of pharmaceutical manufacturing processes, including chemical reactions, reactors, separations, formulations, final finishing steps, and process modeling and control. Novartis is adapting several of these innovative technologies and concepts developed by the center.

In addition to extensive research activities, the center has been engaged in outreach, hosting a successful one-day symposium in November 2012 that included executives from regulatory agencies, pharmaceutical and biotechnology companies, equipment manufacturers, and academia.

The Center for Continuous Manufacturing is led by Bernhardt Trout, MIT center director, and Markus Krumme, Novartis head of continuous manufacturing. In addition, the team consists of Stephen Sofen, MIT executive director, and Stephanie Bright, MIT program coordinator.

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: Daniel Anderson, Paula Hammond, Robert Langer, Christopher Love, and Dane Wittrup. The Koch Institute 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 is cutting-edge research on drug delivery, anchored by the efforts of Anderson, Hammond, and Langer. Paula Hammond was awarded the Department of Defense Ovarian Cancer Teal Innovator Award for creativity, innovation, and leadership on ovarian cancer research.

Faculty Notes

Professor Daniel G. Anderson is continuing his research on new biomaterials for cellular therapy and drug delivery. In particular, his research has lead to significant advances in the development of nanotherapeutics and RNA-based therapy, and technology developed in his laboratory is in clinical development as a genetic therapy for liver disease. His work has led to a number of high-impact publications in journals such as *Nature Biotechnology*, *Nature Nanotechnology*, and *Science*. He is a member of the Department of Chemical Engineering, the Institute for Medical Engineering and Science, the Division of Health Science and Technology, and the Koch Institute, and an associate member of the Broad Institute. He has been actively involved in the joint MIT–Skolkovo Institute of Science and Technology project. In 2013, professor Anderson founded the Skoltech Center for RNA Therapeutics and Biology and become its first director. This center will combine expertise in drug delivery, chemistry, biology, and medicine from experts in the United States and Russia, including the efforts of three Nobel laureates. This multidisciplinary effort seeks to advance science, generate new therapeutics, and foster collaboration between Russian and American scientists; it has a budget of approximately $10 million per year.

Professor Robert C. Armstrong became director of the MIT Energy Initiative (MITEI) in May, having served as the founding deputy director of MITEI since its beginning in late 2006. MITEI continues to grow rapidly in its research, educational, campus, and outreach components. Fifteen companies and public institutions sponsor research as founding and sustaining members of MITEI; altogether, the energy initiative has about 65 industrial and public partners across four continents. MITEI has helped to bring in approximately $490 million in support over its first six years of operation, with 252 energy graduate fellowships spread over 22 departments. Professor Armstrong serves on the AIChE board of directors, the scientific commission of the Eni Enrico Matteo Foundation, and the external advisory board of the National Renewal Energy

Laboratory. He serves on the advisory boards of chemical engineering departments at Georgia Tech; Northwestern University; the University of Colorado, Boulder; and Washington University.

Professor Martin Z. Bazant was promoted to full professor and continued research in electrochemistry, transport phenomena, and applied mathematics. His theoretical work was increasingly complemented by experiments exploring new methods of energy storage and water purification. He published 12 papers, including an invited article in *Accounts of Chemical Research,* on his theory of chemical kinetics and charge transfer based on nonequilibrium thermodynamics, which he has developed over the past seven years. The theory extends the Cahn-Hilliard and Allen-Cahn equations for chemically reacting ionic mixtures and provides the first mathematical description of phase transformations in porous battery electrodes. He delivered 10 invited talks, including the Peter G. Winchell Distinguished Lecture at Purdue University. Professor Bazant held the Joliot Chair at the École Supérieure de Physique et de Chimie Industrielles (or School of Industrial Physics and Chemistry) in Paris, France, and continued to serve on the editorial board of the SIAM Journal on Applied Mathematics. He taught 10.50 Analysis of Transport Phenomena, continued to develop 10.626/426 Electrochemical Energy Systems, and coached MIT teams in the Mathematical Contest in Modeling.

Professor Daniel Blankschtein's research group conducts fundamental theoretical and experimental research in the area of colloid and surfactant science, with emphasis on industrial and biomedical applications. Recent research advances include computer simulation/molecular-thermodynamic modeling of mixed surfactant micellization, molecular dynamics simulations of branched surfactant systems, molecular modeling of surfactant/polymer-induced stabilization of carbon nanotubes and grapheme sheets in aqueous media, molecular modeling of the wetting behavior of water on graphene, oral drug delivery using an ingestible ultrasound-emitting pill, and ultrasound-assisted transdermal vaccination. Professor Blankschtein's group interacts closely with several companies that make use of software developed by his group to facilitate surfactant formulation design. His teaching responsibilities included graduate course 10.40, Chemical Engineering Thermodynamics, in fall 2012, and the Program in Polymer Science and Technology interdisciplinary graduate course 10.43, Introduction to Interfacial Phenomena, in spring 2013. Professor Blankschtein and his students delivered talks and presented posters at the 2012 American Institute of Chemical Engineers annual meeting, and hosted representatives of Procter & Gamble at MIT to deliver tutorials on recent advances in surfactant research. Professor Blankschtein continues to serve on the editorial board of Marcel Dekker's Surfactant Science Series.

Professor Richard D. Braatz continued research in control systems engineering with pharmaceuticals, materials, and energy applications. He redesigned lectures in 10.34 Numerical Methods, and as graduate admissions officer for chemical engineering, he led a very successful recruiting year (greater than 70% acceptance rate). In 2013 he was selected to be a distinguished lecturer by the IEEE Control Systems Society. His numerous invited talks included plenaries on pharmaceutical manufacturing at the IEEE Multi-Conference on Systems and Control and the AIChE annual meeting. Professor Braatz served on numerous award committees and advisory and editorial boards, and was editor-in-chief of *IEEE Control Systems Magazine*.

Assistant professor Fikile R. Brushett began his position in the Department of Chemical Engineering in January 2013, where he currently holds the Raymond A. & Helen E. St. Laurent career development chair. His research aims to accelerate the development of electrochemical engineering systems, with an overarching goal of enabling sustainable energy technologies. The group has been awarded funding from the Joint Center for Energy Storage Research, an Energy Innovation Hub sponsored by DOE and led by Argonne National Laboratory, and from MITEI. The Brushett group presently consists of two postdoctoral students and one pre-freshman.

