# Department of Chemical Engineering

In the Department of Chemical Engineering, the 2010–2011 academic year brought a new degree program (10-ENG), a series of new scientific accomplishments and honors for our faculty, and a great show of Chemical Engineering spirit as MIT celebrated its 150th anniversary. The department has retained its number-one ranking in *US News and World Report* in both the graduate and the undergraduate programs; we have now held the first-place position in chemical engineering for the past 22 years. We were also ranked number one among global universities by QS (formerly *Times Higher Education*).

Sponsored research volume in the department increased once again to a total of $53.3 million over the past year. Of this amount, $30.2 million is directly handled through the department, with the remainder handled by different cost centers at the Institute. These centers include the MIT Energy Initiative (MITEI), the Koch Institute for Integrative Cancer Research, the Ragon Institute, and the DuPont-MIT Alliance, among several others. The high level of interdisciplinary work and collaboration across fields continues to provide a strong basis for innovation in the department, as well as for the development of new investigative tools and computational approaches.

Professor Klavs F. Jensen continues his term as department head, and professor Paula T. Hammond continues as executive officer. Professor William M. Deen remains the department's graduate officer, and Barry Johnston continues to serve as undergraduate officer. Professor Richard Braatz started this year as chair of our graduate admissions program. Chemical Engineering continues to be proud to have two Institute professors as primary faculty members: Daniel C. Wang and Robert S. Langer.

## New Faculty Arrivals

In the upcoming academic year, we will welcome William Tisdale to our Chemical Engineering faculty as a new assistant professor. Will obtained his bachelor's degree in chemical engineering from the University of Delaware (magna cum laude) in 2005 and a PhD in chemical engineering from the University of Minnesota in 2010; he is currently a postdoc within the Department of Electrical Engineering and Computer Science's Organic and Nanostructured Electronics Laboratory. For his doctoral research, Will pioneered the use of a surface nonlinear optical technique for probing charge transfer at interfaces in nanostructured solar cells and then leveraged this ability to demonstrate a possible pathway toward solar cell devices surpassing conventional efficiency limits (published in Science). As an assistant professor at MIT, Will's research program will be focused on understanding and optimizing the flow of energy in nanostructured materials and drawing the connection among processing, morphology, and dynamics. To meet these goals, Will's group will rely heavily on state-of-the-art optical spectroscopy and microscopy techniques. He will start his lab at MIT in January 2012.

In addition, several of our newer faculty completed their first year at MIT after starting this past September, including assistant professor Yuriy Roman, associate professor Dan Anderson, professor Richard Braatz, and professor of the practice Allan Myerson. We continue to look forward to the arrival of Fikile Brushett as an assistant professor in fall

2012; Fikile is completing his postdoctoral stay at Argonne National Laboratories, where he is developing (under the supervision of Dr. John Vaughey and Dr. Dennis Dees) new electrochemically active materials and novel chemistries for room-temperature nonaqueous flow batteries with high-energy efficiency and operating voltage.

## Research and Recognition

Many of our faculty received national and global recognition over the past year. Institute Professor Bob Langer received the prestigious Founder's Award from the National Academy of Engineering as well as the Priestley Medal, which is the top award in chemistry. Professor Greg Stephanopoulos received the Eni Renewable and Non-Conventional Energy Prize; this international award is presented to a single person each year who has pioneered in the area of alternative energy. *Popular Science* magazine recognized associate professor Chris Love on 2010's "Brilliant 10" list of top young scientists, and associate professor Kristala Prather received the Institute's Bose Junior Faculty Teaching Award, the top honor for teaching among young faculty members. Professor Prather also received the 2011 Biochemical Engineering Journal Young Investigator Award. As a part of the celebration of the Year of Chemistry, professors Bob Langer and Michael Strano were named to the list of the top 100 chemists of the decade, and professor Paula Hammond was named one of the top 100 materials scientists of the decade by *Times Higher Education*. Professor Paul Barton won the 2011 Computing in Chemical Engineering Award, which is presented by the Computing and Systems Technology Division of the American Institute of Chemical Engineers (AIChE), and professor Bernhardt Trout received the 2011 AIChE Impact Award. Department chair Klavs Jensen was selected as the recipient of the 2011 William H. Walker Award for Excellence in Contributions to Chemical Engineering Literature, which is also given by AIChE. Finally, the department congratulates Pat Doyle on his promotion to full professor, as well as Kris Prather and Chris Love for their promotions from assistant professor to associate professor without tenure.

It was an exciting year of research for the department, with many new developments coming out of Chemical Engineering laboratories. Professors Daniel Blankschtein and Michael Strano have devised a new means of producing isolated graphene bilayer sheets in large quantities, which may address issues of manufacturability of graphene and lead to faster translation of graphene into products and devices such as transistors, batteries, and optoelectronics (published in the journal *Nature Nanotechnology*). Professor Greg Stephanopoulos and coworkers have found a way to engineer bacteria to produce an important chemical precursor to the expensive cancer drug Taxol, as outlined in the journal *Science*. This approach provides a much lower cost means of producing the key cancer drug and other important therapeutic molecules. Professor Bob Langer and Chemical Engineering graduate student Pedro Valencia and collaborators have designed 3D microfluidic methods of making combinatorial libraries of drug-containing nanoparticles that enable a much more rapid and effective optimization of cancer drug delivery and can lead to a greater understanding of how to design such nanomaterials (as reported in Advanced *Healthcare Materials*). Professor Pat Doyle's lab has used microfluidic techniques combined with high-speed lithography to generate microstructured, multicomponent "bar-code" microgels that can be used to screen for up to 100 proteins in a single test, helping to address medical diagnostics (as described in *Analytical Chemistry*). Details on the paper photovoltaics developed in the Gleason lab were recently published in *Advanced Materials*; these ultrathin coatings generated by the iCVD deposition method have been featured locally and nationally. More information on the work and professional efforts of each of our faculty is included in the Faculty Notes section.

## Undergraduate Education

### Introducing a New Undergraduate Degree

We are very excited to introduce a new Chemical Engineering undergraduate degree program: Course 10-ENG. The degree, which was voted in as a program at the April 2011 Institute faculty meeting, is a response to the need expressed by our undergraduate students for a more flexible option in the pursuit of undergraduate knowledge in the field of chemical engineering. The 10-ENG degree is a flexible engineering degree that will incorporate many of the core components of the traditional chemical engineering degree while providing concentrations for specific relevant areas in the field that can be designed from a set of courses offered by departments across the Institute. The new degree will be accredited by the Accreditation Board for Engineering and Technology as an engineering degree and will be awarded as the bachelor of science in engineering, as recommended by the Department of Chemical Engineering. Students who are seeking a strong chemical engineering core background in combination with knowledge in a specific subtopic area of chemical engineering will now have the opportunity, with the 10-ENG degree, to design a concentration within the four concentration areas that meet their interests and needs. These areas include particular areas of growth in chemical engineering that involve significant interdisciplinary effort, such as energy, biomedical engineering, environmental studies, and materials design and processing. The concentration areas may grow and change over time, and areas of future development will likely include multiscale computational modeling. Students may also work with the Chemical Engineering undergraduate office to propose a new concentration following approval from the department. We believe this new flexible degree program, which is similar to those now offered by the Department of Mechanical Engineering and the Department of Aeronautics and Astronautics, will extend the ability of students to engage in interdisciplinary studies while maintaining a strong chemical engineering core and a solid base in the engineering subdiscipline of their choice. Students will be able to enroll in 10-ENG starting in the fall of 2011.

### 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). Department undergraduate enrollment continues to remain strong: around 240 students in recent years. Chemical Engineering currently has 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, parents' weekend, and other activities. Overall, 68 SB degrees were conferred as of June 2011, with 65% awarded to women. Student quality remains excellent. 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 | 01–02 | 02–03 | 03–04 | 04–05 | 05–06 | 06–07 | 07–08 | 08–09 | 09–10 | 10–11 |
|---|---|---|---|---|---|---|---|---|---|---|
| Sophomores | 47 | 56 | 56 | 95 | 100 | 95 | 96 | 87 | 87 | 80 |
| Juniors | 66 | 49 | 43 | 55 | 83 | 75 | 67 | 77 | 68 | 71 |
| Seniors | 84 | 65 | 41 | 55 | 53 | 83 | 77 | 75 | 73 | 75 |
| **Total** | **197** | **170** | **140** | **205** | **236** | **253** | **240** | **239** | **228** | **226** |

The 10-B program leading to the accredited SB degree in chemical-biological engineering was introduced in 2004 in response to demand from our students for a focused and coherent educational curriculum in biological aspects of chemical engineering, with more in-depth training in advanced modern chemical and molecular biology. The program embodies three primary components: (1) a core in advanced biology comprising subjects in biochemistry, genetics, and cell biology; (2) a core in engineering science comprising subjects in mass and energy balances, thermodynamics, heat, mass and momentum transport, and chemical kinetics; and (3) a capstone design experience that emphasizes problems in chemical-biological engineering while teaching integration and synthesis of fundamental science principles for solving engineering problems and understanding complex systems. Student participation in Course 10-B has been very robust since the outset, with undergraduate enrollment rising from 20 students in 2004 to 105 in 2006, 143 in 2008, and a solid 120 in 2011. Currently, students in the chemical-biological engineering program constitute 53 of the undergraduates in the Department of Chemical Engineering. Thirty-seven seniors in the Class of 2011 graduated with degrees in chemical-biological engineering, and 35 freshmen in the Class of 2014 declared their majors in chemical-biological engineering.

