Department of Chemical Engineering

The Department of Chemical Engineering completed a significant strategic planning exercise in July 2005. In so doing, it examined the major needs and opportunities facing the Department and the profession of chemical engineering in the next 10 years, as well as the steps necessary to position the Department to meet these needs and opportunities. Chemical Engineering rearticulated its goal of being a dynamic department, one with cohesive and exciting academic programs that continuously define the future of the chemical, biological, materials, and energy industries, and one with faculty and students who exercise leadership in education and research and make significant contributions toward solving human needs for the betterment of the world at large. Outlined here are 10 goals comprising the essence of the strategic plan the Department will pursue over the next 10 years:

Scope and infrastructure—tackling the critical necessary conditions

- A profound strategic commitment to shape the future of the discipline and the profession at large underlies all other strategic thrusts.
- The construction of a new building for the Department is a top strategic priority.
- An increase in the number of women and underrepresented minority faculty members and graduate students will be pursued in recognition of the importance of a diverse faculty and student body.

Education—leading the redefinition of core chemical engineering education

- Redesign the undergraduate curricula, starting from a clean slate.
- Provide the necessary resources to maintain the preeminence and differentiating value of the Chemical Engineering Practice MS program.
- Continue to evolve the core graduate curriculum and experiment with new courses at the interface with other disciplines, maintaining the high levels of commitment and investment in human and financial resources.
- Complete the deployment of the Chemical Engineering Practice PhD program and take all the necessary steps to ensure its position as a high value-added educational program.

Research and scholarly activities—defining the future of the chemical engineering academic enterprise

- Strengthen the preeminence and enrich the scope of the biological engineering research program through new hires.
- Strengthen the research program in the following areas through targeted hires:
    a. Products and processes for energy and the environment
    b. Synthesis of new materials, processes, and devices with molecular-level control
    c. Systems engineering of biological and chemical products and processes at the molecular level

- Collaborate with select industrial partners to develop Department-centered, MIT–wide integrated research programs for high-risk, high-profile, and high-impact technological innovations.

In academic year 2006, the Department of Chemical Engineering at MIT maintained its leadership role in the profession, with high productivity and visibility in teaching and research. For the 17th consecutive year, both our graduate and undergraduate programs garnered number one rankings among the nation's chemical engineering departments from *US News and World Report.* Chemical Engineering faculty continue to run vigorous research programs, with sponsored research expenditures of over $23 million for the fiscal year ending June 30, 2006.

The Department of Chemical Engineering is headed by Professor Robert C. Armstrong, while Professor Douglas A. Lauffenburger is director of the Division of Biological Engineering. Professor Gregory C. Rutledge is the executive officer of Chemical Engineering. Professor William M. Deen assumed the role of graduate officer, and Dr. Barry S. Johnston assumed the role of undergraduate officer in AY2006. Professor Paula Hammond continues to serve as graduate admissions officer, while Professors Daniel I. C. Wang and Robert S. Langer each hold the position of Institute Professor. We are proud to announce the promotion of Professor Paula T. Hammond to full professor and Professor Patrick S. Doyle to associate professor.

The Department welcomes the addition of Professor Arup Chakraborty and Professor Narendra Maheshri to the faculty. Professor Chakraborty is one of the leading chemical engineering theorists worldwide. He has made seminal contributions to numerous areas, including heterogeneous catalysis, polymer self-assembly, polymer interfaces, sensor technology for pathogen detection, and cell-cell recognition for the immune system. Professor Maheshri received his BS in chemical engineering and biology at MIT in 1999 with a very impressive record and was awarded an NSF graduate fellowship prior to arriving at UC Berkeley for his graduate work in chemical engineering. Before joining the faculty here, he did postdoctoral research with Professor Erin O'Shea at the University of California–San Francisco. His focus area is cell signaling, and his planned research here at MIT is the design of evolvable biological systems.

