Department of Chemical Engineering

In academic year 2007, the Department of Chemical Engineering at MIT saw continued success maintaining its leadership role in the profession with high productivity and visibility in teaching and research. For the 19th consecutive year, our graduate and undergraduate programs both garnered number one rankings among the nation's chemical engineering departments from *US News and World Report.* The Chemical Engineering faculty continues to run vigorous research programs with sponsored research expenditures of more than $33 million for the fiscal year ending June 30, 2008.

Professor Klavs F. Jensen completed his first full year as department head having been appointed in February 2007. Professor Gregory C. Rutledge stepped down July 2008 from his position as executive officer after a successful four-year term to start a well-earned sabbatical. The Department is grateful to Professor Paula T. Hammond for assuming the position along with continuing her large, well-recognized research effort. Professor William M. Deen continues to serve as the Department's graduate officer, while Dr. Barry S. Johnston serves as undergraduate officer. Professor Arup K. Chakraborty completed a year as the graduate admissions officer with a high rate of successful recruiting of outstanding graduate students in competing with other leading chemical engineering departments. Professors Daniel I. C. Wang and Robert S. Langer both hold the honored position of Institute Professor. We are proud to announce the promotions of professor Patrick S. Doyle to associate professor with tenure and professor Bernhardt L. Trout to full professor. Professor Doyle's research is highlighted in the research section below. The Department welcomed one addition to our support staff: Andre Puca, assistant to professors Robert E. Cohen and Narendra Maheshri.

Professor Karen K. Gleason was named the first associate dean of research for the School of Engineering. Among the significant national recognitions garnered by the Department's faculty, professor Robert S. Langer was awarded the National Medal of Science, professor Robert C. Armstrong was elected to the National Academy of Engineering, and professor Klavs F. Jensen was elected to the American Academy of Arts and Sciences. Professor emeritus János M. Beér was awarded the Hungarian Knight's Cross for his contributions to higher education and research, international cooperation in energy technology, and his lifelong technical scientific achievements in clean combustion of fossil fuels. Professor Kristala Jones Prather was named a Top 35 Young Investigator by *Technology Review*.

Two junior faculty members joined the Department in fall 2007. Professor Michael S. Strano is an expert in the science and engineering of carbon nanotubes, holding a BS degree from Polytechnic University and a PhD from the University of Delaware, and was a junior faculty member at the University of Illinois at Urbana–Champaign before coming to MIT. Professor J. Christopher Love received his BS degree from the University of Virginia and PhD from Harvard University, both in chemistry. His research integrates principles from materials science and chemistry to develop micro- and nanotechnologies that enable new, quantitative biological studies. The Department also enjoyed a successful year of recruiting new faculty. Dr. Brad D. Olsen will join the Department in 2010 and brings expertise in the field of polymer physics, functional polymer nanopatterning, and self-assembly. He holds a BS degree from MIT and a PhD from the University of

California at Berkeley; he is currently doing his postdoctoral training at the California Institute of Technology (CalTech). Dr. Yuriy Roman-Leshkov will also join the Department as a junior faculty member in 2010. Dr. Roman-Leshkov conducts research in the field of catalysis, biorefining, and renewable energy. He obtained BS and PhD degrees in chemical engineering from the University of Pennsylvania and from the University of Wisconsin, respectively; he is currently conducting his postdoctoral research at CalTech.

In the news, professors Robert E. Cohen, Gregory C. Rutledge, and collaborators reported a simple design for manufacturing materials that strongly repel oils. The material, which can be applied as a flexible surface coating, could have applications in aviation, space travel, and hazardous waste cleanup. The team overcame the low surface tension of the oil by creating microfibers that are a blend of a specially synthesized molecule called fluoroPOSS, which has an extremely low surface energy, and a common polymer. They can be readily deposited onto many types of surfaces, including metal, glass, plastic, and even biological surfaces such as plant leaves by a process known as electrospinning developed by professor Gregory C. Rutledge's group. Professor Paula T. Hammond and coworkers made the news for developing a new thin-film coating that can deliver controlled drug doses to specific targets in the body after implantation. The films are made from alternating layers of two materials: a negatively charged pigment and a positively charged drug molecule. The timing and dosage of the drug release can be controlled precisely and remotely by electrical signals. Finally, using carbon nanotubes, professor Michael Strano and his team have built the most sensitive electronic detector yet for sensing deadly gases such as the nerve agent sarin. The sensor consists of an array of carbon nanotubes aligned across microelectrodes; when a particular gas molecule binds to the carbon nanotube, the tube's electrical conductivity changes. Each gas affects conductivity differently, so gases can be identified by measuring the conductivity change after binding.

Undergraduate Education

Since 2004, the Department of Chemical Engineering has offered bachelor of science 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 the highest student-to-faculty ratio 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, 74 SB degrees were conferred as of June 2008, with 61% awarded to women. Student quality remains excellent. The distribution of undergraduate students by class over the last 10 years is shown in the table below.

Undergraduate Enrollment over the Last 10 Years

Class Year	98–99	99–00	00–01	01–02	02–03	03–04	04–05	05–06	06–07	07-08
Sophomores	88	71	67	47	56	56	95	100	95	96
Juniors	90	85	76	66	49	43	55	83	75	67
Seniors	94	103	89	84	65	41	55	53	83	77
Total	**272**	**259**	**232**	**197**	**170**	**140**	**205**	**236**	**253**	**240**

The new program leading to the bachelor of science degree in chemical-biological engineering was introduced in 2004 in response to our students' demand 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 new 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, 150 in 2007, and 143 in 2008. Currently, students in the chemical-biological engineering program constitute 60% of the undergraduates in the Department of Chemical Engineering. Fifty-four seniors graduated with degrees in chemical-biological engineering in the class of 2008, and 47 freshmen in the class of 2011 declared their majors in chemical-biological engineering.

The average starting salary for graduates of the Department of Chemical Engineering is $55,870 (2008 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. The senior surveys indicate that, between 2001 and 2008, 50% to 60% of our students went on to graduate or professional school.