The average starting salary for graduates of the Department of Chemical Engineering is $68,400 (2011 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 in the department and to the continued high demand for our students. Senior surveys indicate that, between 2001 and 2011, 50% to 60% of our students went on to graduate or professional school.

Undergraduates in the Department of Chemical Engineering maintain an active student chapter of AIChE, with invited speakers, presentations at national meetings, and visits to company sites. The student officers of AIChE were Apiradee Sanglimsuwan (president), Alexandra Piotrowski (vice president), Shannon Moran and Michelle Lu (secretaries), Molly Kozminsky (treasurer), Daniel Paik (Class of 2011 representative), Tim Chang (Class of 2012 representative), and Mark Kalinich (Class of 2013 representative).

## Graduate Education

The graduate program in the Department of Chemical Engineering offers master of science degrees in chemical engineering (SM) and in chemical engineering practice (MSCEP), doctor of philosophy (PhD) and doctor of science (ScD) degrees in chemical engineering, and PhD degrees in chemical engineering practice (PhDCEP). The PhDCEP track was established in 2000 in collaboration with the Sloan School of Management. The total graduate student enrollment is currently 240, with 212 in the doctoral program and 28 master's-level degree candidates. In the doctoral program, 200 students are in the PhD/ScD track and 12 are in the PhDCEP track. In the master-level program, 20 are in the MSCEP track. Twenty nine percent of our graduate students are women. Two percent are underrepresented minority students. Forty-one of our graduate students were recipients of outside fellowship awards from the National Science Foundation (NSF), the National Institutes of Health (NIH), the Department of Defense, and others. The distribution of graduate students by degree for the last ten years is shown in Table 2. During the 2010–2011 academic year, 38 doctoral degrees (34 PhD or ScD, 4 PhDCEP) were awarded, along with 43 master's-level degrees (37 MSCEP, 6 SM), for a total of 81 advanced degrees conferred. Thirty-eight students passed the doctoral qualifying exams and were promoted to candidacy for the PhD/ScD or PhDCEP. The department received 427 applications for admission to the doctoral program, offered admission to 61 individuals, and received 43 acceptances of offers, for an acceptance rate of 70%. Of 69 applications for master's-level degrees, the department made 12 offers and received 10 acceptances of offers, for a yield of 83%. Among the incoming graduate class for 2011, 22 are women and two are underrepresented minorities. On average, the incoming graduate class held an undergraduate grade point average (GPA) of 4.95 (out of 5.0).

**Table 2. Graduate Enrollment over the Last 10 Years**

| Degree Level | 01–02 | 02–03 | 03–04 | 04–05 | 05–06 | 06–07 | 07–08 | 08–09 | 09–10 | 10–11 |
|---|---|---|---|---|---|---|---|---|---|---|
| Master's | 38 | 36 | 26 | 19 | 16 | 18 | 26 | 32 | 38 | 28 |
| Doctoral | 209 | 245 | 232 | 216 | 203 | 217 | 212 | 228 | 203 | 212 |
| **Total** | **247** | **281** | **258** | **235** | **219** | **235** | **238** | **260** | **241** | **240** |

## 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.

### DuPont-MIT Alliance

The DuPont-MIT Alliance (DMA) is a research and educational partnership between MIT and DuPont. The goals and aims of DMA are to foster collaboration in research efforts that include technology related to chemical, biochemical, and material sciences and to promote educational activities that are of mutual interest and benefit to MIT and DuPont.

### *Governance*

A steering committee is responsible for the direction of research and educational activities. The committee meets biannually. The current steering committee members on the MIT side of the board include director Claude Canizares, vice president for research and associate provost; associate director Robert E. Cohen, St. Laurent professor of chemical engineering; and Bruce Tidor, professor of biological engineering and computer science. The daily supervision of the program is managed by Patricia Reilly, assistant director. The DuPont director is Dr. Doug Muzyka, supported by the DuPont associate directors: Drs. Henry Bryndza, Steven Freilich, and Roger Siemioko with the assistance of the project director, Dr. Wayne Marsh.

### *Research Focus*

Partnering with MIT continues to bring new research and technologies to DuPont. The direction of the research projects is determined by the unanimous vote of the steering committee. At present, there are 13 research projects in several departments as well as several research activities at Lincoln Laboratory. The 2011 budget for research activities is $2,040,000.

### *Educational Activities*

This academic year, fellowships were awarded to two newly hired associate professors to assist in their research programs: Alisha Shor, under the mentoring of Cullen Buie (Mechanical Engineering), and Denis Terwagne, under the mentoring of Pedro Reis (Mechanical Engineering).

There is a unique cooperation between DuPont and MIT to promote the basic principle of collaborative research that will have a significant impact on the long-term commercial goals of DuPont and the continuously evolving educational culture of MIT.

## Novartis-MIT Center for Continuous Manufacturing

The Novartis-MIT Center for Continuous Manufacturing, now entering its fifth year, was formed with the goal of transforming pharmaceutical manufacturing. Currently, pharmaceutical manufacturing is performed in batch mode, in which each step of a manufacturing process is physically separated from the other steps. The contents from a given process unit must be removed after completion of the operation, placed in a transportation vessel, and moved to the next process unit, through perhaps 20 steps. Each time the equipment must be cleaned and potential variation in batches must be monitored vigilantly. Continuous processing, in which materials flow uninterrupted through the process, offers the potential for leaner processing, higher quality, more flexibility, and, in the end, cost savings.

In order to accomplish this goal of continuous pharmaceutical processing, the center, consisting of between 50 and 60 researchers and 11 faculty from three departments (Chemical Engineering, Mechanical Engineering, and Chemistry), has developed new approaches/methodologies across the entire spectrum of pharmaceutical development activities, including chemical reactions, reactors, separation approaches, final finishing steps, and process modeling and control.

In addition to pursing traditional research activities, a portion of the team has developed and is currently validating the first of its kind end-to-end continuous bench-scale pharmaceutical plant at MIT. The bench-scale plant is a modular platform in which various approaches to continuous manufacturing will be evaluated, in addition to the various technologies that will be developed by the center. The plant is the perfect tool for understanding the complexities of integrated continuous manufacturing.

Since the center's inauguration, our researchers have published in excess of 140 publications, including eight theses, and they have presented findings at numerous international and national meetings. In addition, the center has filed provisional patent applications for a number of breakthrough technologies.

The center is led by Bernhardt L. Trout, MIT center director, and Walter Bisson, Novartis manager. Other members of the center team are James Evans (MIT associate director), Stephanie Bright (MIT program coordinator), and Salvatore Mascia (strategic project manager).

### David H. Koch Institute for Integrative Cancer Research

An exciting event on campus this year was the opening of the new Koch Institute for Integrative Cancer Research, situated directly across from Building 66. The dedication event, in April, featured talks from the major donor, Chemical Engineering alumnus David H. Koch SB '62, SM '63; MIT president Susan Hockfield; director Tyler Jacks; and Massachusetts senator Scott Brown. Five Chemical Engineering faculty members have moved their labs into the Koch building: Dan Anderson, Paula Hammond, Bob Langer, Chris Love, and Dane Wittrup. The Koch Institute brings together cancer biologists and engineers from across departments at MIT to conduct interdisciplinary research focused on improved diagnosis and treatment of cancer. Opportunities provided by the institute include interactions with cancer clinicians, key cancer centers such as the Dana Farber Cancer Institute, the Boston hospitals, and industry partners. Anderson, Hammond, and Langer's programs feature a world-class concentration of expertise in nanostructured vehicles for drug delivery at the Koch Institute. Love and Wittrup join Darrell Irvine and Jianzhu Chen to constitute an immune engineering group with unusual strengths in both the analysis and manipulation of the immune system's response to cancer. Wittrup serves as associate director of the institute.

## Faculty Notes

Professor Daniel G. Anderson is continuing his research on drug delivery and advanced biomaterials, focusing in particular on new approaches to the treatment of diabetes and cancer. In the past year he has given over 20 national and international invited lectures in these areas. The polymers and lipid-like materials developed in his laboratory have recently been commercialized by several different companies and are in the process of being evaluated for their utility as human therapeutics.

Professor Robert C. Armstrong continues to serve as deputy director of MITEI, which continues to grow rapidly in its research, educational, campus, and outreach components. Sixteen companies and public institutions sponsor research as founding and sustaining members of MITEI; the energy initiative has about 60 industrial and public partners overall across four continents. MITEI has helped to bring in approximately $320 million in support over its first four years of operation and around 180 energy graduate fellowships spread over 20 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. During this past academic year he gave lectures at the MIT Energy Futures Conference in Monaco; Transatlantic Science Week in Washington, DC; the MIT Center for Energy and Environmental Policy Research (CEEPR) Fall Workshop; and a meeting of the Kuwait Petroleum Corporation in Kuwait City. He also presented the MITEI-Masdar Distinguished Energy Lecture in Abu Dhabi. In February he led a team of MIT faculty to visit Petrobras in Rio de Janeiro to discuss energy research opportunities with Petrobras and Brazilian universities. He serves on the advisory boards of the chemical engineering departments at Georgia Tech; Northwestern University; the University of Colorado, Boulder; and Washington University. He also serves on the advisory board of the ASP (Alta Scuola Politecnica) program at Politecnico di Torino.