New additions to our support staff are Ruby Velez, assistant to Professor Armstrong; Rosangela dos Santos, assistant to Professors Cooney and Greg Stephanopoulos; Angelique Scarpa, assistant to Professor Trout; and Barbara Balkwill, assistant to Professors Green, Wang, and George Stephanopoulos. Professor Robert A. Brown completed his tenure as provost of MIT and accepted the position of president of Boston University in 2005. Professor Alice P. Gast served as MIT's vice president of research and has accepted the position of president of Lehigh University starting in July 2006.

Professor Howard Brenner retired after a 50-year career in teaching. The Department mourns the passing of Dr. C. Michael Mohr and professor emeritus Robert C. Reid.

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). Student enrollment in the new Course 10-B has been very robust, with 40 sophomores and 49 juniors enrolled in spring 2006. The degree track graduated its first cohort of 14 seniors with the Class of 2006. Sixty-four freshmen in the Class of 2009 declared their major in chemical-biological engineering.

Department undergraduate enrollment increased from 205 to 236 students. Fifty-seven SB degrees were conferred as of June 2006, with 60 percent awarded to women. Also, student quality remains excellent. The distribution of undergraduate students by class is shown in Table 1.

Table 1. Undergraduate Enrollment over the Last 13 Years

Class Year	95–96	96–97	97–98	98–99	99–00	00–01	01–02	02–03	03–04	04–05	05–06
Sophomores	118	87	97	88	71	67	47	56	56	95	100
Juniors	101	121	90	90	85	76	66	49	43	55	83
Seniors	103	110	130	94	103	89	84	65	41	55	53
Total	**322**	**318**	**317**	**272**	**259**	**232**	**197**	**170**	**140**	**205**	**236**

Graduate Education

The Department of Chemical Engineering's Singapore–MIT Alliance-2 program, called Chemical and Pharmaceutical Engineering (CPE), began on July 1, 2006. There will be 11 students in the first year, 6 dual master's students, and 5 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 Steve Buchwald (Chemistry), Patrick Doyle, Alan Hatton, Kristala Prather-Jones, Kenneth Smith, Greg Stephanopoulos, Bernhardt Trout, and Daniel Wang.

On July 1, 2005, MIT officially launched a continuation of the DuPont–MIT Alliance (DMA) for a second five years for $25 million, bringing the total award to $60 million. This is the largest academic-industrial agreement for both partners. Professor Alice P. Gast and Robert E. Cohen, both in Chemical Engineering, serve as the MIT directors of the DMA program. Professors Bernhardt L. Trout, T. Alan Hatton, K. Dane Wittrup, Robert S. Langer, Gregory Stephanopoulos, Charles L. Cooney, and Daniel I. C. Wang all contributed to the tutorials and workshops that comprise the educational thrust of DMA.

The graduate student enrollment is currently 219, with 203 in the doctoral program and 16 master's level degree candidates. The graduate programs include 73 foreign, 58 female, 34 Asian-American, and 10 self-identified minority students. The distribution of graduate students by degree is shown in Table 2. During the academic year, 32 doctoral degrees (PhD and ScD) were awarded, along with 40 SM and/or master's level degrees, yielding a total of 72 advanced degrees conferred. Thirty-four students passed the doctoral qualifying exams and were promoted to candidacy for the PhD/ScD. The Department received 326 applications for admission to the doctoral program, offered admission to 53 individuals, and received 37 acceptances of offers. Among the incoming class for 2006, 16 are female and 8 are minority or Asian-American graduate students. The incoming graduate class held an undergraduate GPA of 4.95 (out of 5.0).

Table 2. Graduate Enrollment over the Last 13 Years

Degree Level	95–96	96–97	97–98	98–99	99–00	00–01	01–02	02–03	03–04	04–05	05–06
Master's	56	64	51	59	54	40	38	36	26	19	16
Doctoral	169	162	167	140	145	166	209	245	232	216	203
Total	**225**	**226**	**218**	**199**	**199**	**206**	**247**	**281**	**258**	**235**	**219**

Space Changes

This year the Department of Chemical Engineering acquired and renovated 7,000 net sq ft of new lab and office space on the 5th floor of Building E19 to accommodate its growing faculty in chemical and biological engineering. The research groups of Professors Chakraborty, Trout, and Wittrup moved into this space in January 2006 and now enjoy intellectual and infrastructural synergies made possible by having this critical mass of theoretical, computational, and experimental chemical-biological engineering research located in Building E19. This move has had the beneficial effect of somewhat relieving overcrowded research groups located in Building 66 and Building 56, which has in turn enhanced research productivity and increased the number of research opportunities for undergraduates within the Department.