Professor Arup K. Chakraborty continued his research at the convergence of physical science, engineering, and medicine. Perhaps, the most important finding emerging from his laboratory this year is the development of a general method that allows the translation of virus sequences into a quantitative fitness landscape. The availability of viral fitness landscapes makes possible the rational design of immunogens for vaccines against scourges such as HIV. The published paper was highlighted by *Cell*, *Immunity*, and similar publications. The laboratory has designed an immunogen based on the Gag polyprotein of HIV that is being moved to animal trials in laboratories at MIT and Massachusetts General Hospital. Professor Chakraborty directed the successful launch of IMES, including the hiring of two new faculty members (one with Chemical Engineering and the Picower Institute, and one with Electrical Engineering and Computer Science). He successfully led the effort to raise philanthropic support for the $10 million renovation of space that will help attract outstanding new faculty to MIT to work at the intersection of engineering, science, and medicine. Professor Chakraborty continues to serve the National Academy of Engineering, the American Academy of Arts and Sciences, and the Dreyfus Foundation in numerous ways. The US Secretary of Defense has recently appointed him as a member of the Defense Science Board, an influential group in determining defense research priorities for our country.

Professor Robert E. Cohen was the 2012 recipient of the Paul J. Flory Polymer Education Award and presented at a daylong symposium in his honor at the New Orleans meeting of the American Chemical Society (ACS). In 2013 he was honored with election as a fellow in the Polymer Division of the ACS. Having competed successfully for funding from the School of Humanities, Arts, and Social Sciences–administered MIT–Balliol College Faculty Exchange, Professor Cohen spent the first six months of 2013 on sabbatical leave at Oxford University, where he has longstanding ties with colleagues in the Department of Engineering Science. In the second half of 2013 he will be in residence at École Supérieure de Physique et de Chimie Industrielles in Paris, where he will collaborate with scientists and engineers on wetting phenomena and environmental water management technologies.

Professor Charles L. Cooney, Robert T. Haslam (1911) professor of chemical and biochemical engineering, continued as the faculty director of the Deshpande Center for Technological Innovation and as faculty lead for the entrepreneurship and innovation activities associated with the MIT–Skolkovo Institute of Science and Technology initiative. In addition, he serves on the National Institutes of Health (NIH) Engagement Committee, the Advisory Committee for Regional Engagement, the MIT–Sanofi Joint Scientific Steering Committee, the executive committee of the Masdar Institute of Science and Technology (Abu Dhabi), the Center of Biomedical Innovation steering committee, the steering committee of the bioengineering section of the MIT Portugal Program, the steering committee of the Novartis–MIT Center for Continuous Manufacturing, the executive committee of the Legatum Center, and the advisory committee to the Singapore–MIT Alliance for Research and Technology (SMART) Innovation Center. He is co-chair of the MIT India Strategy Group. He is the faculty director of the downstream processing summer course held through MIT's Professional Institute. His research focuses on pharmaceutical manufacturing and technological innovation. He was named a fellow of the American Chemical Society. Professor Cooney is also an overseer of the Boston Symphony Orchestra and a trustee emeritus of the Boston Ballet.

Professor Patrick S. Doyle continued to advance his work on DNA polymer physics and microfluidic synthesis of functional microparticles using stop-flow lithography. He received the Michael Mohr Outstanding Faculty Award, which "recognizes excellence in teaching in undergraduate subjects." He was awarded a Singapore Research Chair at MIT and continues to run an active group in Singapore at the SMART center. Professor Doyle delivered keynote talks at the Asian Pacific Congress on Chemical Engineering, International Congress on Rheology, and the Materials Research Society Meeting. He also delivered a series of three invited lectures as part of the Soft Matter Lectureship Award. Professor Doyle continues to serve as the graduate officer for the Department of Chemical Engineering.

Professor Karen K. Gleason presented the Tis Lahiri Lecture at Vanderbuilt University. She also gave invited seminars at Cornell University, Boston University, the Masdar Institute of Science and Technology, the ASC Fluoropolymer 2012 Conference, and the Society of Vacuum Coaters. Her group's work on 2D deterministically wrinkled patterns and on the room temperature passivation of silicon were featured by the MIT News Office. This year she agreed to serve the department as the first postdoctoral officer, overseeing activities for this growing segment of the MIT community. Professor Gleason continues to serve as chief scientific advisor to GVD Corporation, a technology company she cofounded to commercialize inventions from her laboratory. GVD is headquartered in Cambridge, MA, with a commercial manufacturing facility in Greenville, SC.

Professor William H. Green continues as executive officer of the Department of Chemical Engineering. He plays several roles in MITEI, in both research and education, and also plays a leading role in DOE's Energy Frontier Research Center for Combustion Science. Professor Green stepped down from his position as editor-in-chief of the *International Journal of Chemical Kinetics* in July 2013. Research highlights include the invention of a sorbent well suited for CO_2 capture in integrated gasification combined cycle coal plants, the discovery of new reactions of organic peroxides and sulfides, and the accurate prediction of the combustion chemistry of isobutanol, a new biofuel.

Professor Paula T. Hammond has been elected to the 2013 class of the American Academy of Arts and Sciences; she will be inducted into the academy this October. She is the recipient of the 2013 AIChE Charles M.A. Stine Award, which is bestowed annually on a leading researcher in recognition of outstanding contributions to the field of materials science and engineering. She has also been selected to receive the

Department of Defense Ovarian Cancer Teal Innovator Award in 2013, which supports a visionary individual from any field principally outside of ovarian cancer to focus his/her creativity, innovation, and leadership on ovarian cancer research. During her sabbatical this year, she is a visiting scientist at the Dana-Farber Cancer Institute. She is also a visiting professor in the Chemical Engineering Department at the Nanyang Technological University in Singapore. Professor Hammond continues to serve as an associate editor of the American Chemical Society journal *ACS Nano*. She was the Margaret Etters lecturer in chemistry at the University of Minnesota in spring 2013, and she will give a plenary lecture at the Controlled Release Society annual meeting in July. Professor Hammond continues to serve as scientific advisor for Svaya Nanotechnologies, a company based on her patent for spray-layer-by-layer techniques, and as an associate editor for *ACS Nano*. New research developments in her laboratory that have been recently published include a multilayered DNA vaccine delivered with microneedles in a collaboration with the Irvine Laboratory (*Nature Materials*, 2013) and an osteogenic thin film coating that supports bone integration in implants, published in *Science Translational Medicine*.

Professor T. Alan Hatton continued to serve as the director of the David H. Koch School of Chemical Engineering Practice, where he has maintained the international flavor of the program by placing student teams at host companies in Switzerland and the UK, in addition to companies in the US. He has advised Masdar Institute and Skoltech on the potential establishment of Practice School–like programs in Abu Dhabi and Russia. He is an active participant in the Singapore–MIT Alliance (SMA) program on chemical and pharmaceutical engineering and is a member of the scientific advisory boards of the Particulate Fluids Processing Center at the University of Melbourne, and of the GSK–Singapore Partnership for Green and Sustainable Manufacturing in Singapore. He completed his term of service on the editorial advisory board of *Langmuir*, and is an advisory board member of Engineering Conferences International in New York. In addition to a number of presentations at ACS and AIChE meetings, and at a number of companies in the US and abroad, Professor Hatton has given presentations at the Council for Scientific and Industrial Research in Pretoria, South Africa; GHGT-11 (Green House Gas Technologies) in Kyoto, Japan; and the Singapore–MIT Alliance and GlaxoSmithKline symposia in Singapore. He presented the fourth biannual Gregory Botsaris Lecture at Tufts University in April.