Professor Martin Z. Bazant continued to develop models for Li-ion batteries and pseudocapacitors for energy storage, as well as a novel electrokinetic approach to water desalination, also under investigation in his new laboratory (see below). His work on induced-charge electro-osmosis has become widely recognized and includes the most-cited paper in the *Journal of Fluid Mechanics* since its publication in 2004. He delivered the keynote lecture at the 2011 Gordon-Kenan Research Seminar on the Physics and Chemistry of Microfluidics. He published in *Physical Review Letters* the first simple continuum model of solvent-free ionic liquids and molten salts, used in high-voltage supercapacitors and liquid batteries. In its second year, his new subject 10.626 Electrochemical Energy Systems was highly rated by students, and an undergraduate version (10.426) will be offered next year.

Professor Daniel Blankschtein's research group conducts fundamental theoretical and experimental research in the area of colloid and surfactant science, with an emphasis on industrial and biomedical applications. Recent research advances include molecular dynamics simulations of self-assembling surfactant systems, molecular dynamics simulations of surfactant/polymer-induced stabilization of carbon nanotubes and grapheme sheets in aqueous media, development of novel fluorescent surfactants to study/visualize surfactant penetration and distribution in the skin utilizing fluorescence microscopy techniques, and ultrasound-assisted transdermal vaccination. Professor Blankschtein's group interacts closely with several companies that make use of software developed in the group to facilitate formulation design. His teaching responsibilities included the core graduate course 10.40 Chemical Engineering Thermodynamics (fall 2010) and the interdisciplinary graduate course 10.43 Introduction to Interfacial Phenomena (spring 2011). Professor Blankschtein and his students delivered talks and presented posters at the Indian Institute of Technology (Bombay, India), the 2010 Gordon Research Conference on "Drug Carriers in Medicine and Biology," the 2010 AIChE annual meeting, and Procter & Gamble. In addition, Professor Blankschtein and his students hosted representatives of DuPont and Procter & Gamble at MIT to deliver tutorials on recent advances in surfactant research. In May 2011, Professor Blankschtein was presented with the Outstanding Faculty Award by the graduate students in the Department of Chemical Engineering in recognition of outstanding performance in graduate teaching. Professor Blankschtein continues to serve on the editorial board of Marcel Dekker's Surfactant Science Series.

Professor Richard D. Braatz continued research on control systems engineering with pharmaceuticals, materials, and energy applications. He also developed new lectures for 10.551 Systems Engineering. As chair of the department's graduate recruiting committee, he led a very successful recruiting effort that attracted a record number of fellowship students. Professor Braatz served on numerous award committees and advisory and editorial boards, including the eight-person editorial board for the recently published *Control Handbook*, which is the definitive resource for engineers working with modern control systems. He served on the Board of Governors of the Institute of Electrical and Electronics Engineers (IEEE) Control Systems Society.

Professor Arup Chakraborty continued his teaching in two subjects: one a mandatory graduate subject in chemistry (statistical mechanics) and the other a mandatory undergraduate subject in chemical engineering (fluid mechanics). His research has focused on three areas: understanding fundamental questions in T-cell signaling, fundamental questions in how T cells recognize a diverse and evolving world of microbes in a pathogen-specific fashion, and confronting the challenge of how to design a vaccine against HIV. Professor Chakraborty has published papers in all three areas, perhaps the most notable being a paper that was published in the *Proceedings of the National Academy of Sciences* identifying regions of immunological vulnerability in HIV. This work brought together statistical physics with structural data and human clinical data. It suggests a new paradigm for the design of vaccines against HIV and was highlighted with a story in the *Wall Street Journal* (as well as numerous other news outlets). Professor Chakraborty has served the Departments of Chemistry and Chemical Engineering in numerous ways, and he served on the provost's ad hoc committee to assess the future of the Harvard-MIT Division of Health Sciences and Technology (HST) program. Additionally, Professor Chakraborty has played a leading role in the Ragon Institute and served on other national and international advisory councils.

Under support from a Juvenile Diabetes Research Foundation grant in collaboration with Viacyte Corporation and an American Recovery and Reinvestment Act (ARRA) Challenge Grant, professor Clark K. Colton's research group has made several important findings related to the maintenance and differentiation of stem cells for use in regenerative medicine. They discovered that manipulation of oxygen levels at various stages during differentiation of human embryonic stem cells leads to substantial enhancements in the yield of insulin-secreting cells for curing diabetes. They also found that extended culture under hypoxic conditions following differentiation led to marked decreases in the incidence of tumor-forming residual pluripotent cells. Professor Colton was active in the expansion of the capstone laboratory experience for juniors and seniors. He has been instructor-in-charge of 10.26 Chemical Engineering Projects Laboratory and developed 10.29 Biological Engineering Projects Laboratory following the creation of Course 10B. This past year he created 10.27 Energy Engineering Projects Laboratory under a curriculum grant from MITEI. The three subjects were taught simultaneously. Course 10.27, which involved five additional instructors new to these subjects, was very popular and attracted half of all students taking project laboratories.

Professor Charles L. Cooney, the Robert T. Haslam (1911) professor of chemical and biochemical engineering, continued as the faculty director of the Deshpande Center for Technological Innovation. He serves on the Innovation Engagement Committee, the NIH Engagement Committee, the Knight Science Journalism Fellowships Advisory Board, the Advisory Committee for Regional Engagement, the MIT Community Service Fund Board, the MIT Sanofi Aventis 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 Centre. He is cochair of the MIT-India Strategy Group. Professor Cooney is a member of the advisory committees to the Technology Innovation Program of the National Institute of Standards and Technology and the Massachusetts Life Sciences Collaborative. He is the faculty director of the downstream processing summer course held through MIT's Professional Institute. His research focuses on pharmaceutical manufacturing technology and technological innovation. He was named a fellow of the American Chemical Society (ACS). During the 2010–2011 academic year, he was on sabbatical at Balliol College at Oxford University in the fall term, and in the spring he was at the SMART Innovation Centre in Singapore and the Singapore University of Technology and Design. Professor Cooney is also an overseer of the Boston Symphony Orchestra and a trustee emeritus of the Boston Ballet.

Professor William M. Deen's group continued its NIH-supported research on the role of nitric oxide and other reactive nitrogen species in carcinogenesis. Methods were developed to deliver precisely controlled amounts of nitric oxide or nitrogen dioxide to cultured cells, to determine the nitric oxide exposure of cells cocultured with activated macrophages, and to estimate the concentrations of nitric oxide within human cutaneous melanomas. He visited the Department of Chemical and Biological Engineering at the University of Pennsylvania for an invited seminar in October 2010, and some of the group's nitric oxide work was presented at the AIChE annual meeting in Salt Lake City in November. A major project completed was the manuscript for the second edition of Professor Deen's graduate textbook, Analysis of *Transport Phenomena* (Oxford University Press), which will be published in the fall. Professor Deen received two teaching awards in May 2011: the Ruth and Joel Spira Award for Distinguished Teaching (MIT School of Engineering) and the C. Michael Mohr Award for Outstanding Undergraduate Teaching (MIT Department of Chemical Engineering). As graduate officer, Professor Deen continued to oversee the graduate programs in the Department of Chemical Engineering.

Professor Patrick S. Doyle continued to advance his work on single-molecule DNA physics and microfluidic synthesis of functional microparticles. His work on barcoded microgel particles has now matured to the point that the process was described in a recent invited *Nature Protocols* article, and the particles themselves are now commercially available from Firefly Bioworks, a start-up company he cofounded. He spent the spring term on leave at the MIT SMART Centre in Singapore, where his lab is studying the biophysics of single-DNA molecules. He continues to serve as an editorial board member for the journal *Biomicrofluidics*. He delivered keynote or plenary lectures at the Materials Research Society meeting, the University of Michigan Macromolecular Science and Engineering Symposium, the American Physical Society northeast polymer physics meeting, the annual Pacific Rim Conference on Rheology, the Gordon Research Conference on Microfluidics, and the International Workshop on Colloids and Interfaces in Korea. In addition, he gave a number of invited lectures at various institutes including National Taiwan University, Seoul National University, National University of Singapore, and University of Tennessee.

Professor Karen K. Gleason completed her three-year role as associate dean of engineering for research, in which she oversaw and fostered interdisciplinary and international research centers reporting to the School of Engineering. She will begin a sabbatical year in September 2011. Her group continues to develop the fundamental science behind the chemical vapor deposition of polymers as well as the engineering required to transition this technology. She authored an invited perspectives article in the *AIChE Journal*. Professor Gleason delivered numerous invited lectures, including keynote addresses at the 6th International Conference on Hot Wire Chemical Vapor Deposition in Paris, France, and at the Printed Electronics & Photovoltaics Europe Conference in Dusseldorf, Germany. At the latter, her group's work was recognized with the Technical Development Materials Award. Prototype photovoltaic cells and arrays produced by her group in collaboration with professor Vladimir Bulović's laboratory have been viewed at the request of notable leaders including the CEO of Eni S.p.A., the president of Italy, and President Obama's science and technology advisor, John Holdren; they have also been featured on numerous news outlets including CNET, Discovery News, and CNN. Her group's work on microworm implantable sensors was published in the *Proceedings of the National Academy of Sciences* and featured on the MIT home page. 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 site in Greenville, SC.