Undergraduates in the Department of Chemical Engineering maintain active student chapters of the American Institute of Chemical Engineers (AIChE) and the Society for Biological Engineering (SBE), with invited speakers, presentations at national meetings, and visits to company sites. The student officers of AIChE were Amanda Lanza (president), Balaji Sridhar (vice president), Ellen Sojka (secretary), Matthew Walker (treasurer), Manisha Manmohan (class of 2008 representative), Kathryn Schumacher (class of 2009 representative), and Katrina Westerhof (class of 2010 representative). The student SBE chapter was led this year by Jasmina Aganovic (president).

In 2007–08 the Department's undergraduate programs came up for accreditation by the Accreditation Board for Engineering and Technology (ABET), as part of a schoolwide review of programs in engineering, which occurs every seven years. The BS degree program in Chemical Engineering (Course 10) is seeking re-accreditation while the newer SB degree program in chemical-biological rngineering (Course 10-B) is seeking first-ever accreditation as a dual-name degree in both chemical engineering and biological engineering. After extensive preparation and self-study, the programs hosted a site visit by ABET evaluators in October 2007. The reviews were favorable, and full accreditation of both programs is anticipated later in 2008.

Graduate Education

The graduate program in the Department of Chemical Engineering offers master of science degrees in chemical engineering (MS) and in chemical engineering practice (MSCEP), doctor of philosophy (PhD) and doctor of science (ScD) degrees in chemical engineering, and doctor of philosophy degrees in chemical engineering practice (PhDCEP). The PhDCEP track was established in 2000 in collaboration with the Sloan School. The total graduate student enrollment is currently 238, with 212 in the doctoral program and 26 master's level degree candidates. In the doctoral program, 193 students are in the PhD/ScD track and 19 are in the PhDCEP track. In the master's level program, 17 are in the MSCEP track. Thirty percent of our graduate students are women. Three percent are underrepresented minority students. Forty-two of our graduate students received outside fellowship awards, including from the National Science Foundation (NSF), National Institutes of Health, Department of Defense, and others. The distribution of graduate students by degree for the last 10 years is shown in the table below. During the 2008 academic year, 28 doctoral degrees (26 PhD or ScD and 2 PhDCEP) were awarded, along with 43 master's level degrees (39 MSCEP, 4 MS), for a total of 71 advanced degrees conferred. Forty-four students passed the doctoral qualifying exams and were promoted to candidacy for the PhD/ScD or PhDCEP. The Department received 355 applications for admission to the doctoral program, offered admission to 56 individuals, and received 44 acceptances of offers, for an acceptance percentage of 79%. From 73 applications for master's level degrees, the Department made 30 offers and received 25 acceptances of offers, for a yield of 83%. Among the incoming class for 2008, 27 are women and 1 is an underrepresented minority. On average, the incoming graduate class held an undergraduate grade point average of 4.95 (out of 5.0).

Graduate Enrollment over the Last 10 Years

Degree Level	98–99	99–00	00–01	01–02	02–03	03–04	04–05	05–06	06–07	07–08
Master's	59	54	40	38	36	26	19	16	18	26
Doctoral	140	145	166	209	245	232	216	203	217	212
Total	**199**	**199**	**206**	**247**	**281**	**258**	**235**	**219**	**235**	**238**

Research Centers

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

The Department of Chemical Engineering's Singapore–MIT Alliance program is called Chemical and Pharmaceutical Engineering (CPE) and completed its first year on June 30, 2007. Professor Bernhardt Trout is the codirector of this program with Professor Raj Rajagopalan, head of Chemical and Biomolecular Engineering, National University of Singapore. There are currently 28 students in the program, 13 dual master's degree candidates, and 15 direct entry PhD students. The research part of CPE focuses on metabolic engineering, chemical catalysis, and downstream processing. The MIT faculty involved with CPE are Professors Patrick Doyle, Alan Hatton, Kenneth Smith, Gregory Stephanopoulos, Bernhardt Trout, and Daniel Wang.

The DuPont MIT Alliance (DMA) has a budget of $60 million over 10 years to support research and educational programs of mutual interest. This is the largest academic–industrial agreement for both partners. The DMA Steering Committee is responsible for the direction of the research and educational activities. Professors Claude Canizares, Robert Cohen, and Bruce Tidor represent the MIT side of the Steering Committee. An Internal Advisory Committee (IAC) assists the Steering Committee, including the process of peer reviewing white papers and proposals submitted to the Alliance for funding. The present IAC member list includes Professors Mary Boyce, Yet-Ming Chiang, Kimberly Hamad-Schifferli, Rebecca Henderson, Klavs Jensen, Rajeev Ram, Anthony Sinskey, Bernhardt Trout, and K. Dane Wittrup. DMA is administered from a suite of offices in Building 66 that also serve the needs of DuPont professionals when they visit the Institute. Information of general interest can be found on the DMA website at http://web.mit.edu/dma/www/. On the research side of the Alliance, in the past year more than $3 million of research funds were distributed to 16 principal investigators who have engaged 26 graduate students and 15 postdocs in their DMA-funded research. Faculty principal investigators presented research updates to their DuPont counterparts in May 2008 at the Experimental Station in Wilmington. The graduate students and postdocs funded under the Alliance presented oral briefings and posters to a delegation of DuPont professionals at a one-day symposium at MIT in September 2007. Also in the past academic year, first-year graduate students from 10 different academic departments and centers at MIT were appointed as DuPont Presidential Fellows, funded from DMA's Education Program. These appointments bring the total number of unrestricted first-year fellowships awarded under Alliance funding to 136. Also within the Alliance's Education Program, DMA hosted several one-day tutorials and thematic workshops covering programs of interest to DuPont's professional staff.