Faculty Notes

Professor Robert Armstrong continued to serve as department head. During 2005 he served as chair of the Council for Chemical Research, and he is very active in leading a series of discipline-wide discussions on "Frontiers in Chemical Engineering Education." This educational activity has as its goal the first major revision in chemical engineering undergraduate curriculum in over 45 years. He was named the 2006 winner of the Bingham Medal of the Society of Rheology, the society's highest honor. During this past academic year he gave invited/plenary lectures at the Ninth International Conference on Chemical Engineering in Portugal, at Texas Tech University, Purdue University, and Wayne State University. He serves on the advisory boards of chemical engineering departments at Georgia Tech, Northwestern University, Virginia Tech, the University of Washington, the University of Wisconsin, and Stanford University. He cochaired MIT's Energy Research Council with Professor Ernest Moniz from Physics.

Professor Daniel Blankschtein continued to serve as graduate officer during the fall of 2005, and was responsible for the educational and social well-being of approximately 220 graduate students in the Department. His research group conducts fundamental theoretical and experimental research in the area of colloid and interface science, with emphasis on industrially and biomedically relevant applications. Professor Blankschtein's teaching responsibility included the interdisciplinary course 10.55 Colloid and Surfactant Science, which was well attended by students from across the Institute. Professor Blankschtein and his students delivered oral presentations and presented posters at the American Institute of Chemical Engineers Annual Meeting, the Meeting of the Society of Cosmetic Chemists, the Meeting of the American Academy of Dermatology, the International Conference on Biopartitioning and Purification held in the Netherlands, and the Conference on Enzymatic Hydrolysis and Biomass held in

Brazil. Professor Blankschtein delivered an invited talk at the 2005 Gordon Research Conference on "Barrier Function of Mammalian Skin" and continues to serve on the editorial board of Marcel Dekker's Surfactant Science Series.

Professor Robert E. Cohen was named a fellow of the American Institute of Chemical Engineers in 2005, and he received his citation in a ceremony at the November 2005 Annual Meeting in Cincinnati. At MIT he continues to direct the operation of the DuPont–MIT Alliance, a broadly based $5 million per year research and education collaboration, now in its 7th year of operation. He also served the Institute for a second year as chair of the Committee on Nominations, which is charged with the responsibility of staffing the various standing committees of the Faculty. His numerous invited and contributed research presentations included a plenary presentation at the Asilomar Conference on Polymers in Pacific Grove, CA. His collaborative research with Professor Michael Rubner, director of the Center for Materials Science and Engineering at MIT, led to patent applications on novel antifogging coatings, a topic that received widespread attention in the popular press and in radio and TV coverage. He competed successfully in 2005 for a post in the MIT–Balliol College Exchange Program, and in January of 2006 he took up his visiting fellow position at Balliol. The visiting position also affords access to Oxford University's Department of Engineering Science, the site of Professor Cohen's year of postdoctoral study in 1973.

Professor Charles L. Cooney continued as the faculty director of the Deshpande Center for Technological Innovation and chaired the Center's annual IdeaStream Symposium in April 2006. He took a leadership role in the defining of the manufacturing initiative in the Center for Biomedical Innovation and continued as the colead, representing the School of Engineering, in developing the MIT British Petroleum Projects Academy Initative in partnership with the Sloan School of Management. Professor Cooney chaired a symposium on Academic Innovation at the Chemical Heritage Foundation in March. He continued as chair of the Food and Drug Administration Advisory Committee for Pharmaceutical Sciences and is a member of the MIT Community Service Fund Board, the Lemelson MIT Screening Committee, and the MIT Committee on Intellectual Property. Professor Cooney is also an overseer of the Boston Symphony Orchestra and a trustee of Boston Ballet.