Professor William H. Green organized the 7th International Conference on Chemical Kinetics at MIT (July 10–14, 2011), which featured 250 presentations on all aspects of chemical reactions. He develops methods for predicting combustion chemistry to evaluate proposed alternative fuels. He plays key roles in the Department of Energy's Combustion Energy Frontier Research Center, the Saudi Aramco–MIT project on fuel desulfurization, and MITEI's project on energy conversion with CO2 sequestration, and he received grants to initiate five new energy research projects this year. Professor Green continues to serve as the editor of the *International Journal of Chemical Kinetics*.

Professor Paula Hammond has recently been named the Koch professor of engineering as the recipient of a new chair established by David H. Koch to support the engagement of engineers in the field of cancer, and she moved her laboratories this past year into the new Koch Institute for Integrative Cancer Research. In her work as the executive officer of the department, she successfully introduced the new 10-ENG degree program, which enables students to take a chemical engineering core program along with a track or concentration in specific subareas of chemical engineering, including energy, materials, biomedical, and the environment. This new degree program, voted in by the faculty in April 2011, will be introduced to students in the 2011–2012 academic year. With regard to research, Professor Hammond's work on the generation of layer-by-layer nanoparticles with pH-sheddable outer layers that enable accumulation of nanoparticles in the hypoxic regions of tumors was featured as a cover article in *ACS Nano* in June 2011 and was covered in the science press. Her collaboration with Angie Belcher led to a new paper in *Nature Nanotechnology* on virus-based solar devices. Developments in surface-based drug delivery led to several new papers and initiated projects with Sanofi-Aventis and with Johnson & Johnson through the Transcend Program. Professor Hammond was recognized as one of the top 100 materials scientists by *Times Higher Education* (Thomson-Reuters) as part of the 100 years of chemistry celebration. Over the past academic year she presented invited seminars at several venues, including the University of California, Los Angeles; Georgia Tech; Caltech; and Stanford University. Professor Hammond continues to serve as a 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*.

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, Italy, Brazil, Singapore, and Austria in addition to the United States. He is an active participant in the Singapore-MIT Alliance (SMA) program on chemical and pharmaceutical engineering. Professor Hatton has served as a member of the scientific/technical advisory boards of the Particulate Fluids Processing Center at the University of Melbourne, the GSK-Singapore Partnership for Green and Sustainable Manufacture in Singapore, Vale Energia Limpa (a joint venture between Vale and SGC Energia), and Vale Energia Solucia. Over the past year, he has given a number of invited lectures at meetings of ACS, the Defense Threat Reduction Agency, and AIChE, as well as talks at the Engineering Conferences International (ECI) on Nanofluids in Montreal, Canada, and Separations Technologies in Kona, Hawaii. He presented a keynote address and offered a master class at the Netherlands Process Technology Symposium on "The Future of Process Technology–Process Technology of the Future" in Eindhoven. Professor Hatton also participated in workshops with Philip Morris International; and at workshops in Talloires, France; Cambridge, MA; and Rio de Janeiro (at Petrobras). Professor Hatton is on the technical committees of the 2011 International Solvent Extraction Conference in Santiago, Chile, and the 2010 ECI Separations Conference in Hawaii. He is on the editorial advisory boards of *Current Opinion in Colloid and Interface Science* (as coeditor of the section on applications), *Chemical Engineering Research and Design*, and *Langmuir*. He is an advisory board member of ECI.

In addition to his responsibilities as department head, professor Klavs F. Jensen continues his research on functional micro- and nanostructured materials and devices for chemical and biological applications. With collaborations in chemistry, he has explored a wide range of microfabricated systems for chemical and biological applications with particular emphasis on systems for which microfabrication provides unique process advantages. These systems also form the basis for continuous flow synthesis and separation developments as part of the new Novartis-MIT Center for Continuous Manufacturing. The ability to operate at high pressure and temperature conditions not easily achieved in batch is being exploited in the synthesis of nanoparticles for optical and catalytic applications relevant to energy conversion through MITEI-sponsored projects. Biological applications, specifically the devices to facilitate the transport of macromolecules across cell membranes, are being pursued in collaboration with Koch Institute researchers. Professor Jensen was appointed as a knight of the Order of the Dannebrog by the queen of Denmark. During the past academic year, he gave plenary lectures on microreaction technology at international conferences and universities, including the Royal Society of Chemistry and Imperial College. He served on advisory boards to chemical engineering departments for the Korean Advanced Institute of Science and Technology, Princeton, and Stanford. Professor Jensen also participated in the governing board of the Technical University of Denmark and the scientific advisory board of the Singapore A*STAR Institute for Bioengineering and Nanotechnology.

Professor Jesse H. Kroll's group continued its laboratory research on the multiphase organic chemistry of the atmosphere and its relationship to climate and air quality. His work on measuring and interpreting the oxidation state of atmospheric organic carbon was published in *Nature Chemistry*. He taught a new graduate-level course on atmospheric chemistry (1.84/10.817/12.807) and gave invited talks at the American Chemical Society annual meeting, the European Geosciences Union General Assembly, and the Telluride Science Research Center workshop on organic aerosol. In 2010–2011, Professor Kroll received an NSF CAREER award and an ACS Petroleum Research Fund Doctoral New Investigator grant.

In AY2011, professor Robert S. Langer received an honorary degree from Bates College, was elected as an international fellow of the Royal Academy of Engineering (United Kingdom) and was selected by the American Chemical Society to receive the 2012 Priestley Medal. In addition, he received the National Academy of Engineering's Founders Award, the Warren Alpert Foundation Prize, the Boston Museum of Science Walker Prize, Dartmouth College's Robert Fletcher Award, the IEEE Engineering in Medicine and Biology Society's Academic Career Achievement Award, and the Society of Cosmetic Chemists' Frontier of Science Award. He presented several lectures, including the École Polytechnique Fédérale de Lausanne (Switzerland) Class Day Speech; the Joslin Diabetes Center's Kroc Lecture; the Uniformed Services University Bullard Lecture; the University of Maryland's Dean Lecture; the Dartmouth College Thayer School of Engineering Investiture Lecture; the Children's Hospital Boston Judah M. Folkman Lecture; the University of Washington's Allan S. Hoffman Lecture; the University of California, Davis, Storer Life Sciences Lecture; and the Massachusetts Eye and Ear Institute Dohlman Visiting Professorship Lecture.

Professor J. Christopher Love continued to develop new bioanalytical processes for profiling immune responses to chronic diseases and assessing clonal variation in biomanufacturing processes using single-cell microtechnologies. He was selected to *Popular Science's* 9th Annual "Brilliant 10" list for his research on the applications of microtechnologies to single-cell analysis. In addition, he was awarded the Latham Family career development professorship and joined the intramural faculty at the Koch Institute for Integrative Cancer Research. He delivered invited lectures at various venues, including the Beckman Scholars Symposium, NIH, Pfizer, the Duke Human Vaccines Institute, and professional society and technical meetings (Microbes and

Mucosal Immunity, Single Cell Analysis Summit, Engineering Science for Animal and Cell Technology). In spring 2011, he once again taught his well-received elective course 10.495/595 Molecular Design and Bioprocess Development of Immunotherapies to chemical engineers, biological engineers, and Leaders for Global Operations students. Finally, his work in the area of single-cell technologies for drug discovery and immune monitoring led to the creation of a new company, Enumeral Biomedical, located in the Cambridge area.

Professor Narendra Maheshri continues his fundamental studies on the dynamics of eukaryotic gene regulation as well as technological approaches to generating phenotypic diversity. This past year, he delivered invited lectures at several international conferences, including the q-bio Conference on Cellular Information Processing, the Heraeus Seminar on Biothermodynamics of Metabolic and Ecological Networks, the European Molecular Biology Laboratory Conference on Chromatin and Epigenetics, and the Workshop on Stochastic Systems Biology, along with seminars at Harvard, MIT, and Katholieke Universiteit Leuven. His group has developed a new technology to target DNA mutagenesis, presented at DuPont through the DuPont-MIT Alliance. He also took part in the Academic Leaders Program at Instituto Tecnólogico de Monterrey (Querétaro, Mexico), where he conducted workshops and delivered a plenary lecture to the general public.

Allan S. Myerson joined the department this past fall as professor of the practice. For the prior two years, he worked with the Novartis-MIT Center for Continuous Manufacturing. Also, he served as dean of engineering and science, provost, and senior vice president at the Illinois Institute of Technology in Chicago before returning to full-time research and teaching in 2008. During his first year at MIT, Professor Myerson established a laboratory focusing on crystallization science and technology with a particular emphasis on pharmaceutical process development and manufacturing, and he continued his work with the Novartis center as a principal investigator. Professor Myerson serves as an associate editor of the ACS journal *Crystal Growth and Design* and as a scientific advisor to the Pharmaceutical Solid State Cluster in Ireland. He was named a divisional fellow by ACS's Industrial and Engineering Chemistry Division in 2010.