The Novartis–MIT Center for Continuous Manufacturing was inaugurated on September 28, 2007, with the aim of transforming pharmaceutical manufacturing from a complicated series of batch processing steps to continuous processing, in which materials flow uninterrupted through the process. The transformation holds promise for leaner processing, higher quality, more flexibility, and, in the end, cost savings. To accomplish this goal, the center is developing new technologies across a diverse range of areas, including chemical reactions, reactors, separations approaches, final finishing steps, and process modeling and control. These new technologies will lead to realization of the "wide-pipe vision," in which raw materials enter the beginning of the pipe continuously. Along the way reactants, solvent, and excipients enter continuously, while waste is removed continuously. Finally, at the outlet, tablets are removed continuously to be sent to packaging. As part of its research activities, the team is also developing a full, end-to-end continuous bench-scale pharmaceutical plant at MIT. This bench-scale plant will be a modular research tool, in which various approaches to continuous manufacturing will be evaluated. In addition to yielding important research results for Novartis drug projects, the plant will serve as a unique educational tool for students. The center is led by professor Bernhardt L. Trout, MIT center director, and Dr. Walter Bisson, from Novartis. In addition, the team consists of Dr. James Evans, MIT associate director; Stephanie Bright, MIT program coordinator; 12 staff members from Novartis; 10 MIT faculty; and 40 MIT graduate students and postdocs. The MIT faculty involved include professors Paul Barton, Charles Cooney, Alan Hatton, Klavs Jensen, and

Bernhardt Trout from Chemical Engineering; professors Steven Buchwald and Timothy Jamison from Chemistry; and professors Jung-Hoon Chun, Martin Culpepper, and David Hardt from Mechanical Engineering. The center has a budget of $40 million for the first five years.

Faculty Notes

Professor Robert Armstrong serves as deputy director of the MIT Energy Initiative (MITEI) and worked with the director, Ernest Moniz, in launching the research, educational, campus, and outreach components of the initiative over its first full year of operation. Nine companies were recruited to sponsor research as members in MITEI. MITEI has raised more than $130 million in research support and 175 graduate fellowships in energy in its first year of operation. This year Professor Armstrong was elected to the National Academy of Engineering. During the past academic year, he gave the Presidential Lecture at the American Dermatological Association and the Barnett F. Dodge Distinguished Lecture in Chemical Engineering at Yale University. He serves on the advisory boards of chemical engineering departments at Georgia Tech, Northwestern University, the University of Washington, the University of Tennessee, and the University of Wisconsin.

Professor emeritus János Beér continued his membership on the National Coal Council, Advisory Council to the US Secretary of Energy. He was invited lecturer at the Fourth World Conference on the Future of Science in Venice, Italy, at the Hungarian Academy of Sciences in Budapest, at the Leaders in Engineering Lecture Series at the University of Maryland, and at the University of Utah's Conference on the Future of Coal. He received the Hungarian President's Award, The Knight's Cross of the Order of Merit of the Hungarian Republic, for his contributions to higher education and research, international cooperation in energy technology, and his lifelong technical scientific achievements in clean combustion of fossil fuels.

Professor Daniel Blankschtein's research group conducts fundamental theoretical and experimental research in the area of colloid and surfactant sScience, with an emphasis on industrial and biomedical applications. Professor Blankschtein's teaching responsibilities included the core graduate Course 10.40, Chemical Engineering Thermodynamics and the interdepartmental graduate Course 10.44J, Statistical Thermodynamics of Complex Liquids. Professor Blankschtein and his students delivered talks and presented posters at the 2007 AIChE Annual Meeting, at the 2007 American Association of Pharmaceutical Scientists Annual Meeting, at the DuPont Experimental Station, at Procter & Gamble, and at the 9th US–Japan Symposium on Drug Delivery Systems held in Maui. Professor Blankschtein continues to serve on the editorial board of Marcel Dekker's *Surfactant Science Series*.

Professor Chakraborty's group made significant advances in understanding the adaptive immune response to pathogens, particularly in the area of T cell receptor development. Three papers from this research are under various stages of review at *Cell* and *PNAS*. In 2008 he received the Distinguished Alumnus Award from the Indian Institute of Technology Kanpur, the highest award given to its alumni in recognition of their achievements of exceptional merit. His teaching responsibilities included the mandatory

graduate course, Chemical Reactor Engineering, and the interdepartmental graduate course, Statistical Thermodynamics with Applications to Biological Systems. Professor Chakraborty served as chair of the Graduate Admissions Committee for Chemical Engineering and also chaired the Strategic Planning Council for the School of Engineering. Outside of MIT he served as chair of the National Research Council Committee on Biomolecular Materials and Processes and delivered more than 20 invited lectures.

In December 2007, Professor Robert E. Cohen and his team of collaborators from MIT and Edwards Air Force Base published a paper in *Science* that received immediate recognition from his peers and a great deal of attention in the popular press. "Designing Superoleophobic Surfaces" (*Science* 2007; 318:1618) demonstrated for the first time robust resistance to wetting by low-surface-tension liquids such as alcohols and oils. He participated in organizing novel educational workshops: "MIT–Princeton Microsymposium on Polymers" and "Diverse Leaders of Tomorrow"—the latter a 2.5-day event providing mentoring to minority students with aspirations toward academic careers. Cohen continues to administer the activities of the DuPont–MIT Alliance.

Professor Charles L. Cooney continued as faculty director of the Deshpande Center for Technological Innovation and chaired the center's Annual IdeaStream Symposium in May 2008. He continued to serve as the co-lead, representing the School of Engineering, in developing the MIT–BP Projects Academy, in partnership with the Sloan School of Management. He traveled with the MIT president and others on the MIT India visit in November 2007. Professor Cooney launched the International Innovation Initiative in fall 2007. He is a member of the MIT Community Service Fund Board, the Lemelson–MIT Screening Committee, the MIT Committee on Intellectual Property, the Faculty Committee on Staff and Administration, 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 at the MIT Masdar Institute of Science and Technology and the Legatum Center, and the Global Studies Committee; he also served on the search committee for dean of the Sloan School. He was director of the Downstream Processing Summer course held through the Professional Institute. Professor Cooney is also an Overseer of the Boston Symphony Orchestra and a Trustee of the Boston Ballet.