Professor Patrick S. Doyle was invited to give the Colburn Memorial Lecture at the University of Delaware. He codeveloped and ran a short course on microscopy as applied to rheology at the annual Society of Rheology meeting in Vancouver. He delivered invited talks at several conferences and institutions, including the American Chemical Society (ACS) Special Symposium on Confined Fluids; the ACS Special Symposium in Honor of Alice Gast, Stanford University; the New England Complex Fluids Meeting; and US Genomics. His work entails fundamental studies of complex fluids in flows and fields.

Professor Karen K. Gleason returned from a sabbatical year at GVD Corporation, a start-up company she cofounded, to become associate director of MIT's Institute for Soldier Nanotechnologies (ISN). Professor Gleason was awarded the Professor Franciscus Cornelis Donders chair, which will support her as a visiting professor in the Department of Physics and Astronomy at University of Utrecht, Netherlands, in the summer of 2006. In the past year, she presented a keynote address to the Millennium Research for Advanced Information Technology (MIRAI) Low-k Workshop in Tsukuba, Japan, and also gave invited presentations on her group's research on chemical vapor deposition technology at the Interuniversity MicroElectronics Center (Leuven, Belgium), the Chemical Engineering Department at the City College of New York, the Electrochemical Society Meeting (Denver), and the American Institute of Chemical Engineers (Cincinnati).

Professor William H. Green received the 2006 C. M. Mohr Award for outstanding undergraduate teaching in the Chemical Engineering Department. This new award honors Dr. C. Michael Mohr, who set a high standard for undergraduate teaching before his death in June 2005. Professor Green also received the Certificate of Merit from the American Chemical Society's Division of Environmental Chemistry for research on solvation. He taught in the Summer School on Sustainability in 2005, in the faculty short course in energy in 2006, and served on the Energy Research Council. He was elected to the board of the regional section of the Combustion Institute.

Professor Paula T. Hammond celebrated her promotion to full professor this year, as she continues her service as the chair of Graduate Admissions for the Department. New developments in the formation of sequential drug delivery thin films led to a second year of funding from the Deshpande Center for Innovation and a landmark paper on the method in the *Proceedings of the National Academy of Science.* Other new research thrusts include a collaborative effort with Professor Angela Belcher of Materials Science and Engineering in the incorporation and self-assembly of viruses in polyelectrolyte multilayer systems, which led to papers in *Nature Materials* and *Science* (with Professor Yet-Ming Chiang) in 2006. Exploratory research efforts continued in the development of linear-dendritic block copolymers for drug delivery and nanostructured materials, with new sponsorship provided by the National Institutes of Health (NIH). Professor Hammond delivered lectures at numerous universities, corporations, and conferences, including the Japan-American Conference on Hybrid Materials and Nanostructures in Asilomar, CA, the Gordon Conference on Biopolymers at Salve Regina, RI, and the Gordon Conference on Supramolecular Chemistry in Ventura, CA. She also participated in a symposium series on Commercializing Academic Innovation at the Chemical Heritage Foundation and was the keynote speaker for the Robert M. Langer Symposium held at Yale University. She continues to serve as a team leader and active researcher in ISN.

Professor Kristala Jones Prather joined the faculty in 2004 and is establishing a laboratory with research focused on the design of biosynthetic pathways for microbial production of organic chemicals. Her work builds upon advances in metabolic engineering and the nascent field of synthetic biology. She was recognized with a Camille and Henry Dreyfus Foundation New Faculty Award in 2004. In June of 2005, she became an Office of Naval Research Young Investigator. This year, Professor Prather received an award for outstanding undergraduate teaching.

Professor Gregory C. Rutledge continued his role as the executive officer of the Department of Chemical Engineering. In 2006, he was named a fellow of the American Physical Society for his work on the structure-property relationships of macromolecules. He is a member of the editorial board of *Polymer* and is a founding editor of the *Journal of Engineered Fabrics and Fibers.* He serves on the Gender Equity Committee for MIT's School of Engineering, the Research Award Selection Committee of the Society of Plastics Engineers, and he co-organized the American Chemical Society (ACS) Symposium on Advances in Methods and Applications of Molecular Simulation. He delivered invited lectures at the University of Nebraska, the 5th International Discussion Meeting on Relaxations in Complex Systems, the ACS Symposium on Complex Fluids in Confined Spaces, Autopolymer '05, Techtextil, and the 34th annual Leermakers Symposium at Wesleyan University on "Challenges to Chemistry from Other Disciplines." His research involves the molecular engineering of soft matter through the development of molecular simulations, materials characterization, and electrospinning of polymer nanofibers.