In addition to his responsibilities as department head, professor Klavs F. Jensen served as chair of the School of Engineering Committee on Diversity while continuing his research on functional micro- and nano-structured materials and devices for chemical and biological applications. With collaborations in chemistry, he has explored a wide range of miniaturized flow systems for chemical applications with particular emphasis on systems for which continuous processing provides unique performance advantages. These systems also form the basis for continuous flow synthesis and separation developments as part of the Novartis–MIT Center for Continuous Manufacturing and the “Pharmacy on Demand” program sponsored by the Defense Advanced Research Projects Agency. The ability of small systems to operate at high pressure and temperature conditions not easily achieved in batch processing is being exploited in the synthesis of nanoparticles for optical and catalytic applications relevant to energy conversion through MITEI-sponsored projects. Biological applications, specifically devices to facilitate the transport of macromolecules across cell membranes, are being pursued in collaboration with Koch Institute researchers. During the past academic year, Professor Jensen gave plenary lectures on microreaction technology at international conferences and universities, including the Richard H. Wilhelm Lectures at Princeton University. He served on advisory boards to chemical engineering departments for the Korean Advanced Institute for Science and Technology (KAIST), Princeton University, and the University of Wisconsin. Professor Jensen also participated in the governing board of the Technical University of Denmark and on the scientific advisory board for the Singapore A*STAR Institute for Biotechnology and Nanotechnology.

Members of professor Jesse H. Kroll's group continued their research aimed at understanding the multiphase chemistry of the Earth's atmosphere. In addition to lab studies, the group participated in two multi-group field measurements focused on atmospheric composition, the Two-Column Aerosol Project (Cape Cod, MA, February 2013), and the Southern Oxidant and Aerosol Study (Centreville, AL, June 2013). During Independent Activities Period, Professor Kroll and members of his group ran "Traveling Research Environmental eXperiences," taking 14 undergraduates to the Big Island of Hawaii to measure the influence of volcanic emissions on local air quality. At the 2012 national meeting of the American Association for Aerosol Research, Professor Kroll received the Kenneth T. Whitby Young Investigator Award.

In 2012 and 2013, Robert Langer received honorary degrees from Boston University, Tel Aviv University, and Ben Gurion University. He was elected as a fellow of the American Institute of Chemical Engineers and as a charter fellow of the National Academy of Inventors. Langer received the Wolf Prize in Chemistry, the American College of Clinical Pharmacology's Distinguished Investigator Award and the college's Honorary Fellow Award, the Industrial Research Institute Medal, the IEEE Medal for Innovations in Healthcare and Technology, the Society of Biomaterials Founders Award, the American Institute of Chemists' Chemical Pioneer Award, the Priestley Medal, the Terumo International Prize, the Wilhem Exner Medal and the Nature Biotechnology Feodor Lynen Award. He presented the DuPont Inaugural Thomas H. Chilton Lecture, the BC^2 Annual Lecture (Wellesley College), the Warren L. McCabe Lecture (North Carolina State University), the Lucas Lecture (Colorado School of Mines), the Reed Izatt and James Christensen Lecture (Brigham Young University), Professor Dame Julia Polak Inaugural Lecture (Imperial College), Eliahu Caspi Memorial Lecture (University of Massachusetts Medical School), the Gladstone Distinguished Lecture (University of California, San Francisco) and the Kavli Foundation Innovation in Chemistry Lecture (American Chemical Society).

Professor J. Christopher Love continued his research applying new bioanalytical processes to profile immune responses in chronic diseases, including HIV/AIDS, multiple sclerosis, Type 1 diabetes, cancer, and food allergies. His laboratory also continued to assess clonal variation in biomanufacturing processes, directed toward lowering the costs of producing protein therapeutics to promote global access. The lab received two new awards from the NIH Single-Cell Analysis Program to promote the development of its core technology for adoption by other academic investigators, and an

NIH Director's Project award for research on Type 1 diabetes. Professor Love delivered 22 invited lectures, including lectures at the Pittsburgh Conference on Analytical Chemistry and Applied Spectroscopy (two), St. Jude's Hospital, Stanford University, California Institute of Technology, University of Minnesota, New York University, Northwestern University, and the NIH Vaccine Research Center, and a plenary lecture at the International Society of Neuroimmunology. Professor Love also remained active as a member of the Koch Institute and an associate member at both the Broad Institute and Ragon Institute.

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

Professor Bradley D. Olsen's group continued its research efforts in the areas of block copolymers, polymer gels, and protein-based materials for applications in defense, energy, sustainability, and human health. This research is supported by the Air Force Office of Scientific Research, the Institute for Soldier Nanotechnologies, DOE's Office of Basic Science, the National Science Foundation, and the Defense Threat Reduction Agency. During the year, Professor Olsen published 11 peer-reviewed papers and presented 17 invited lectures, including a keynote lecture at the MIT EmTech India conference and a plenary lecture at the American Institute of Chemical Engineers annual meeting Division 8a symposium. Of these presentations, two were at international meetings and four were visits to corporate research centers. His group also submitted a provisional patent application on new injectable hemostats. Olsen was awarded a 2013 National Science Foundation Faculty Career Development Program award from the Division of Materials Research and will start his tenure as the Paul M. Cook career development assistant professor on July 1. He served as an instructor for 10.566, Structure of Soft Matter, a new course on the structure of soft materials, and 10.569, Synthesis of Polymers, during the 2012–2013 academic year.

Professor Kristala L. J. Prather continued her research activities primarily in the areas of metabolic engineering and synthetic biology as the Theodore T. Miller career development associate professor. Her group recently published papers in the *Proceedings of the National Academy of Sciences* reporting the synthesis of odd-chain fuels and chemicals, and in *Nature Communications* describing the first-ever biological synthesis of 3-hydroxy-γ-butyrolactone, a molecule of significance as a pharmaceutical intermediate. A patent for the latter technology was issued in January (US patent no. 8,361,760). Professor Prather gave 16 invited lectures, including the keynote lecture at the Biocatalysis Gordon Research Seminar and a Frontiers of Chemical Research lecture at the Council for Chemical Research's annual meeting. Honors she received in the past year include serving as the Van Ness Lecturer at the Rensselaer Polytechnic Institute and selection as one of four Young Scientists to represent the United States at the World Economic Forum Annual Meeting of the New Champions (Tianjin, China). Professor Prather remained active in the academic community, serving on the editorial boards of three biotechnology journals and as co-chair for the 2013 International Conference on Biomolecular Engineering. Her teaching activities included 10.28 Chemical-Biological Engineering Laboratory and 10.10 Introduction to Chemical Engineering, and she continues to serve as co-director of the long-running Fermentation Technology course founded by professor Daniel I.C. Wang and offered through the MIT Professional Education program. Most recently, Professor Prather was promoted to the rank of associate professor with tenure (effective July 1, 2013).