Professor Patrick S. Doyle continued work in fundamental studies of complex fluids in microfluidic flows and fields. He delivered invited lectures at various locations including Cornell and Harvard Universities, Luminex Corporation, Agilent Corporation, and Kodak. His work on developing a new method for multiplexed detection of biomarkers using bar-coded particles continues to advance and was recognized by being designated a Deshpande–Lemelson Foundation Project, which has valuable societal impact. He developed and cotaught a new short course on microfluidics at the Society of Rheology Annual Meeting, and he was program chair for the fluid dynamics section of AIChE. Lastly, he was a founding Scientific Advisory Board Member of Genome Corporation.

Professor Karen K. Gleason was appointed associate dean of engineering for research, effective April 2008. This new role follows the completion of a three-year term as associate director of MIT's Institute for Soldier Nanotechnologies (ISN). Last June, she represented ISN at Emerging Defense Technologies in Paris, France. Her group's

research on chemical vapor deposition (CVD) technology of polymeric coatings was the subject of a featured article in the journal *Advanced Functional Materials*. Professor Gleason gave invited presentations in Taipei and Tokyo, as part of the MIT ILP-Epoch Taiwan Symposium and MIT in Japan: 10th Annual Symposium, respectively. Additional invited presentations were given at the 16th European Conference on Chemical Vapor Deposition, held in Den Haag, Netherlands; the American Vacuum Society Meeting in Seattle, Washington; the University of Calgary; the University of Michigan; and Drexel University. She also continued as chief scientific advisor to GVD Corporation, a start-up company she cofounded seven years ago. Professor Gleason will chair the Fifth International Conference on Hot-Wire Chemical Vapor Deposition to be held in Cambridge in August 2008.

Professor William H. Green, Jr., chairs the steering committee for MITEI's major project on conversion with CO_2 sequestration and is principal investigator for several other energy research projects. He welcomed eight new members into his research group and published more than a dozen major journal papers this year. He continues as associate editor of the *International Journal of Chemical Kinetics* and as organizer of the sessions on combustion reaction engineering at the national meetings of AIChE. He served on search committees for faculty positions in three departments and on the committee that recommended improvements in MIT's environmental programs.

In the past academic year, Professor Paula T. Hammond has published two key research papers that describe electrochemically triggered responsive drug release films and polyelectrolyte multilayer thin film membranes that provide significant improvement in the performance of nafion in methanol fuel, both of which were featured in *Technology Review*, *Materials Today*, and other venues. She was the 2007 Lucy Pickett Lecturer at Mt. Holyoke College, the 2008 Karl Kammermeyer Distinguished Lecturer in Chemical and Biochemical Engineering at the University of Iowa, and the WISEST Visiting Lecturer at the University of Illinois, Chicago. Professor Hammond has also become an associate editor for the new American Chemical Society (ACS) nanomaterials-focused journal, *ACS Nano*, which has just completed its first year of publication. She has given invited talks at several institutions and conferences, including the Foundations of Nanoscience Conference in Snowbird, Utah; the Second US–Poland Workshop on Polymer Science in Gdansk, Poland; and the Koch Institute for Cancer Research 2008 Summer Symposium. Professor Hammond has agreed to serve as the Chemical Engineering Department's next executive officer, succeeding Professor Greg Rutledge, starting in July 2008. Professor Hammond has also been engaged in several activities directed toward increasing diversity at MIT. She is currently chair of the Initiative on Faculty Race and Diversity, which seeks to investigate and address MIT's ability to recruit and to retain underrepresented minority faculty. As former chair of the MIT Summer Research Program (MSRP) Redesign Team, she and her fellow committee members, including associate dean Christopher Jones, received the 2008 Irwin Sizer Award for Significant Improvements to MIT Education, presented at the MIT Awards Convocation this May. The MSRP Redesign Team worked to restructure the MSRP program to make it a more effective mentorship and recruiting tool for prospective graduate students at MIT.

Professor T. Alan Hatton continued to serve as director of the David H. Koch School of Chemical Engineering Practice, where he has strived to maintain the international flavor

of the program by placing student teams at host companies in Switzerland, Germany, and Singapore; a new station is planned for India this fall. He is also an active participant in the SMA program on Chemical and Pharmaceutical Engineering, and the Novartis–MIT Center for Continuous Manufacturing. Professor Hatton held an appointment as an Honorary Fellow of the University of Melbourne and is a member of the Scientific Advisory Board of the Particulate Fluids Processing Center at that university, a member of the Advisory Board of the Department of Chemical and Biological Engineering at Tufts University, and a member of the Chemical and Biomolecular Engineering Departmental Review Board for the University of Maryland. Over the past year, he has given a number of invited lectures at ACS and AIChE meetings and seminars at GE Healthcare (Uppsala, Sweden), University of Waterloo, and DuPont. One of his papers topped the list of most-accessed papers in Langmuir for 2007, and another was among the top 100 most cited in *I&EC Research*. Professor Hatton chaired a conference on "The Role of Structure in Chemical, Biological and Environmental Separations" (Costa Rica, January 2008), co-organized a symposium at the ACS meeting in Boston, is on the Organizing Committee of the International Solvent Extraction Conference ISEC 2008 (Tucson 2008), and is on the international advisory committees for the Polymer Networks Group (Cyprus 2008) and "International Symposium on Colloids and Surface Science" (Kolkata 2007). He was the chief guest at the latter conference, where he also presented a plenary lecture, in addition to presenting the first in a series of "Visionary Lectures" at the Indian Statistical Institute in Kolkata. He gave a keynote talk at the Magnetic Fluids Conference in Kosice, Slovakia (2007). He is on the editorial board of the journal *Current Opinion in Colloid and Interface Science* and coeditor of the section on Applications and sits on the Board of Engineering Conferences International.