During the 2010–2011 academic year, Bradley D. Olsen served as an assistant professor in the Department of Chemical Engineering. His group's research focused on the chemistry and physics of new materials systems based on engineered proteins and protein-polymer conjugates for applications in biomaterials, defense, and energy conversion. His group published its first paper in the journal *ACS Nano* on the topic of globular protein self-assembly using diblock copolymers, and he was awarded the 2011 American Physical Society Division of Polymer Physics/UK Polymer Physics Group Exchange Lectureship. He was a co-instructor for 10.40 Chemical Engineering Thermodynamics during the fall of 2010 and taught 10.569 Synthesis of Polymers during the spring of 2011.

Professor Kristala L.J. Prather is continuing her research activities, primarily in the areas of metabolic engineering and synthetic biology. In addition to several presentations at professional conferences, she gave 16 invited lectures, including presentations at four international meetings and the National Academy of Sciences Kavli Frontiers of Science Symposium (Irvine, CA). Prather gave testimony on the applications of synthetic biology before the US Presidential Committee for the Study of Bioethical Issues and also represented MIT at the World Economic Forum in Davos, Switzerland. She was recognized with two awards this year, the MIT School of Engineering Junior Bose Award for excellence in teaching and the Biochemical Engineering Journal Young Investigator Award. In February 2011, Prather was promoted to the rank of associate professor without tenure, and she was recently selected to be the next Theodore T. Miller career development professor.

Professor Yuriy Roman started his position as an assistant professor in the Department of Chemical Engineering in August 2010. His research group focuses on heterogeneous catalysis, materials design, and biomass conversion. His current group consists of two first-year graduate students and four postdoctoral associates. Research projects are aimed at developing novel catalytic approaches to convert biomass-derived carbohydrates (e.g., glucose and xylose) into new monomers for polymer production and hydrocarbon molecules to be used as fuel, with a strong emphasis on the design of catalysts that are active and stable in the presence of water. In the fall he taught a new Integrated Chemical Engineering (ICE) module, 10.492 Heterogeneous Catalysis for Energy Applications, and in the spring he cotaught 10.37 Chemical and Biological Reaction Engineering with Professor Wittrup.

Gregory C. Rutledge is the Lammot du Pont professor of chemical engineering. Professor Rutledge's research is in the area of molecular engineering of soft matter, in particular the development of process-structure-property relationships for engineered polymers, through the use of molecular simulation and experimentation. His group is currently studying crystallization and morphology of semicrystalline polymers using molecular simulation techniques. In the lab, they are developing the technology of "electrospinning" for the fabrication of novel nanofibers and membranes for a variety of applications ranging from chemical protection materials to water desalination membranes. Over the past year, Professor Rutledge delivered two multi-lecture series on these topics at the University of Bayreuth (Germany), as part of the International Summer School on "Heterogeneous Nucleation and Microstructure Formation," and at Tsinghua University (Beijing, China), as a visiting faculty member. He also delivered numerous keynote and invited lectures at universities and international conferences. He is an associate editor or editorial board member for *Macromolecules*, *Polymer*, and the *Journal of Engineering Fibers and Fabrics*, and he currently serves as editor for the *Handbook of Polymer Crystallization*.

Joseph R. Mares assistant professor Hadley D. Sikes set up a fully functional biomolecular engineering lab with the help of several students and a postdoc in January 2011 as space became available in Building E19. Her lab specializes in molecular biotechnology development with the goal of improving human health. Current areas of focus include detection of rare cells, detection of epigenetic markers of disease, and engineering enzymes that perturb intracellular redox states in human cancers. Professor Sikes presented some of this work at the Society for Biological Engineering's International Conference on Biomolecular Engineering in January 2011 and at the

Burroughs Wellcome Fund Career Awards at the Scientific Interface meeting in June 2011. Professor Sikes also attended the annual AIChE meeting, accepted an invitation to take part in the Howard Hughes Medical Institute/Federation of American Societies for Experimental Biology workshop "Engaging Basic Scientists in Translational Research," and was honored by her undergraduate institution, Tulane University, with the 2011 School of Science and Engineering Outstanding Young Alumnus Award. In addition to teaching an undergraduate integrated chemical engineering module and a core graduate subject, Professor Sikes enjoyed acting as an academic advisor to sophomore Course 10 majors, coordinating the departmental seminar series, and serving on the graduate admissions committee.

Professor George Stephanopoulos presented a plenary lecture, "Nanoscale Process Systems Engineering: Design, Fabrication, Monitoring and Control," at the ESCAPE-21 conference, where his paper "Towards Robust Fabrication of Non-Periodic Nanoscale Systems via Directed Self Assembly" was also presented. In addition, he presented the 2010 Ruckenstein Lecture at the University of Buffalo and the 2010 L.T. Fan Lecture at Kansas State University.

Professor Gregory Stephanopoulos continued to serve as director of the Laboratory of Bioinformatics and Metabolic Engineering, focusing on the development of technologies for biosynthesis of biofuels and biobased products from renewable resources. In the medical area, research continued to investigate the metabolic aspects of cancer with a particular focus on the identification of therapeutic metabolic targets. Professor Stephanopoulos continued his service on the advisory boards of four academic institutions and as chair of the managing board of the Society for Biological Engineering, which promotes the integration of biology and engineering to provide enabling technologies for industrial and medical applications. He delivered the 2011 Paul C. Wilber Distinguished Lecture at Rice University and continued to serve as editor-in-chief of the journal *Metabolic Engineering* and on the editorial boards of eight other scientific journals. In addition to numerous research presentations at professional society meetings (AIChE, ACS, American Society for Microbiology), he delivered plenary and keynote lectures at the IEEE International Conference on Bioinformatics and Bioengineering (Philadelphia); the Samsung Advanced Institute of Technology (Seoul, Korea); the 4th China Bioindustry Convention (Jinan, People's Republic of China); the 8th International Conference of Metabolic Engineering (Jeju Island, Korea); the 8th Pathways, Networks and Systems Conference (Rhodes, Greece); the14th International Biotechnology Symposium (Rimini, Italy); the 6th Gothenburg Life Sciences Conference (Gothenburg, Sweden); the German Conference on Bioinformatics (Braunschweig, Germany); the World Future Energy Summit (Abu Dhabi); and the Institute of Medicine Workshop on Synthetic and Systems Biology (Washington, DC). Professor Stephanopoulos was honored with the 2010 George Washington Carver Award from the Biotech Industry Organization. He also won the 2011 Eni Renewable and Non-Conventional Energy Prize and was elected as a corresponding member of the Academy of Athens (2011).

Associate professor Michael Strano was recently ranked 19th among the best chemists worldwide for the 2000–2010 decade by Thompson Reuters, and he was the only chemical engineer worldwide in the top 20. He was appointed as a Kavli Frontiers of

Science Fellow by the National Academy of Sciences and delivered a keynote lecture to the academy this past spring. He was given an honorary lectureship by the Council of Scientific Society Presidents, where he gave an address at the council's annual meeting in Washington, DC. His laboratory discovered a series of peptides in bee venom that recognize various explosives and pesticides and enable new types of nanosensors. This work, published in the *Proceedings of the National Academy of Sciences*, was featured in a live national interview given by Professor Strano on CNN. Two Strano laboratory breakthroughs in the area of solar energy, the exciton antenna concept (*Nature Materials*, 2010, Vol. 9, pages 833–839) and regenerating, biomimetic photoelectrochemical cells (*Nature Chemistry*, 2010, Vol. 2, pages 929–936), were also featured on Danish television in a documentary on alternative energy. In addition, his laboratory recently developed nanopores based on the interior of single-walled carbon nanotubes and demonstrated new transport mechanisms important for water desalination and other separations in a recent article in *Science* (2010, Vol. 329, pages 1320–1324). His laboratory also pioneered a new method for creating bilayer and trilayer graphene solutions, published in *Nature Nanotechnology*, enabling the exploration of these materials for engineering applications for the first time.

Professor Bernhardt L. Trout continues in his role as director of the Novartis-MIT Center for Continuous Manufacturing. The first contract for $40 million ends in May 2012, and he has been working with colleagues at MIT and Novartis for a five-year renewal. He has also continued his role as cochair of the SMA program on chemical and pharmaceutical engineering. In addition, he runs a laboratory of 25 graduate students and postdocs focusing on pharmaceutical small-molecule manufacturing and biopharmaceutical formulation and stabilization. He set up the MIT–Benjamin Franklin Project for the Advancement of the Arts and Sciences, a project designed to enhance engineering and scientific education, and is director of the MIT Concourse Program. He gave more than 15 invited talks and published or submitted over 20 research papers. He recently won the Annual Impact Award from AIChE's Computational Molecular Science and Engineering Forum.

Professor Daniel I.C. Wang continues his research and teaching activities in the SMA program. He is coadvisor to four PhD candidates in the program. In August 2010, he helped teach the chemical reaction kinetics course in Singapore. His other activities include his role on the scientific advisory board of the A*STAR Bioprocess Technology Institute. He was also invited by Sir George Radda, chairman of the A*STAR Biomedical Research Council, to be on the council's New Horizon Program. He reviewed joint proposals with industrial involvement during the past year. He continues to direct and teach in the 10.48s Fermentation Technology annual summer course. In August 2010, this course was offered at MIT for the 47th consecutive year, making it the longest-offered summer course at MIT. In September 2010, he started a new research project under MITEI with Saudi Aramco on the microbial desulfurization of crude oil. Lastly, he presented the plenary lecture at the 2011 Asian Congress on Biotechnology in Shanghai, China.