Professor Yuriy Roman served as the Texaco Mangelsdorf career development assistant professor in chemical engineering. He continued his work on heterogeneous catalysis and materials design for the conversion of alternative feedstock, including biomass, natural gas, and CO_2. This work has attracted sponsorship from a variety of federal and industrial sources, including NSF, DOE, BP, and ENI S.p.A., among others. He published six peer-reviewed journal articles and filed two patent applications. His work on water-tolerant Lewis acids for the conversion of biomass-derived carbohydrates appeared in the journals *Nature Communications* and *Angewandte Chemie*. Professor Roman gave five invited lectures, including three seminars at corporate research centers. In spring 2013, he became the vice-president of the New England Catalysis Society. He also served as an instructor for 10.492 Integrated Chemical Engineering Topics I in fall 2012 and as a co-instructor for 10.37 Chemical Kinetics and Reactor Design in spring 2013. Together with his wife, Roman continued to serve as associate housemaster in Ashdown House.

Professor Gregory C. Rutledge is the Lammot du Pont professor of chemical engineering. His research involves the molecular engineering of soft condensed matter. The Rutledge group develops process-structure-property relationships for advanced plastics by molecular simulation. In the laboratory, they are pioneering the technology of "electrospinning" for the fabrication of novel nanofibers and membranes for a variety of applications. Recent alumni of the group have joined the faculty of Cornell University, California State Polytechnic University Pomona, and India Institute of Technology Mumbai. Over the past year, Professor Rutledge delivered invited or plenary lectures in Luxembourg, Australia, Taiwan, Japan and the US, as well as at the Gordon Research Conference on Polymer Physics. He was the invited speaker on semicrystalline materials for the National Science Foundation workshop on the Materials Genome Initiative. He organized the fall 2012 meeting of the Fiber Society in Boston, with Cheryl Gomez of Qinetiq North America. He is co-editor for the *Handbook of Polymer Crystallization*, associate editor of the *Journal of Engineering Fibers and Fabrics*, and on the editorial boards for the journals *Macromolecules* and *Polymer*. He is co-chair of the Committee on Research Computing at MIT and coordinator of accreditation by ABET for the Department of Chemical Engineering.

Professor Hadley D. Sikes and her research group continued their work in the area of molecular technology development with the overarching goal of improving human health. One set of projects focuses on low-cost, user-friendly diagnosis of disease using samples of bodily fluids. Targeted diseases include several cancers, malaria, and tuberculosis. Other efforts within the group focus on developing molecules and methodologies for quantitative measurement and modulation of redox states in living human cells. The goal of this work is defining and exploiting therapeutic windows for treating cancers using redox-based approaches. Hadley and several lab members presented talks and posters at the annual meeting and at the Society for Biological Engineering's (SBE) International Conference on Biomolecular Engineering. The lab received two new awards to support future research, one from the congressionally directed Medical Research Program (Prostate Cancer) and one from the NIH as part of MIT's Center for Environmental Health. Hadley served her research communities as conference chair of the Sensors Topical conference (AIChE), as a protein engineering session chair (AIChE and SBE), and as a regular member of a NIH study section.

Professor George Stephanopoulos continued his research, "Process Systems Engineering at the Nanoscale: Conceptual Design, Fabrication, and Operation of Nanoscale Processes," with particular focus on the following specific research directions: optimal control for the assembly of nanoparticles to structures with desired geometries, and conceptual reformulation of intracellular transformations into four interacting networks of molecular interactions.

In collaboration with professors Prather, Olsen, and Roman, George Stephanopoulos embarked on an integrated study for the identification of commercial polymers from biomass and the biochemical and catalytic paths for their manufacturing. In October 2012 he was inducted as fellow of the American Academy of Arts and Sciences and in November 2012 at the AIChE annual meeting he received the Founder's Award for Outstanding Contributions to the Field of Chemical Engineering. At the annual meeting of the American Institute of Chemical Engineers in Pittsburgh, PA, Professor Stephanopoulos presented the following papers: "Sustainability in the Chemical Industry through Collaborative Process Engineering,""NanoScale Process Systems Engineering: Design, Fabrication, Monitoring, and Control," and "The Work and Legacy of Arthur W. Westerberg." In fall 2012 he also presented the keynote address at the Chemical Engineering Graduate Students Association symposium at Carnegie Mellon University.

Professor Gregory Stephanopoulos, the W.H. Dow professor of biotechnology and chemical engineering, continues to serve as director of the Laboratory of Bioinformatics and Metabolic Engineering. The efforts to engineer microbes in order to convert them to little chemical factories for the production of fuels and chemicals continued, with successes in various areas, such as tyrosine synthesis and xylose assimilation by yeast for biofuel production. In parallel, he continued the investigation of the metabolic aspects of cancer, with particular focus on the identification of therapeutic metabolic targets. Besides running his laboratory of 25 researchers, Professor Stephanopoulos continued his service on the advisory boards of four academic institutions and as chair of the Managing Board of SBE, which promotes the integration of biology and engineering to provide enabling technologies for industrial and medical applications. He delivered the 2012 Global Distinguished Lectures at KAIST, the 2012 Alumni Lectures at the University of Massachusetts, and the 2013 Mason Lectures at Stanford University. He also continues to serve as editor-in-chief of the journal *Metabolic Engineering*, and on the editorial boards of eight other scientific journals. Besides numerous research presentations at professional societies' meetings (AIChE, ACS, American Society for Microbiology), he also delivered plenary and keynote lectures at the National Academy of Engineering–National Academy of Sciences joint conference on synthetic and systems biology; at the 15th International Biotechnology Symposium, in Daegu, Korea; and at the international conference of the CO_2 Forum, Large-volume CO_2 Utilization, in Lyon, France. During this academic year, professor Greg Stephanopoulos won the Siegfried Medal (University of Zurich) for outstanding accomplishments in process chemistry and the John Fritz Medal from the American Association of Engineering Societies. He was also elected a fellow of the American Academy of Microbiology.