Professor Klavs F. Jensen continues his research on functional micro- and nanostructured materials and devices for chemical, optical, and electronic applications. With collaborations in chemistry and biology, 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 development 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. During the past academic year, he gave invited/plenary lectures at the Gordon Research Conference on the Physics and Chemistry of Microfluidics, the Third International Conference on Bioengineering and Nanotechnology, the First European Process Intensification Conference, and the AIChE Annual Meeting. He chaired the international evaluation committee for chemical engineering at the Technical University of Denmark, and he continued to serve on the scientific advisory board for the Singapore A*STAR Institute for Nano and Biotechnology, the international advisory panel for Danish research infrastructure, and the steering committee for the International Conference on Miniaturized Chemical and Biological Systems. He was made a fellow of the American Academy of Arts and Sciences and was elected to the American Association for the Advancement of Science (AAAS).

In 2007, Robert Langer received the National Medal of Science, the Herman Mark Award, the ACS Chemistry of Materials Award, and the Wening Memorial Award and

was elected to the Biotechnology Hall of Fame. He received an honorary doctorate from Yale University, was named the Alexander Rich Lecturer at MIT, the Shucart Lecturer at Tufts University, the Findling Lecturer at the Mayo Clinic, the Keck Distinguished Lecturer at Lehigh University, and the Ford Lecturer at Case Western Reserve University. In 2008, Langer received the Max Planck Research Award and the Acta Biomaterialia Gold Medal and was named a Millennium Technology Prize Laureate. He was also awarded the 2008 Prince of Asturias Award for Technical and Scientific Research by the Fundación Príncipe de Asturias. This is the top award any Spanish institution grants to any citizen, and it is often called the "the Spanish Nobel Prize." He was also the Rohm and Haas Lecturer at the University of California, Berkeley, and the Invitrogen Lecturer at the University of California, San Diego.

Professor J. Christopher Love joined the faculty in September 2007 and established his research laboratory in January 2008. His research focuses on developing micro- and nanotechnologies for quantitative analysis of immune responses. The lab's first manuscript describing a technique for profiling blood cells from patients with type I diabetes is in press. He delivered invited lectures at Merck & Co., GlycoFi (a Merck subsidiary), and Harvard University. He also participated on the US team of the NSF-MEXT US–Japan Young Researchers Exchange in the area of nanotechnology and was invited to the National Academies Keck Futures Initiative Conference on aging, longevity, and healthspan.

Professor Kristala Jones Prather continued research in metabolic engineering and synthetic biology. She gave invited lectures at the University of Rochester and Carnegie Mellon University and was keynote lecturer at the 2nd Annual Fellows Symposium of the Institute for Genomic Biology at the University of Illinois at Urbana–Champaign. She also visited the MIT Club of South Texas (Houston) as their annual Institute lecturer. Professor Prather was awarded one of the first seed grants from the MITEI for microbial synthesis of new biofuels and was selected as a *Technology Review* "TR35" Young Innovator.

Professor Gregory C. Rutledge was named the Lammot du Pont professor of chemical engineering in 2007. He continued his role as executive officer of the Department of Chemical Engineering with responsibility for space and undergraduate programs in the Department. This year he oversaw the first review for accreditation of the new degree program in chemical-biological engineering (Course 10-B) and for reaccreditation of the chemical engineering degree program (Course 10) by the Engineering Accreditations Commission of ABET. He continued to serve on MIT's Computer Space Task Force and is an advisory board member of MIT's High Performance Computing Center Project. He is a member of the editorial board of *Polymer* and is a founding editor of the *Journal of Engineered Fibers and Fabrics*. He delivered invited lectures at the 50th Anniversary Symposium of the Discovery of Polymer Single Crystals in Boston, ; the Nanostructured Materials and Membrane Modeling and Simulation Workshop in Patras, Greece; and Macro 2008: Polymers at Frontiers of Science and Technology, the World Polymer Congress of the International Union of Pure and Applied Chemistry, in Taipei, Taiwan, in addition to lectures presented in academia and industry. His research involves the molecular engineering of soft matter through the development of molecular simulations, materials characterization, and electrospinning of polymer nanofibers.

Upon returning from his sabbatical leave at ETH Zurich (Swiss Federal Institute of Technology), Professor Gregory Stephanopoulos continued his research activity as director of the Laboratory of Bioinformatics and Metabolic Engineering with increased emphasis on biofuels research. Seminal research from previous years is finding its way into critical applications for efficient production of biofuels from renewable resources. Professor Stephanopoulos also continued his service on the advisory boards of six academic institutions and the managing board of SBE, which promotes the engineering applications of biology to industry and medicine. He delivered this year's Academy Lecture at the Missouri Science and Technology University and was also honored with selection as the First Biennial Ken Nobe Lecturer of the University of California, Los Angeles. He continued to serve as editor-in-chief of the journal *Metabolic Engineering*, published by Elsevier, and on the editorial boards of seven other scientific journals. In addition to numerous research presentations at professional society meetings (AIChE, ACS, American Society for Microbiology), he has delivered plenary and invited lectures at the 13th European Congress on Biotechnology (Barcelona), the 15th Annual International Conference on Microbial Genomics, Biochemical Engineering XV (Quebec City), the International Conference on Biorefineries (Beijing), the 2008 AAAS Meeting (Boston), the Joint Annual Meeting of VAAM/GBM Societies (Frankfurt), and a conference on the energy crisis sponsored by the Italian Academy in Tuscany. During this year, Professor Stephanopoulos was honored with the C. Thom Award of the Society for Industrial Microbiology and the Founders Award of AIChE.

Professor Michael S. Strano joined the Department this past year and moved his laboratory in spring 2007 to the MIT campus. Over the past year, he has focused on rebuilding his program, teaching graduate and undergraduate courses in Course 10, and adapting to life at the Institute. Highlights over the past year include winning the 2008 Outstanding Young Investigator Award from the Materials Research Society. He also received a 2008 ONR Young Investigator Award for his proposal on "Short Wavelength Optical Modulators for Undersea Communications via Franz-Keldysh Oscillations in Electronically Sorted Single Walled Carbon Nanotubes." He is also a 2008 Alfred P. Sloan Fellow. He had the honor of delivering the Colburn Lecture at the University of Delaware this past semester.