Professor Jefferson W. Tester's research program focuses on clean chemical processing and renewable energy technologies, with new research thrusts in biomass conversion in hydrothermal media and advanced drilling technology using spallation and fusion methods. This past year, he continued to serve as chair of the National Advisory Council of the US Department of Energy's National Renewable Energy Laboratory and as cochair 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, American Council on Renewable Energy, and the Paul Scherrer Institute of the Swiss Federal Institute of Technology. He gave invited lectures at the University of Colorado, Imperial College, the University of Alberta, Stanford University, the Italian Energy Festival, Osaka Prefecture University, the Royal Society, Rensselaer Polytechnic Institute, Ente Nazionale Energia Elettrica (ENEL) Rome's Energy Challenges Conference, and Barcelona's Energy Technology Conference. During the summer of 2005, Professors Tester and Jeffrey Steinfeld (Chemistry) led an American Chemical Society PRF sustainability short course at MIT. A new textbook, *Sustainable Energy: Choosing among Options,* coauthored by Professor Tester along with Professors Michael Golay and Michael Driscoll (Nuclear Science and Engineering), Dr. Elizabeth Drake (Laboratory for Energy and the Environment), and Dr. William Peters (ISN), was released by MIT Press. In the spring of 2006, Professor Tester spent time at Chalmers Technical University (Sweden) as the Wenner-Gren Distinguished Lecturer.

Professor Bernhardt L. Trout set up major new projects with biopharmaceutical companies. The objectives for these projects are to understand degradation mechanisms of therapeutic proteins and antibodies and use that understanding to engineer new generation biopharmaceutical formulations. He has also set up new projects in the areas of energy and the environment. He has been invited as a plenary lecturer in the Physics and Chemistry of Ice Conference in Bremerhaven, Germany, in addition to the Protein Stabilization Conference in Breckenridge, CO. He has given several invited talks at universities, including Texas A&M, Drexel, the University of Rome (Italy), and the Institute for Advanced Studies in Trieste (Italy). He also continues to be a fellow of Next House.

Research Highlights

Adaptive Immune Response (Arup Chakraborty)

Professor Chakraborty is developing the principles governing the adaptive immune response using an approach at an intersection of engineering, the physical sciences, and biology. Higher organisms, like humans, have an adaptive immune system that enables them to combat pathogens that they have never encountered before. The adaptive immune response is orchestrated by a class of cells called T lymphocytes (T cells). Their importance in maintaining our health is highlighted by the fact that HIV infections compromise the adaptive immune system by infiltrating T cells, which then makes a patient susceptible to a host of opportunistic infections. On the other hand, spurious activation of T cells results in a variety of autoimmune disorders such as multiple sclerosis, diabetes, and arthritis. Thus, understanding how adaptive immunity is regulated is an important fundamental question in biology with far-reaching consequences for the development of intervention protocols that may alleviate human suffering.

In spite of enormous progress, the mechanisms that underlie T cell activation are not understood. This is because they are the result of cooperative dynamic processes involving many molecular components acting in concert. This inherent cooperativity makes it difficult to intuit underlying mechanisms by observing a few experimental reporters. Recent advances in video microscopy have produced vivid images of the consequences of these cooperative dynamic processes and have encouraged efforts to confront the challenge of elucidating the pertinent mechanistic foundations of T cell activation and its misregulation. Over the last hundred years, statistical mechanics has evolved as a discipline focused on understanding cooperative processes, albeit in simpler synthetic systems. A few years ago, Professor Chakraborty's research group was fortunate to have recognized that statistical mechanical methods, along with the principles of reaction engineering, could become powerful complements to genetic, biochemical, and imaging experiments in unraveling the mysteries of T cell activation. They have developed and applied these methods, in close synergy with experimental studies carried out in leading immunology laboratories, to shed light on significant questions relevant to T cell biology. The primary focus of Professor Chakraborty's research is to build on these successes to develop the principles that underlie how T cells get activated as well as the aberrant regulation of these processes. A hallmark of his work is that, while the computational/theoretical studies carried out in his group are at the cutting edge of engineering and statistical physics, it is also closely synergistic (indeed, collaborative) with experiments in the leading immunology laboratories in the world.