Professor Michael S. Strano has continued his research focusing on the chemical engineering of low-dimensional systems. He recently delivered the Barnett F. Dodge Distinguished Lecture in Chemical Engineering at Yale University; the 2013 Stratis V. Sotirchos Memorial Lectureship, awarded at the 9th Panhellenic Scientific Chemical Engineering Congress in Athens, Greece; and was appointed to the Defense Science Study Group of the US Department of Defense. He was awarded the 2012 AIChE Nanoscale Science and Engineering Forum Award at the annual meeting of the AIChE last year. He was the keynote lecturer at the 2012 Brazilian Physical Society Meeting and the 2012 Sukant Tripathy Annual Memorial Symposium at the University of Massachusetts, and an invited speaker at the Gordon Conference on electron transfer systems in August. He delivered invited lectures in the chemical engineering departments of Purdue University, the California Institute of Technology, the University of Colorado, Boulder, and North Dakota State University, and at the Mayo Clinic Physiology Department in Rochester, MN, among others. He also delivered a TED talk at the Embry-Riddle Aeronautics Institute on "Energy Conversion Using Thermopower Waves." Professor Strano joined the editorial board of the ACS journal *Langmuir*, and became associate editor of *Current Protocols in Chemical Biology* during the past year. The Strano research group recently published a new theory of the electron transfer chemistry of graphene, showing experimentally that electron-hole puddles induced by a given surface can promote, or completely suppress, the chemical reactivity of graphene. This lead to a new technique, published in *Nature Chemistry* as "Chemical Reactivity Imprint Lithography." The Strano laboratory has also recently extended DNA origami to the templating of graphene, demonstrating the production of nanoscale rings and cross-bar structures from a new solution phase method reported in *Nature Communications*. Professor Strano continues to serve on the AIChE Awards Committee.

William A. Tisdale entered his first full year in the Department of Chemical Engineering, where he is currently the Charles and Hilda Roddey career development assistant professor. Tisdale's research interests lie in understanding and controlling the movement of energy in nanostructured materials, with particular emphasis in advanced optical spectroscopy and imaging techniques. In September his research group moved into newly renovated laboratory space on the first floor of Building 66. In April, Tisdale received the 2013 Early Career Award from the DOE Office of Basic Energy Sciences. Tisdale was a co-instructor for 10.302 Transport Processes and 10.27 Energy Engineering Projects Laboratory.

Professor Bernhardt L. Trout continued as director of the Novartis–MIT Center for Continuous Manufacturing and as co-chair of the SMA chemical and pharmaceutical engineering program, in addition to running a laboratory of 20 graduate students, post-doctoral associates, and staff focusing on pharmaceutical small molecule manufacturing and biopharmaceutical formulation and stabilization. This year, the Novartis–MIT Center successfully completed its historic fully automated end-to-end continuous pharmaceutical process. The focus of the center is now on developing a set of platform technologies to exploit the value of continuous processing across the board. Other recent scientific accomplishments in the Trout group include elucidation of the molecular mechanisms of heterogeneous nucleation of small molecular organics through both computational and experimental methods and the development of methods to predict viscosity and protein-protein binding of biotherapeutics. Professor Trout gave more than 10 invited talks, including several keynote and plenary talks, and published or submitted more than 20 research papers and five patent applications. He is on the scientific advisory boards of three companies. He has also developed a new educational initiative, the Benjamin Franklin Project, aimed at broadening the education of MIT undergraduates in the realms of ethics, the foundations of economics and leadership, and the origin of modern science.

Professor Daniel I.C. Wang continued to be involved in SMA activities. He has two PhD candidates in Singapore. Both of these students spent the spring term at MIT. He continued his SMA research on high throughput systems for mammalian cells and his research with Saudi Aramco on the microbial desulfurization of crude oil. He attended the Biochemical and Molecular Engineering conference in Beijing, China, for which he was the honorary chairman. In addition, he was invited by the Bioprocessing Technology Institute of A*STAR, Singapore to serve as chairman of the scientific advisory board.

Six years ago Professor Dane Wittrup co-founded Adimab LLC, an industry-leading human antibody discovery company. Last year a cocktail of three anticancer antibodies discovered at Adimab entered clinical trials in collaboration with Merrimack Pharmaceuticals. Recently Adimab announced nonexclusive technology platform transfer deals with GlaxoSmithKline and Biogen Idec, empowering those companies to use Adimab's antibody discovery methods to discover new drugs. Wittrup laboratory alumni progressed in their academic careers: Jennifer Cochran was awarded tenure at Stanford University, Bala Rao was awarded tenure at North Carolina State University, and Eric Shusta at the University of Wisconsin was awarded the ACS BIOT Young Investigator Award. Research in the Wittrup laboratory is shifting strongly toward understanding and developing immunotherapy for cancer.

Research Highlights

Structured Nanoemulsion Composite Materials (Patrick S. Doyle)

Hydrogels—viscoelastic solids consisting primarily of water contained within a structure-forming gelator—have attracted significant interest as scaffolding materials for applications in molecular separations, stimulus-responsive materials and devices, and biotechnology. Similarly, organogels, in which the gelator is dispersed in an oil or non-polar solvent, have received significant attention for use in pharmaceuticals, nanotemplating, and photonics. Both types of gel are typically formed by physical or chemical crosslinking of structure-forming components, such as synthetic or naturally occurring small molecules and polymers. In particular, self-assembly provides a low-energy route for structure formation and allows for facile encapsulation of macromolecules, colloids, and biological entities such as cells and bioactives. Emerging applications, including advanced therapeutics and sol-gel syntheses, have identified a need for self-assembled "organohydrogels" consisting of a plurality of both oil and water, where both polar and non-polar domains are required within the same microenvironment for the simultaneous encapsulation of both hydrophilic and hydrophobic species.

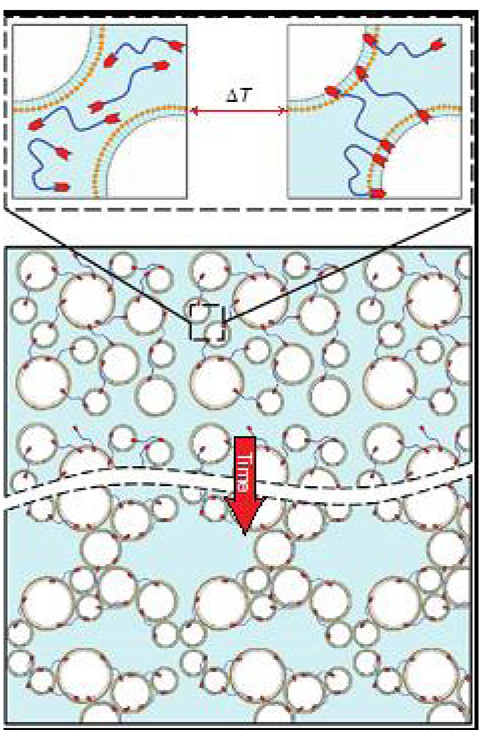

Figure 2: Schematic diagram of the hypothesized gelation mechanism.

The Doyle group has recently discovered (*Nature Materials* 2012) a new class of organohydrogels from oil-in-water nanoemulsions (30–300nm droplets) containing an end-functionalized oligomeric polymer as a gelling agent. The nanoemulsions exhibit an abrupt thermoreversible transition from a low-viscosity liquid to a fractal-like colloidal gel of droplets with mesoscale porosity and solid-like viscoelasticity with moduli approaching 100 kPa, the highest reported for an emulsion-based system. They hypothesize that gelation is brought about by temperature-induced interdroplet bridging of the gelator, as shown by its dependence on the gelator chemistry (Figure 2). Gel formation is robust over a wide range of compositions, droplet sizes, and gelator chemistries, allowing facile control of their mechanical properties and microstructure (Figure 3).