Professor Jefferson W. Tester's research program focuses on clean chemical processing and renewable energy technologies with increasing emphasis on biomass conversion in hydrothermal media and advanced drilling technology using spallation and fusion methods. This past year, he continued cochair responsibilities for the Energy Education Task Force as a part of MITEI. Professor Tester continued to serve as chair of the National Advisory Council of the US Department of Energy's National Renewable Energy Laboratory and as chair of the Governor's Advisory Committee of the Massachusetts Renewable Energy Trust. He also served on advisory boards for Los Alamos National Laboratory, Cornell University, the American Council on Renewable Energy, and the Paul Scherrer Institute of the Swiss Federal Institute of Technology. Professor Tester chaired an MIT-led assessment of the potential of geothermal energy in the United States, which led to the release of a major report, *The Future of Geothermal Energy.* In response to the findings and recommendations of that report, he provided testimony to the US Congress on three occasions and to the Australian Parliament.

Professor Tester also gave invited lectures at Southern Methodist University, the National Research Council, The Future of Science Conference in Venice, The Rome Festival of Science, the University of Puerto Rico, Cornell University, Iowa State University, the World Energy Conference, and the Washington International Renewable Energy Conference.

Professor Bernhardt L. Trout set up major new projects with biopharmaceutical companies, including the new Novartis–MIT Center for Continuous Manufacturing, which began in summer 2007. He revamped and has been running the SMA CPE program. He is a member of the Committee on the Undergraduate Program as well as multiple other Institute and departmental committees. He has been the invited or keynote speaker at various conferences on protein stabilization and pharmaceutical manufacturing.

Professor Daniel I. C. Wang was cochair for the International Organizing Committee at the 13th International Biotechnology Symposium in Dalian, China. He was awarded an honorary professorship at the East China University of Science and Technology, Shanghai, China. He delivered the keynote lecture at the Industrial Biotechnology International Conference, Naples, Italy. He participated in and delivered an address at the NSF/China Workshop on Energy and Environment in Tianjin, China. He continued to hold the Distinguished Temasek Professorship at the National University of Singapore. He participated in the MIT–Portugal Program and presented a two-week course in Lisbon, Portugal. Lastly, the *Journal of Biotechnology and Bioengineering* honored him with its latest award, the Daniel I. C. Wang Award, for the most outstanding publication for investigators under 35 years of age.

Research Highlights

Encoded Hydrogel Particles for High-Throughput Molecular Diagnostics (Patrick S. Doyle)

Detection of nucleic acids and proteins is a fundamental tool that lies at the heart of a broad range of applications from clinical diagnostics to pathogen detection in biodefense to genetic engineering in agriculture. Such biomolecule analysis is most efficiently accomplished by multiplexing—detecting many targets simultaneously in a single sample. Nucleic acids (DNA and RNA) are particularly attractive targets as they can be conveniently amplified and labeled for detection while they provide a high degree of specificity, thus minimizing false-positive results.

Two broad classes of commercially available technologies are commonly used for multliplexed analysis. Microarrays (DNA chips) are ideal for high-density applications that demand the detection of 10,000(+) nucleic acid targets in a single sample, while bead-based systems are required for high-throughput analysis of thousands of samples per day but provide only a modest density of ~100 targets per sample. As the field of molecular diagnostics progresses, it is becoming clear that there exist several arenas that require medium-density (100–3,000 targets), high-throughput screening. These include *in vitro* cancer diagnostics, drug discovery, and neonatal screening. Unfortunately, the multiplexing tools available today cannot efficiently accommodate these applications.

To this end, Professor Doyle's group is developing a technology that can meet the emerging demands in molecular diagnostics, providing higher performance at a lower cost. The process consists of three parts: synthesis of bar-coded particles, incubation with a sample, and particle scanning in a flowthrough microfluidic device (*Science* 2007). This is shown schematically in Figure 1.

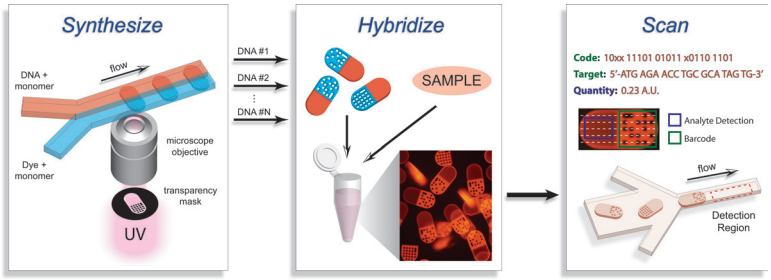

Figure 1. Schematic of multiplexed analysis using bar-coded hydrogel particles. Particles are synthesized with an encoding region and a probe-loaded region using continuous-flow lithography, mixed and incubated with a sample, and then scanned in a flowthrough device.

Particles are created by using microfluidic-based synthesis techniques developed by the Doyle group, called continuous flow lithography (CFL, *Nature Materials* 2006) and stop flow lithography (SFL, *Lab on a Chip* 2007). These processes allow for the creation of geometrically complex microparticles (triangles, rods, or any two-dimensional extruded shape) by coupling microfluidics and photolithography. Additionally, the method allows for the polymerization across laminar coflowing streams of UV-curable monomers, providing a means to synthesize multifunctional particles.

The bar-coded particles are designed to have two functionalities: one fluorescent, graphically encoded region that identifies the probe attached to the particle and one probe-loaded region. More regions can be created by simply coflowing multiple streams. Control regions (where no binding should occur) can also be built into each particle. In one design, the particles bear a 20-bit code through the use of unpolymerized holes in the wafer-shaped structure, thus offering the possibility of more than 10^6 unique codes. The method of particle synthesis is unique from all others in that particle synthesis, encoding, and biomolecule functionalization are combined into a single step.

The particle materials and multifunctional design are also unique. Particles are composed of a porous, hydrogel that provides an ideal environment for nucleic acid hybridization, allowing the system to be extremely sensitive and highly specific for the designated targets. Furthermore, the ability to physically separate the code region from the probe region on a particle allows the use of fluorophores with similar spectral characteristics for encoding and target detection and so requires only one illumination and detection source (i.e., is a single color approach). This will allow for more compact and economical scanners.