Professor Dane Wittrup moved his research group into the new Koch Institute for Integrative Cancer Research building and has taken on the duties of associate director of the institute. The Koch Institute is one of the most exciting places in the world to carry out interdisciplinary work on the development of new cancer biotherapeutics, housing a dozen leading cancer biologists and an equal number of engineering faculty, including Chemical Engineering colleagues Anderson, Hammond, Langer, and Love. Wittrup group alumni taking academic positions this year include Ben Hackel (PhD 2009), as assistant professor of chemical engineering at the University of Minnesota, and David Colby (PhD 2005), as assistant professor of chemical engineering at the University of Delaware. Two biotech start-up companies cofounded by Wittrup, Adimab and Eleven Biotherapeutics, were listed in the 2010 Fierce Biotech 15.

## Research Highlights

### Synthetic Nanoparticles for Controlling Genes: Delivery of Short Interfering siRNAs (Daniel Anderson)

The discovery of RNA interference (RNAi), in which short, double-stranded pieces of RNA (siRNA) can specifically silence target genes, led to the 2006 Nobel Prize. It has also led to considerable excitement in the pharmaceutical industry and billions of dollars in research investment, since these molecules have the potential to silence essentially any disease gene in the body—if they can be delivered to the appropriate target tissue. The delivery of siRNA in a therapeutically relevant manner requires the development of a nanoparticle that protects the siRNA molecules; can traverse through the blood and bypass a variety of physiological barriers, including the kidneys and immune system; and can actually enter inside of target cells to deliver its payload (Figure 1).

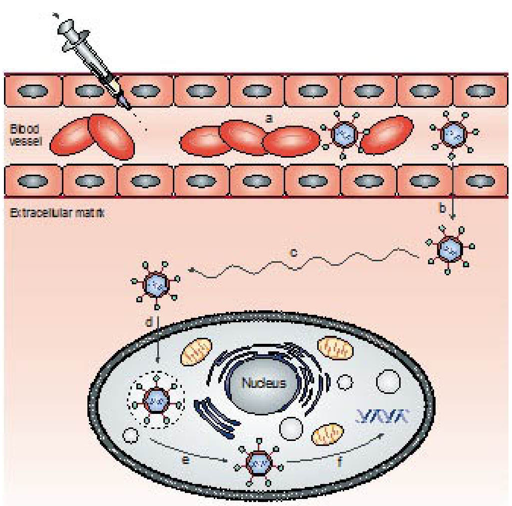



Figure 1. Physiological barriers to the systemic delivery of small interfering RNA (siRNA) nanoparticles. An injected nanoparticle must avoid filtration, phagocytosis, and degradation in the bloodstream. (a); be transported across the vascular endothelial barrier (b); diffuse through the extracellular matrix (c); be taken up into the cell (d); escape the endosome (e); and unpackage and release the siRNA to the RNA interference (RNAi) machinery (f). (adapted from Whitehead et al., Nature Reviews Drug Discovery, 2009).

Daniel Anderson, an associate professor of chemical engineering and health science and technology and an intramural member of the Koch Institute for Integrative Cancer Research, has recently developed the first combinatorial "libraries" of siRNA nanoparticles. Using robotic methods, the Anderson laboratory creates libraries of different compounds and nanoparticles, with each library consisting of hundreds or thousands of chemically distinct lipid-like or polymeric materials. These are then evaluated for their potential to deliver therapeutic payloads in different models of disease.

Using these methods, the Anderson laboratory has developed siRNA delivery nanoparticles with potential for the treatment of cancer, viral infection, and genetic disease. The initial advances reported in 2008 (Akinc et al., *Nature Biotechnology*) continue to be improved, with next-generation formulations now able to simultaneously and specifically silence 10 different gene targets in the liver in a single injection (Figure 2). Importantly, the potency seen with these siRNA nanoparticles has been translated to higher animals—showing similar performance in nonhuman primates. The ability to silence many different gene targets simultaneously is therapeutically important as many diseases are complex, with many different targets that must be addressed for clinical effect.

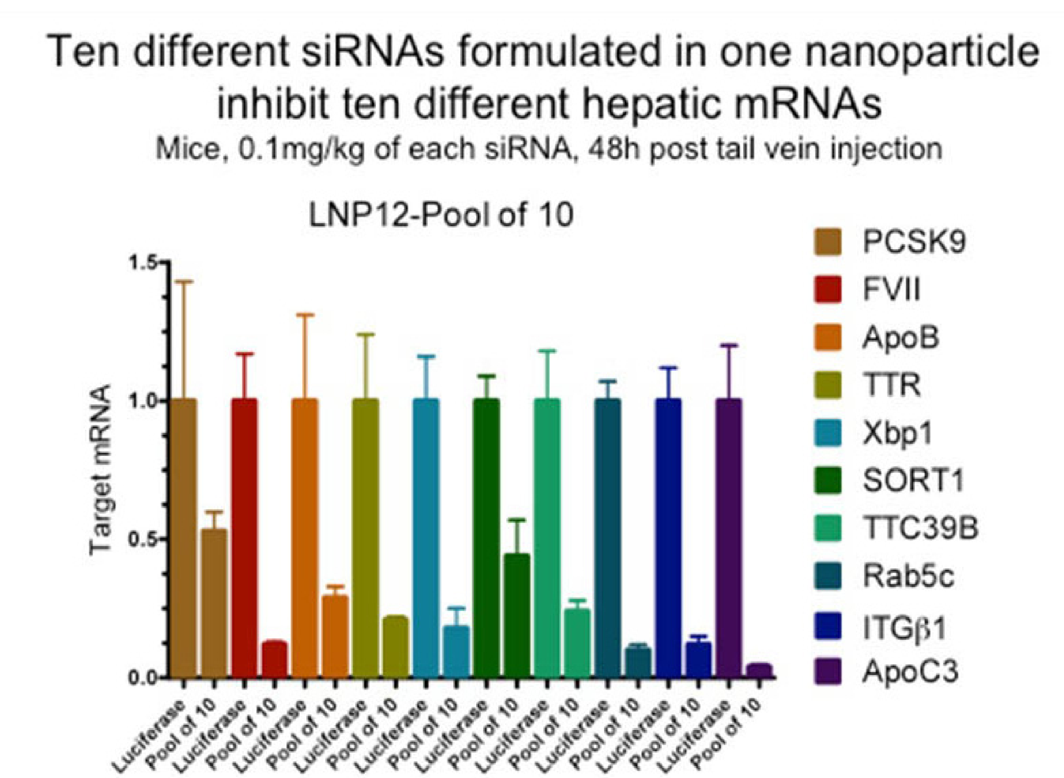



*Figure 2. Ten different siRNAs were formulated with Anderson laboratory nanoparticles, and following intravenous injection specific silencing can be seen with all 10 (see Love et al., Proceedings of the National Academy of Sciences, 2010).*

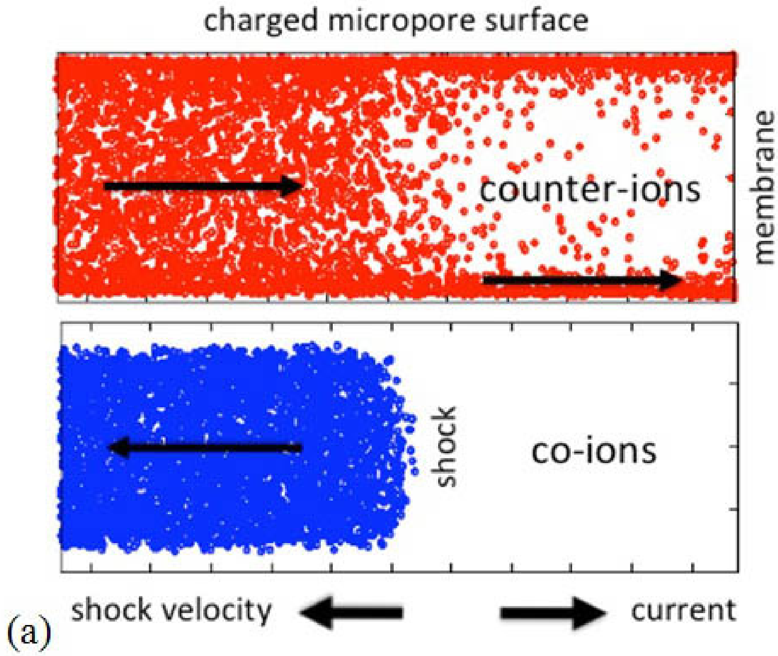
In the past few months, these initial delivery advances have progressed beyond delivery to the hepatocytes of the liver. New formulations have now been developed to extend delivery ability to a range of tissue, including the liver cells (hepatocyte, Kupffer cells, stellate cells, and endothelium), the endothelium of many organs (kidney, liver, spleen, heart, skeletal muscle, lung), and immune cells such as various leukocyte populations (e.g., monocytes, macrophages, and dendritic cells) in both rodents and primates. Formulations in these libraries have demonstrated potential in delivery to various tumor types, ranging from subcutaneous xenografts to orthotopic and transgenic models. The ability to manipulate the genetic pathways of living animals with synthetic siRNA nanoparticles offers an exciting new method for the treatment of disease and is enabling the study of genomics in vivo, thereby providing an important tool for fundamental research on the genetic basis of physiology and disease.