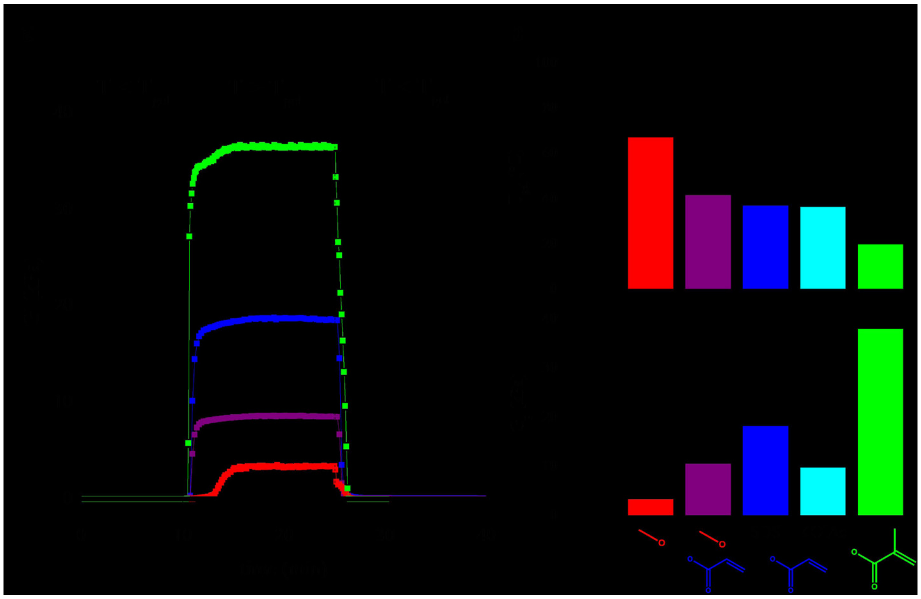

Figure 3: Control of organohydrogel properties through variation of PEG end-functional chemistry. (a) Oscillatory time sweep rheology measurements of gelation kinetics and reversibility during temperature jumps. (b) Measured gel temperature, Tgel, and plateau modulus, Gp, as a function of PEG functional chemistry.

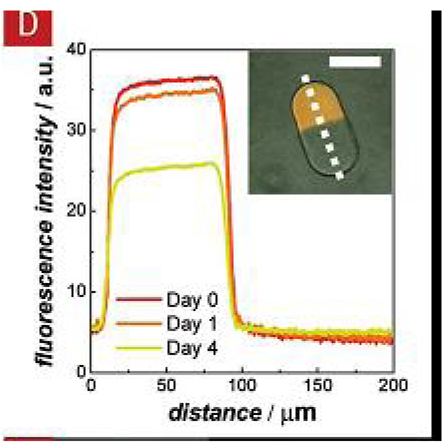

Figure 4: Example composite hydrogel microparticle containing region-specific nanoemulsion compartments. Nanoemulsions were labeled with a green or orange fluorophore to distinguish them.

Recently the Doyle group expanded on these discoveries by using crosslinkable gelators that enable the nanoemulsion microstructure to be "frozen" through photopolymerization, resulting in soft composites with enhanced mechanical properties (*Advanced Materials* 2012). An example microparticle motif is shown in Figure 4, where the Doyle group's flow lithography technique has been used to create microparticles loaded with two types of nanoemulsions (colored green and orange for clarity) that are localized in discrete compartments within a single microparticle. The encapsulation of nanoemulsions within a hydrogel matrix affords these materials several advantages compared with other advanced materials for encapsulation of hydrophobic compounds. The ability to produce nanoemulsions at high volume fractions allows for precise control of loading within the hydrogel, while the ability to tune the hydrogel network allows for a controlled barrier to release.

Over the past few months, the group has expanded the technique to create biomimetic red blood cells. The motif is a soft discoid hydrogel loaded with a fluorinated nanoemulsion. The fluorinated oil provides oxygen delivery, and the microgel delivery vehicle is designed to mimic the physical and chemical characteristics of a red blood cell. Additionally, similar constructs are being pursued to formulate and deliver hydrophobic drugs. Exciting possibilities exist in the future to continue to expand upon this tunable nanoemulsion platform to provide a new class of functional soft materials.

Responsive Mechanical Transitions in Injectable Protein Gels (Bradley D. Olsen)

Injectable hydrogels are being investigated for a wide variety of different therapies, ranging from drug delivery to tissue engineering for use as mechanical fillers in tissue. In all cases, the ability to introduce an injectable biomaterial using minimally invasive techniques promises to yield therapies that speed patient recovery and minimize medical costs and complications. One particularly attractive approach to such injectable biomaterials is to use shear-thinning gels. These gels are formed by reversible associations between groups decorating a polymer chain; under shear the reversible associations can be disrupted, leading to fluid-like macroscopic mechanical response. After the cessation of shear, the materials spontaneously self-heal, allowing the rapid recovery of solid-like mechanical properties. Such shear-thinning gels offer the particular advantages of being formulated as gels that are stable across a wide range of conditions ex vivo, that offer rapid setting times inside the body, and have the ability to be formulated without small molecule crosslinkers, which are often cytotoxic.

A major challenge in the application of such gels is that easy injection requires a low yield stress, meaning that the gels will flow through a narrow needle with a hand-operated syringe. However, once an implant is injected, many applications require it to be tough and durable to withstand normal physiological loads. Therefore, it is desirable to have injectable materials that can responsively transition from a shear-thinning state to a toughened state. Our group has developed such a system based on biocompatible shear-thinning artificially engineered protein polymer gels.

A protein is engineered consisting of alternating soluble polyelectrolyte domains and associating coiled-coil domains. Under a wide variety of conditions, the coiled-coils associate into pentameric bundles, inducing gelation of the protein midblock. These gels have been previously shown to exhibit shear-thinning and are cytoprotective during injection, a process which can often lyse a large fraction of cells. The thermoresponsive polymer poly(N-isopropylacrylamide) (PNIPAM) is grafted onto each end of the protein midblock, forming triblock copolymers that self-assemble to form a second, reinforcing network upon heating of the material above approximately 20°C. At low temperatures, the single protein network is shear-thinning; however, at high temperatures the copolymer self-assembly forms a “double-network” structure that creates a large reinforcement in the gel (Figure 5). These pioneering studies were led by MIT Course 10 graduate student Matthew Glassman with the help of a summer student, Jackie Chan, and were featured on a cover of the journal *Advanced Functional Materials*. A patent is currently pending on this technology.