After hybridization of fluorescently labeled targets, the particles are flowed through a microfluidic device, where they are aligned by flow-focusing and scanned with a detector. Overall, the technology is inexpensive and extremely versatile. The approach

has been applied to both DNA and RNA detection and validated for applications in drug discovery and *in vitro* cancer diagnostics. With help from MIT's Deshpande Center, Professor Doyle and a recent graduate from his group are hoping to push the technology toward commercialization.

The Doyle lab's approach to particle synthesis has implications far beyond diagnostics. Flow lithography has already been used to synthesize mesoscopic surfactants (*Langmuir* 2007), photonic structures (*Angewandte Chemie International Edition* 2007), and cell-loaded particles for tissue engineering (*Lab on a Chip* 2008). With enormous, largely untapped, potential the approach will continue to be an intense area of research in Professor Doyle's group.

Near-Infrared Optical Modulation of Carbon Nanotubes for Biomedical Sensors (Michael S. Strano)

The Strano laboratory continues its focus on the chemistry of low-dimensional systems and, specifically, transduction mechanisms for nanosensors. In recent work, they have demonstrated a new class of sensors for life science and biomedical applications based on single-walled carbon nanotubes (SWNT). These carbon-based molecular cylinders have tunable, near-infrared fluorescent emission in a region of the electromagnetic spectrum through which biological materials, such as tissue and blood, exhibit minimal autofluorescent background and enhanced optical transparency. Their lack of photobleaching makes them ideally suited for long-term monitoring. To date, the Strano laboratory has developed chemical interfaces and transduction mechanisms for specific detection of glucose, divalent metal cations, and DNA hybridization even through blood and other highly scattering media. Recent work has focused on the optical responses of carbon nanotubes to osmotic pressure gradients in a hydrogel-based, tissue-implantable construct (Figure 2). The effort thus far is able to validate and expand upon existing theories of lattice strain and optical modulation for one-dimensional quantum confined systems. The Strano laboratory hopes to study and further refine such systems for use as real-time glucose sensor devices that are optically queried.

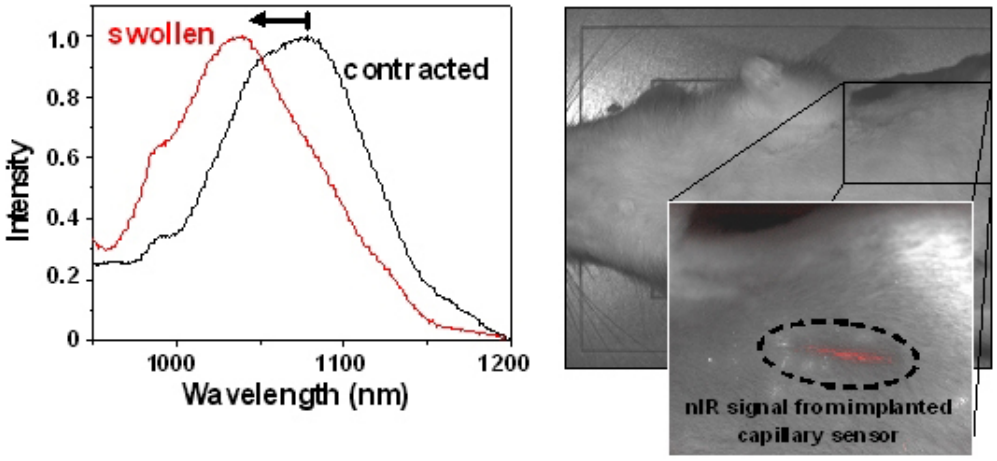

Figure 2. A SWNT-hydrogel sensor shows shifts in SWNT fluorescence in response to the swelling state of the hydrogel (left). A SWNT fluorescence sensor implanted beneath the skin of a rat can easily be imaged through the tissue (right).

Nanoscale sensing elements have other advantages, such as the potential for single molecule analyte detection in physically or biologically constrained environments. The Strano laboratory has recently demonstrated that a pair of carbon nanotubes can provide four nearly orthogonal optical modes for signal transduction that can be used to identify distinct classes of genotoxic analytes (Figure 3). The system can uniquely fingerprint, for example, chemotherapeutic drugs and reactive oxygen species, which are spectroscopically differentiated into four distinct classes. The team also recently demonstrated single-molecule sensitivity of hydrogen peroxide, one of the most common genotoxins and an important signaling molecule. The sensors have been tested in real time within live mammalian cells, demonstrating the first multiplexed optical detection from a nanoscale biosensor and the first label-free tool to optically discriminate between genotoxins.