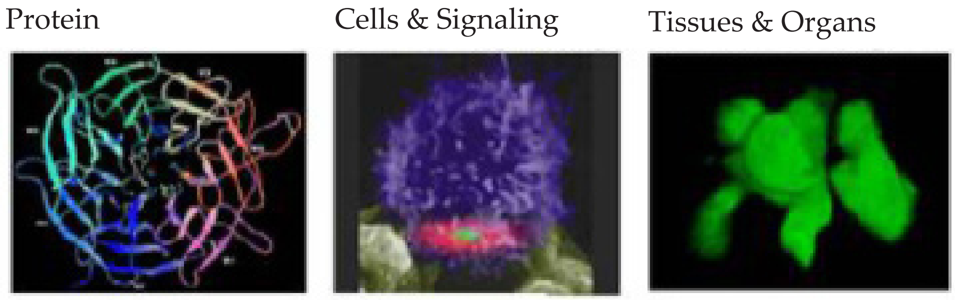

Figure 1. Multiscale cooperative processes underlying T cell activation. Signaling complexes assemble at the molecular scale upon interaction of T cells (blue) with molecular signatures of pathogen displayed on antigen presenting cells (green). Various signaling complexes in the T cell must act cooperatively on length scales that span the cell. These processes occur as T cells hunt for antigen in tissues.

T cell activation involves processes that occur over a wide range of length and time scales (Figure 1). Events that occur over molecular time and length scales influence events on the scale of the entire cell, which in turn regulate behavior on the scale of tissues and organs. Interestingly, this is not a one-way street; phenomena that occur on larger scales also influence events on shorter scales. The focus of the Chakraborty group is on unraveling the mechanistic underpinnings of these hierarchically cooperative processes via computational studies that are synergistic with in vitro and in vivo experimentation carried out by their collaborators. To develop this new paradigm in molecular immunology research further, they have recently established the Immune Response Consortium, a major NIH–funded effort based at MIT that brings together physicists, chemists, engineers, and immunologists.

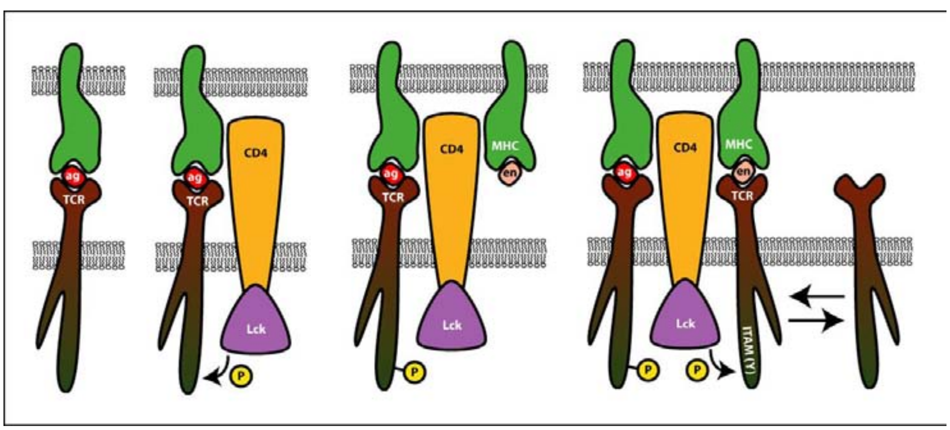

Figure 2. A cooperative mechanism underlying T cell sensitivity to antigen. Antigen-derived (Ag) pMHC bind TCR to nucleate signaling complexes because they are held together for a sufficiently long time to enable the recruitment and binding of the kinase Lck, which phosphorylates TCR to initiate signaling. Some of the multitude of endogenous (En) pMHC can associate with this complex. TCR that bind to such En pMHC can be triggered in spite of the short half-life of this interaction because Lck is already spatially localized in the signaling complex, thereby amplifying signaling from minute amounts of Ag pMHC. In the absence of Ag pMHC, spurious triggering does not occur because En pMHC bind TCR for too short a time to nucleate signaling complexes with Lck.