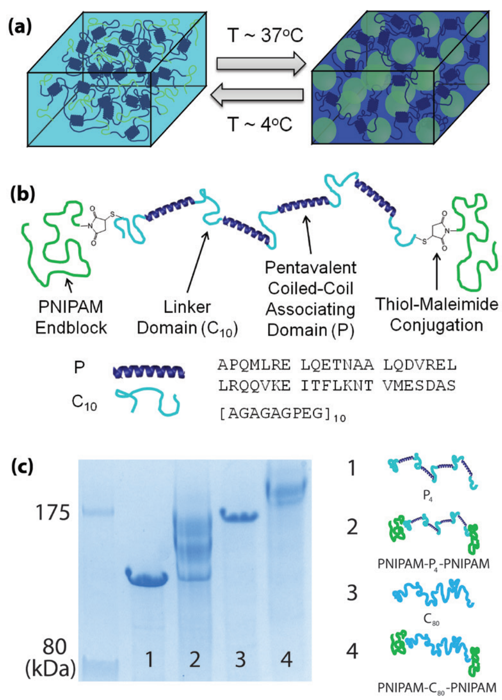

Figure 5. (a) Schematic of responsive self-assembly of PNIPAM triblock copolymer domains within a physically associating protein gel as a responsive mechanism to reinforce shear-thinning gels. (b) Molecular design of a hybrid triblock copolymer with a biofunctional protein midblock and synthetic polymer endblocks to achieve the reinforcement behavior.

It can be shown that the large mechanical enhancement is directly related to nanostructural transitions within the gels. The key is to engineer the responsive self-assembly such that the PNIPAM domains form micellar structures that occupy the largest possible volume, effectively jamming together to reinforce the gel (Figure 6). The report of this finding was featured as a "hot article" from the journal *Soft Matter* for June 2013. The ability to perform such stiffening and toughening transitions in shear-thinning biomaterials has attracted significant commercial interest. Applications are currently being developed or discussed in fillers for facial reconstruction, tissue stiffeners to prevent preterm birth, underwater adhesives, cosmetics, and cartilage replacement jointly with physicians, entrepreneurs, and potential corporate partners. In addition, the popular appeal of these materials has led to articles in MIT News and *Popular Mechanics*.

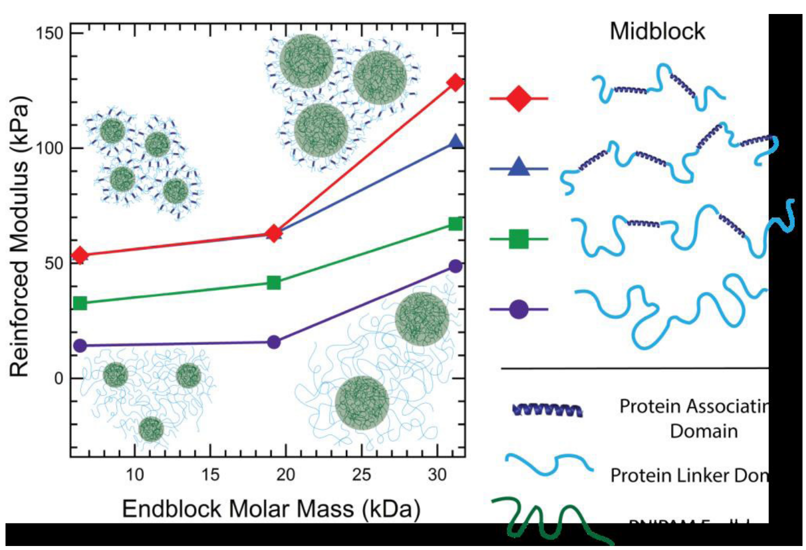

Figure 6. The greatest mechanical enhacements are observed when large, space-filling micelles are self-assembled within protein gels.

A different set of responsive mechanical transitions can be achieved when the same protein molecules are allowed to polymerize in response to redox stimuli, producing high molecular weight chains that can physically entangle within the gel (Figure 7). Topological entanglements between polymer chains are well-known to lead to high toughness in polymer melts, but typically such entanglements are absent in polymer gels due to the large amount of solvent that spaces out and disentangles the molecules. A summer researcher in our group, Shuali Li, discovered that very high molecular weight proteins may be prepared using oxidatively responsive cysteine couplings, triggering a transition from an unentangled gel to an entangled gel. While the modulus of the gel remains nearly unchanged, MIT graduate student Shengchang Tang showed that the presence of entanglements leads to a dramatic enhancement in the extensibility of the gel—up to 4,000 % engineering strain—and consequently a large increase in the toughness of the material. In contrast, the lower molecular weight protein gel has properties like Jell-O, easily fracturing at low strains. The large difference in performance is believed to be due to strain-induced chain alignment in the entangled system, which promotes a high degree of strain hardening within the protein hydrogel at large extensions. These results demonstrate that chain entanglement provides a second route to responsively reinforce injectable biomaterials, providing multiple molecular mechanisms for achieving dramatic changes in mechanical properties.

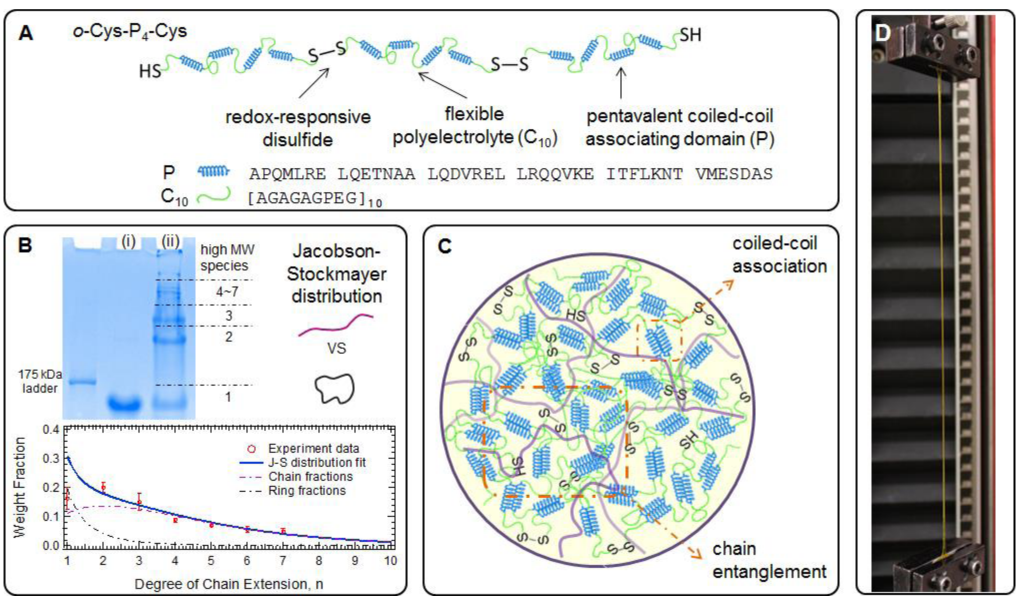

Figure 7 (A) Molecular design of oxidatively responsive chain extended artificially engineered protein. (B) Sodium dodecyl sulfate-polyacrylamide gel electrophoresis (SDS-PAGE) characterizing the molecular weight and its distribution of extended chains: (i) Cys-P_4-Cys before oxidation reaction, and (ii) chain extended protein mixture. The molecular weight distribution is analyzed by densitometry and further fit to a Jacobson-Stockmayer distribution that takes into account the intramolecular looping. (C) Schematic illustration of double network combining coiled-coil association and chain entanglement in protein hydrogels. (D) Extension to 3,100% engineering strain.