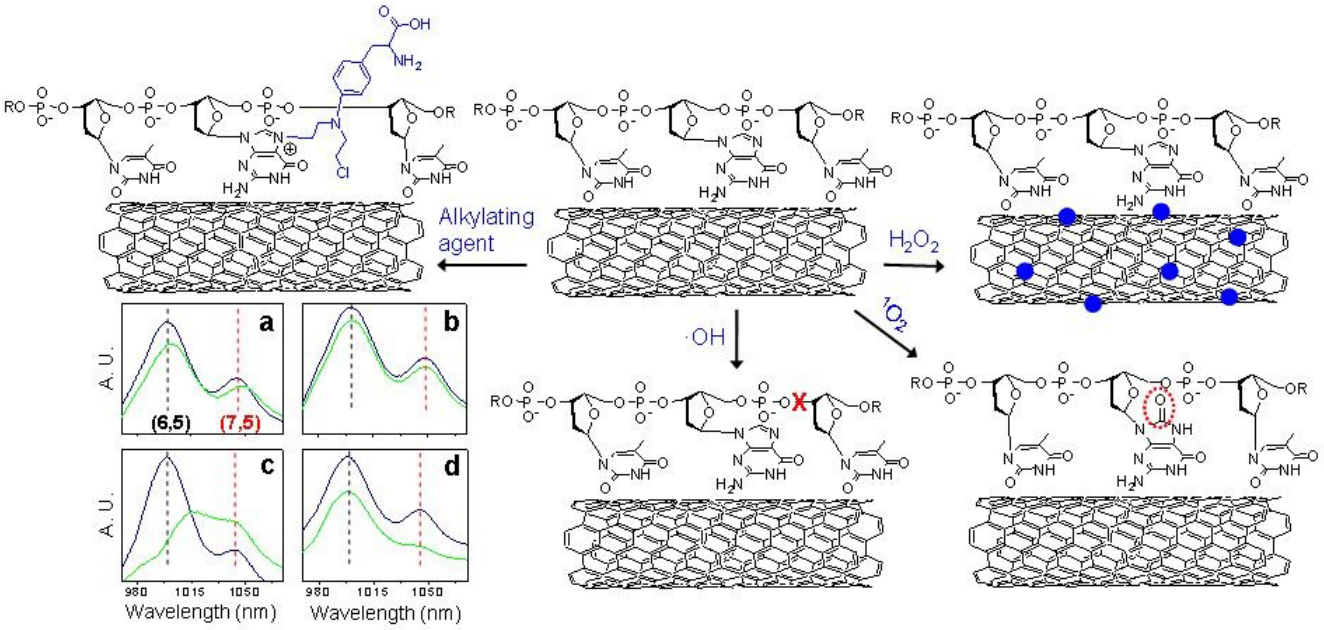

Figure 3. Four genotoxic chemistries elicit distinct optical responses from a pair of two DNA wrapped carbon nanotubes: (a) alkylation, (b) hydrogen peroxide physisorption, (c) singlet oxygen, (d) hydroxyl radical.

Annual Lectures, Seminars, and Symposia

The Department once again hosted an extremely successful series of four annual major lectures. In the fall, Dr. Peter S. Kim, President of Merck Research Laboratories, delivered the eighth Frontiers of Biotechnology Lecture, speaking on "Improving Human Health Through Translational Research." In November 2007, Berkeley University Professor Gabor Somorjai gave the 22nd Hoyt C. Hottel Lecture on "Frontiers of Surface Science: Transition from Studies of Crystal Surfaces in Vacuum to High Pressure and Liquid-based Bio-interfaces and Nanoparticles Leads to New Science and Applications."

During the spring 2008 semester, we hosted Dr. Stephen N. Oesterle, senior vice president for medicine and technology at Medtronic, Inc., whose seminar "Medicine

for the Millennium: How MIT Has Served as a Muse for Medtronic" was a hit as the 14th Alan S. Michael Lecture in Medical and Biological Engineering. Finally, Professor John F. Brady of CalTech presented the 30th Annual Warren K. Lewis Lecture, "Osmotic Propulsion: The Osmotic Motor." Earlier that week, he discussed his research in the Lewis Research Lecture, "From Proteins to Peas: Diffusion Across Scales."

Our Departmental Seminar Series featured a distinguished group of academic and industry leaders from Yale University; the University of Wisconsin; the University of Minnesota; Northwestern University; University of California, Berkeley; Harvard University; University of California, Santa Barbara; the University of Delaware; Purdue University; the New University of Lisbon; University of California, San Diego; Stanford University, and Microbia Precision Engineering, Inc. As part of the spring seminar series, the Department also presented some of its own faculty to prospective students as they visited campus: Professors Paula T. Hammond, Robert C. Armstrong, and Institute Professor Robert S. Langer.

Departmental Awards

The Department Awards Ceremony took place on May 12, 2008, 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 Barry Johnston and Professor Herbert Sawin were selected by the undergraduate students.

The Edward W. Merrill Outstanding Teaching Assistant Award was presented to graduate student Patricio Ramirez Munoz for his work in Courses 10.490 and 10.493 Integrated Chemical Engineering. It was also presented to Jit Hin Tan for his work in Course 10.10 Introduction to Chemical Engineering. The Outstanding Graduate Teaching Assistant Award was presented to Salmaan Baxamusa for his service to Course 10.34 Numerical Methods Applied to Chemical Engineering and to Amanda Engler for her work in Course 10.40 Chemical Engineering Thermodynamics.

Chemical Engineering Special Service Awards were conferred to the members of the Graduate Student Council: Amanda Lanza, Mahriah Alf, Miles Barr, Daniel Bonner, Tanguy Chau, John De Rocher, Michael Johnson, Ben Lin, Jordi Mata-Fink, Nicholas Musolino, Kevin Nagy, Arvind Prabhakar, Joseph Scott, Anita Shukla, Kevin Solomon, Su Kyung Suh, and Mitchell Tai. In addition, Kevin Krogman was awarded the Chemical Engineering Rock for outstanding athleticism and Amanda Lanza was recognized for her year as president of the Student Chapter of the American Institute of Chemical Engineers. 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 Melanie Chin and Daniel Klein-Marcuschamer.

Our undergraduates also earned numerous accolades over the course of the year. The Merck Fellowship Award was presented to Jennifer Yeh in recognition of her scholastic excellence. Jennifer Yeh also received the National Goldwater Scholarship Award for her scholastic excellence. Jennifer Resvick was presented with the Cunningham Scholar Award, which is given to promote women in engineering. The Robert T. Haslam Cup,

which recognizes outstanding professional promise in chemical engineering, went to Nina Mann. The Department's oldest prize, the Roger de Friez Hunneman Prize, awarded to the undergraduate who has demonstrated outstanding achievement in both scholarship and research, this year went to Darren Verploegen.

The Department is quite pleased to recognize Linda Mousseau and Barbara Driscoll as the Department's Outstanding Employees of the Year for their dedication and exceptional service to faculty, staff, and students. The School of Engineering Infinite Mile Award went to department member Steve Wetzel, manager of engineering facilities.

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

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

Paula T. Hammond
Executive Officer
Bayer Professor of Chemical Engineering

More information about the Department of Chemical Engineering can be found at http://web.mit.edu/cheme/index.html.