### Water Purification by Shock Electrodialysis (Martin Z. Bazant)

In this century, the shortage of fresh water is expected to surpass the shortage of energy as a global concern for humanity. The vast majority of water on Earth is too salty to drink (approximately 97%, mostly in the oceans) or locked in ice (approximately 2%, in icecaps and glaciers). The remaining fresh water is nonuniformly distributed and scarce in many population centers ranging from California to Saudi Arabia. Water delivery from natural sources or seawater desalination is often infeasible, due to costly and inefficient transport over long distances. Even when fresh water is available, billions of people live with unacceptable levels of water contamination by human or industrial waste, bacteria, viruses, fertilizers, radioactive particles, heavy ions, and other toxic impurities. Small-scale, distributed water purification systems could have a major impact, but standard methods require large-scale chemical plants for efficiency. Membrane fouling is also a persistent issue.

The Bazant lab is developing a new electrodialysis technology that addresses these problems by exploiting nonlinear electrokinetic phenomena in porous media. Traditional electrodialysis (ED) removes ions from water flowing between a stack of ion exchange membranes with alternating cation and anion selectivity. The application of a current across the membrane stack transfers ions from the alternating fresh water streams into adjacent brine streams. Reverse osmosis, which removes pure water by pressure-driven flow though nanoporous membranes, is currently more energy efficient for seawater desalination, but ED can be preferable for more dilute (brackish) or contaminated water because only the charged impurities are removed.

The rate-limiting step in ED is the transport of ions to the membranes by diffusion and convection, but the Bazant lab has predicted theoretically—and confirmed experimentally—that larger, “overlimiting” currents can be sustained in charged porous media. Although the beds of nanoporous particles have been used to enhance transport to ED membranes, a new effect occurs in microporous media (with thin double layers): the propagation of a “desalination shock,” or sharp salt concentration gradient, away from the membrane (Figure 3a). The shock leaves behind a macroscopic region of deionized water, where the current is carried by surface conduction and electro-osmotic flow driven by the large electric field. The group is developing mathematical models of these nonlinear phenomena, coupled to experiments.



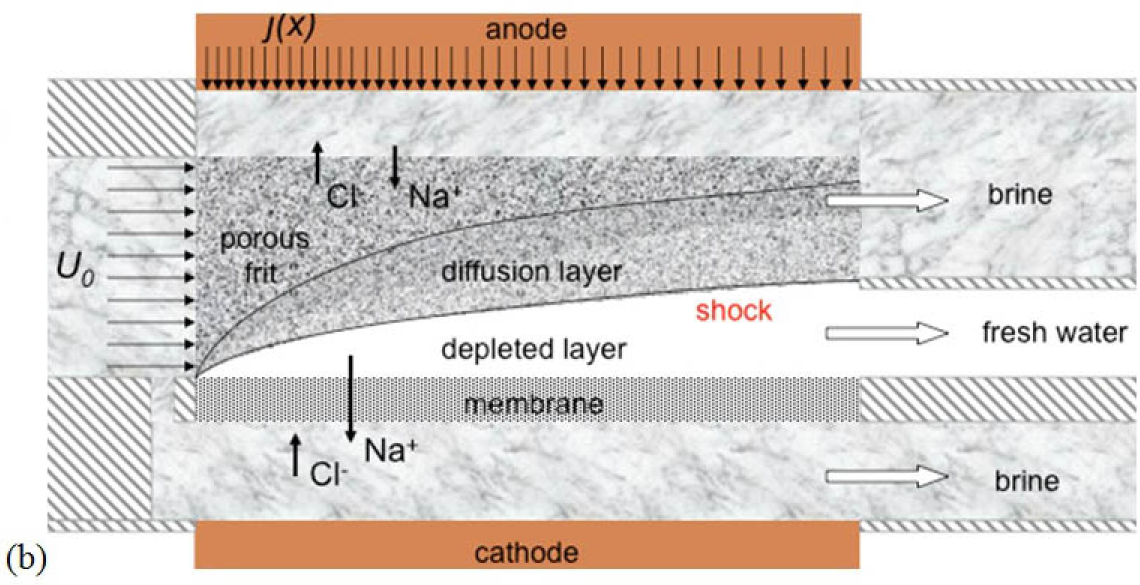




*Figure 3. Principles of shock electrodialysis. (a) Brownian dynamics simulation of a desalination shock propagating through a microchannel away from an electrodialysis membrane, showing the removal of co-ions of the same sign as the wall and membrane charge. (b) This nonlinear phenomenon can be cheaply scaled up in a microporous medium, and cross flow can be used to extract pure water between the shock and the membrane.*

The idea behind "shock ED" is to perform a continuous extraction of pure water behind the shock via a cross flow driven by electro-osmotic and/or applied pressure (Figure 3b). In addition to deionization, the porous medium provides ultrafiltration and rejection of all small co-ionic impurities in the same step, which aids in system miniaturization and efficiency. Since most small impurities (e.g., organic compounds, viruses) are negatively charged and most toxic ions are positively charged (e.g., As3+, Pb2+, Cu2+, Zn2+) in water, a negatively charged porous medium, such as a silica glass frit, can be used with a cation exchange membrane, such as Nafion, to remove most impurities (except for positive nanoparticles) in a single step.

As a proof of principle, the Bazant lab recently demonstrated continuous Cu2+ removal from aqueous CuSO4 by shock ED. The first prototype consists of a silica glass frit and Nafion sandwiched between copper electrodes (Figure 4a, 4b). After subtracting electrode overpotentials, the current-voltage data are consistent with theoretical predictions in the overlimiting regime (Figure 4c). The next steps are to optimize the system, guided by mathematical models, and to test different solution chemistries.

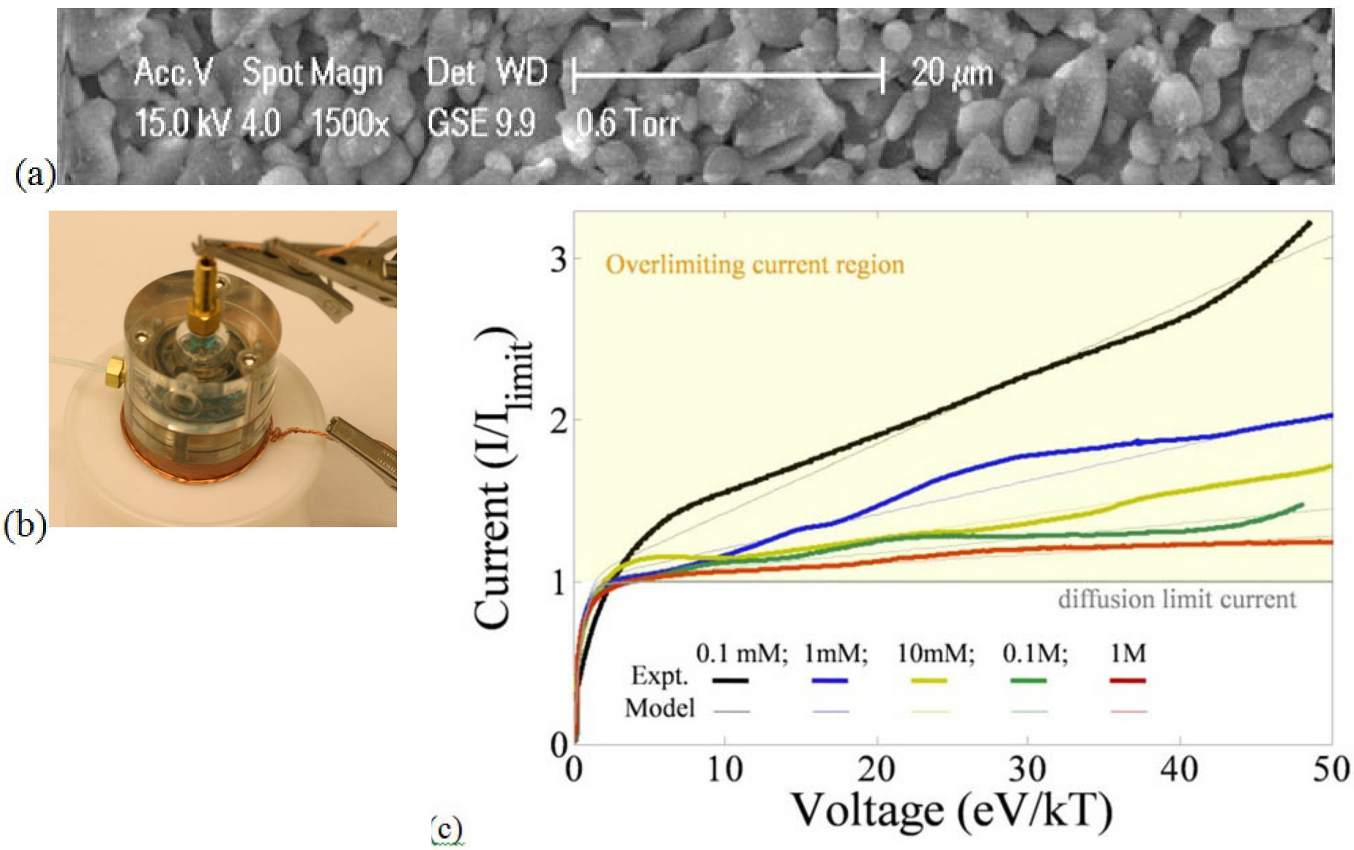



*Figure 4. First shock ED prototype. (a) Scanning electron microscopy (SEM) image of the silica glass frit. (b) The packaged device (3-cm diameter). (c) Steady-state current-voltage relations at different CuSO4 concentrations, comparing theory and experiment and demonstrating overlimiting current due to surface transport in a porous medium for the first time.*

## Annual Lectures

During 2010–2011, the Chemical Engineering Department hosted a distinguished group of academic and industry leaders; highlights are noted below. Webcasts for all major lectures can be accessed at http://web.mit.edu/cheme/news/webcast.html.