Lectures, Seminars, and Symposia

During 2012–2013, the Chemical Engineering Department hosted a distinguished group of academic and industry leaders who spoke on topics highlighting cutting-edge research addressing today's energy and health-related challenges. Seminar speakers included recent alumnus Hal Alper, now an assistant professor of chemical engineering at the University of Texas at Austin, and our own Robert Armstrong, the recently promoted director of MITEI. Highlights are noted below. Webcasts for all major lectures can be accessed at http://web.mit.edu/cheme/news/webcast.html.

Hoyt C. Hottel Lecture (November 30, 2012): "Emerging Technologies and the Future of Energy Production." Dr. Eric Toone, principal deputy director of DOE's Advanced Research Projects Agency discussed the current and future projects and goals of that agency. The Advanced Research Projects Agency funds novel technology ideas with the potential to improve energy security and reduce energy emissions. Since its start three years ago, the agency has generated promising technologies in a range of areas, such as batteries, cost-effective biofuels, and more efficient buildings. New program ideas include fast charging for electric vehicles, smart and autonomous sensing, better materials, biofuel crops, and ultra-low-cost hydrogen.

Alan S. Michaels Lecture (May 3, 2013): "What's in Your Blood? Molecular Deconvolution of the Human Serum Antibody Repertoire in Health and Disease." George Georgiou from the University of Texas at Austin's chemical engineering, biomedical engineering, and molecular genetics and biology departments, discussed his current research. His laboratory developed a suite of proteomic, microfluidic, protein engineering, and informatics technologies that enabled the deconvolution of the identities and relative amounts of antibodies in biological fluids and the delineation of the relationships between antibody production and the relevant B cell immunological mechanisms. He used this approach to elucidate a number of key questions in medicine and human health, including the repertoire and functionality of antibodies elicited in humans following vaccination, and the number of different antibodies in toto that are typically present in the blood. These technologies enable the development of potent therapeutic antibodies to infectious diseases, discovered via the mining of the protective antibody responses in convalescent patients, and more efficient metrics for new vaccines.

Warren K. Lewis Lecture (April 5, 2013): "Management's Codependence on Mother Earth: Sustainability in the Chemical Industry and the Four-Dimensional Analysis." Dr. Yoshimitsu Kobayashi, chief executive officer and president of Mitsubishi Chemical Holdings Corporation, discussed his much-praised management practice, called "kaiteki." When he assumed the leadership of Mitsubishi Chemical Holdings Corporation in 2007, Dr. Kobayashi radically restructured and repositioned the companies of the holding group in order to streamline and rationalize its traditional commodity-chemicals business while investing heavily to capture the opportunities offered in the marketplace by high-added-value functional products in human health and higher quality of living. Central to Dr. Kobayashi's management thinking was the concept of "good chemistry for kaiteki," which in Japanese implies "good chemistry for sustainability, health, and comfort." His management plan for the group of companies was guided by this concept. He established a new research institute to support his effort in a global scope. He wrote an influential book, *Good Chemistry for Kaiteki*. He established himself—in the words of David N. Weidman, chairman and chief executive officer of Celanese Corporation—as "a thought leader of responsible business."

Departmental Awards

The Department of Chemical Engineering's awards ceremony took place on May 13, 2013, in the Gilliland Auditorium of the Ralph Landau building. This year's recipients of the Outstanding Faculty Awards were professor William Deen (graduate students' choice) and Patrick Doyle (selected by the undergraduate students).

The Edward W. Merrill Outstanding Teaching Assistant Award was presented to PhD student Shengchang Tang for his work in 10.213 Chemical and Biological Engineering Thermodynamics. The Outstanding Graduate Teaching Assistant Award was presented to PhD student Chih-Jen Shih for his service to 10.50 Analysis of Transport Phenomena. All third-year graduate students are required to present a seminar on the progress of their research; the two recipients of the Award for Outstanding Seminar were Nigel Reuel and Sagar Chakraborty.

Chemical Engineering Special Service Awards were conferred on the following members of the Graduate Student Council: Steven Edgar, Sean Faltermeier, Rachel Hoffman, Kevin Kaczorowski, Lionel Lam, Rosanna Lim, Katie Maass, Sakul Ratanalert, Ray Smith, and Ben Woolston. The following members of the Graduate Student Advisory Board were also recognized: Emily Chang, Mo Jiang, Katie Maass, Sayalee Mahajan, Brandon Reizman, Tatyana Shatova, Ray Smith, Shengchang Tang, and Muzhou Wang. In addition, Ben Woolston was awarded the Chemical Engineering Rock Award for his contributions to athletics within the department. The following undergraduate students were recognized for their service to the student chapter of the American Institute of Chemical Engineers: Mark Kalinich, Ksenia Timachova, Jean Fang, Alan Miranda, Samantha Hagerman, Kimberly Aziz, Brian Alejandro, Michelle Teplensky, Tejas Navaratna, Paige Finkelstein, Charlotte Kirk and David Hou

Chemical Engineering undergraduates earned numerous accolades over the course of the year. The Xi Chapter of Phi Beta Kappa voted to invite five members of the Chemical Engineering Class of 2013 to membership in the society in recognition of their excellent academic records and commitment to the objectives of a liberal education: Nikita Consul, Tiffany Peng, Roberta Poceviciute, Eric Trac, and Camille Wasden. Julia B. Sun '15 was recognized as an Amgen Scholar. The Robert T. Haslam Cup, which recognizes outstanding professional promise in chemical engineering, went to Linh T. Bui. The department's oldest prize, the Roger de Friez Hunneman Prize—which is awarded to the undergraduate who has demonstrated outstanding achievement in both scholarship and research—this year went to John Yazbek. The Wing S. Fong Prize, awarded to a chemical engineering senior of Chinese descent with the highest cumulative GPA—given in honor of Wing S. Fong's hard work and dedication to his adopted home, university, and country—this year went to Tiffany Peng.

The department is pleased to recognize Joel Dashnaw as the department's Outstanding Employee of the Year for his dedication and exceptional service to faculty, staff, and students. Alison Martin was presented with a Chemical Engineering Individual Accomplishment Award for her contributions to the Chemical Engineering Headquarters Office. The School of Engineering Infinite Mile Award was given to Gwen Wilcox.

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

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