> 25th Hoyt C. Hottel Lecture (September 22, 2010): "Energy Innovation at Scale." Steven E. Koonin, the US Department of Energy's undersecretary for science, discussed how business and economics are the real keys to progress in the energy frontier. Koonin explained that the decisions about building new power plants or investing in major new energy infrastructure are more complex than most people realize. Having spent five years working for BP before assuming his present government role, he was in an ideal position to explain and address this complexity.
>
> 10th Frontiers of Biotechnology Lecture (April 15, 2011): "Recent Advances in Yeast Biotechnology—From Humanized Yeast, to Synthetic Immune Systems in Yeast, to ..." Tillman Gerngross, founder of GlycoFi, Adimab and Arsanis, is a professor of bioengineering at the Thayer School of Engineering at Dartmouth College and an adjunct professor in the Department of Biology and Chemistry at Dartmouth. At GlycoFi, Gerngross and his team developed a method for humanizing the glycosylation machinery in yeast to produce human therapeutic proteins, including antibodies, with fully human carbohydrate structures. In 2006, *Nature Biotechnology* named Gerngross as one of the most notable people in biotechnology in the past 10 years. In 2007 Gerngross cofounded Adimab, which over the past four years has developed a premier antibody discovery technology. Gerngross discussed his work on the glycoprotein engineering in yeast, as well as the personal evolution that brought him to this forward-thinking research.

*Figure 5. US undersecretary for science Steven Koonin meets with Chemical Engineering graduate students before giving the 25th Hoyt C. Hottel Lecture on September 22, 2010.*

33rd Warren K. Lewis Lecture (April 29, 2011): "Engineering Products and Processes for a Sustainable World." Gary S. Calabrese, director of photovoltaic technologies and senior vice president at Corning Inc., discussed some of the cutting-edge glass products Corning is currently working on, as well as growing energy issues. A past advisor to *Chemical and Engineering News* and cochair of the National Academies' Board on Chemical Sciences and Technology, Calabrese currently serves as an advisory board member of the Council for Chemical Research, the American Chemical Society, and Lehigh University's Department of Chemical Engineering. He is an inventor with 11 patents and has authored over two dozen technical publications.

17th Alan S. Michaels Lecture (May 6, 2011): "Regenerative Engineering Paradigms for Musculoskeletal Tissues." Cato T. Laurencin, professor of chemical engineering and dean of the School of Medicine at the University of Connecticut, is a nationally prominent orthopedic surgeon, bioengineering expert, and administrator. He is an expert in shoulder and knee surgery and an international leader in tissue engineering research. At MIT, he discussed his group's work in engineering tissues and gave insight into the future of the area, as well as inspiring the audience to take chances and "dare to be daring."

## Chemical Engineering and MIT's 150th Anniversary Celebration

During MIT's 150-day celebration of its sesquicentennial, Chemical Engineering faculty and students took a significant role in demonstrating the Institute's "inventional wisdom."

- Institute Professor Robert S. Langer and professor emeritus Kenneth A. Smith were interviewed as part of the "MIT 150 Infinite History" video project.
- Professors Paula T. Hammond, Douglas A. Lauffenburger, and Robert S. Langer, as well as graduate student Rebecca Ladewski, contributed to the symposium, "Conquering Cancer through the Convergence of Science and Engineering"
- During the campus-wide open house on April 30, 2011, Chemical Engineering undergraduate and graduate students hosted chemical engineering demonstrations outside the Landau Building. Throughout the day, these fun interactive activities enthralled alumni, children, teenagers, and their parents as they learned about biofuels, drug delivery systems, non-Newtonian fluids, and new water-repellent technology being created for the US Air Force. The cornstarch-based non-Newtonian fluid demonstration was described by one of the young observers as "the coolest thing I've seen all day."


*Figure 6. Course 10 graduate students show a future chemical engineer and her father the uncanny powers of a non-Newtonian fluid.*

*Figure 7. First-year graduate student Stephanie Schulze demonstrates hydrophobic materials to open house attendees and families.*

## Departmental Awards

The department awards ceremony took place on May 9, 2011, in the Gilliland Auditorium of the Ralph Landau Building. We are pleased to recognize this year's recipients of the Outstanding Faculty Awards: professor Daniel Blankschtein was the graduate students' choice, and professor William M. Deen was selected by the undergraduate students. The Ruth and Joel Spira Award for Distinguished Teaching, which recognizes excellence in teaching in engineering, was presented to Professor Deen.

The Edward W. Merrill Outstanding Teaching Assistant Award was presented to postdoc Ayse Asatekin Alexiou for her work in 10.213 Chemical and Biological Engineering Thermodynamics. The Outstanding Graduate Teaching Assistant Award was presented to Jaisree Iyer for her service to 10.40 Thermodynamics.

Chemical Engineering Special Service Awards were conferred to the members of the Graduate Student Council: David Borrelli, Caleb Class, Jonathan Gilbert, Jonathon Harding, Cary Opel, Timothy Politano, Katie Quinn, Brandon Reizman, Nisarg Shah, Rathi Srinivas, Carla Thomas, Nicholas Wren, and Nicole Yang. In addition, Jon DeRocher was awarded the Chemical Engineering Rock for outstanding athleticism. 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 Jaisree Iyer and Shawn Finney-Manchester.

Our undergraduates also earned numerous accolades over the course of the year. The following undergraduate students were recognized for their service to the student chapter of the American Institute of Chemical Engineers: Pear Sanglimsuwan, Alexandra Piotrowski, Molly Kozminsky, Shannon Moran, Michelle Lu, Diana Wu, Allison Hinckley, Mary Boyd, Saloni Jain, Elizabeth Ohrt, Daniel Paik, Tim Chang, and Mark Kalinich. The Xi Chapter of Phi Beta Kappa voted to invite seven members of the Chemical Engineering Class of 2011 to become members of the society in recognition of their excellent academic records and commitment to the objectives of a liberal education: Christopher Boyce, Amrita Karambelkar, Ann Ouyang, Alina Rwei, Danielle Wang, Stephanie Wang, and Kellie Young. Christopher Boyce was the recipient of the Gates Cambridge Scholarship for 2011. The National Goldwater Scholarship Award was presented to Joshua Cohen for his devotion to science. The Merck Fellowship Award was presented to Yunxin Jiao in recognition of her scholastic excellence. The Robert T. Haslam Cup, which recognizes outstanding professional promise in chemical engineering, went to Allen Lin. The department's oldest prize, the Roger de Friez Hunneman Prize, is awarded to an undergraduate who has demonstrated outstanding achievement in both scholarship and research; this year it went to Ann Ouyang. This year was the first time we presented the Wing S. Fong Award. It is awarded to the chemical engineering senior of Chinese descent with the highest cumulative GPA, in honor of Wing S. Fong for his hard work and dedication to his adopted home, university, and country. This year's prize was awarded to two equally worthy students: Danielle Wang and Stephanie Wang.

The department is quite pleased to recognize Fran Miles as its outstanding employee of the year for her dedication and exceptional service to faculty, staff, and students. Mark Kalinich, Class of 2013, was presented with a Chemical Engineering Individual Accomplishment Award for his contributions to the department's open house during MIT's 150th anniversary celebration. Emily Chang, Abhinav Akhoury, and Pedro Valencia were also presented with Chemical Engineering Individual Accomplishment Awards for their dedication and hard work as teaching assistants for 10.302 Transport Processes this past fall. The School of Engineering Infinite Mile Award was given to Richard Lay, senior fiscal officer. Rich has proven to be an exceptional fiscal officer who is always willing to expand his knowledge base, to develop better systems, to help others excel, and to find creative solutions for complicated problems. The Student Office (Suzanne Maguire, Katie Lewis, and Fran Miles) received a team Infinite Mile Award from the School of Engineering for the ACCESS Program. Suzanne, Katie, and Fran have gone beyond their already high-quality efforts for the undergraduate and graduate students in the department to establish a vibrant, intellectually stimulating program that addresses long-standing diversity needs. Moreover, the program is now being expanded with their leadership to also include Chemistry and Materials Science and Engineering. The Ellen J. Mandigo Award for Outstanding Service is given annually to a member of the School of Engineering staff who has demonstrated, over an extended period of time, the qualities Mandingo valued and possessed in great abundance: intelligence, skill, hard work, and dedication to MIT. This year Su Chung, director of the Administrative Services Office for Chemical Engineering and Materials Science and Engineering, was the recipient.

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

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

**Paula T. Hammond**
**Executive Officer**
**David H. Koch Professor in Engineering**