An example of the kind of questions that Professor Chakraborty's group addresses is provided by work that they do in collaboration with Professor Mark Davis's laboratory at Stanford University's School of Medicine. T cells recognize the protein component of pathogens. Proteins coded for by the pathogen are spliced into peptide (p) fragments that can bind to protein products of the major histocompatibility (MHC) gene complex. These pathogen-derived pMHC molecules are displayed on the surface of antigen-presenting cells (APC). The T cell receptor (TCR) expressed on T cell membranes can bind these pMHC molecules to initiate signaling processes that can lead to T cell activation. APC surfaces also display a large number of pMHC molecules where the peptide is derived from endogenous proteins ("self"). Recent single-molecule imaging experiments carried out in Mark Davis' laboratory demonstrated that T cells can detect as few as 10 molecules of pathogen-derived pMHC molecules in a "sea" of 30,000 endogenous ones. This remarkable sensitivity is not accompanied by frequent spurious triggering (autoimmune responses). How is this remarkable ability to discriminate between "self" and "non-self" regulated by the T cell? The Chakraborty group has developed and applied sophisticated statistical mechanical approaches, which, in close synergy with experiments in Professor Davis' laboratory, have begun to elucidate the pertinent mechanisms (Figure 2). A major finding is that endogenous pMHC molecules play a key role in the ability of T cells to detect minute amounts of antigen by amplifying signaling via a highly cooperative mechanism. This result has broad implications for a host of fundamental questions in immunology.

Multiscale Analysis of Pharmaceutical Powder Processing (Charles L. Cooney)

One of the challenges associated with modern medicine is the consistent manufacture of drug products to assure safe and efficacious delivery each and every time. With 80 percent of the drug products manufactured as solid dosage forms, this need translates to assurance that each tablet or capsule has the same amount of active drug that is released at the same rate to the patient. From a process engineering perspective, we need to design and control operations at the multiton scale that when subdivided into tablets lead to identical aliquots at subgram scale. This problem is compounded by the trend toward highly active drugs that comprise less the 5 percent of the mass of a tablet, thus making the challenge of assuring homogeneity at the subgram scale even more difficult.

We have addressed this multiscale problem by seeking to understand how the properties of the smallest divisible unit of a pharmaceutical preparation—the particle—influence flow and mixing behavior of powder mixtures. Can one predict large-scale process performance from microscale powder properties? With such knowledge, one should be able to influence tablet design by manipulation of relevant particle properties. In pursuit of this goal, we developed an online, noninvasive method to measure powder-mixing dynamics using light-induced fluorescence (LIF) of one material in the mixture; commonly, the active pharmaceutical ingredient will fluoresce while the nonactive excipients comprising

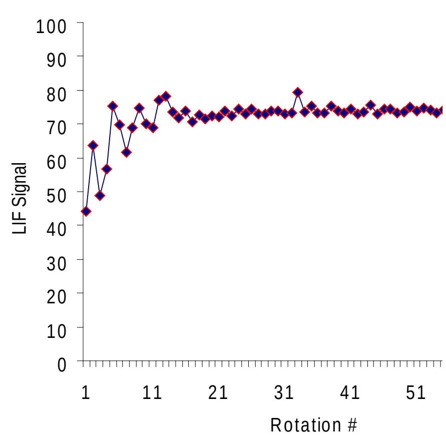

Figure 3. Powder blending kinetics

the bulk of the tablet do not. With LIF, we measure in real time the mixing kinetics for dry powders as if they were fluids; this provides a performance metric for large-scale mixing, as seen in Figure 3.

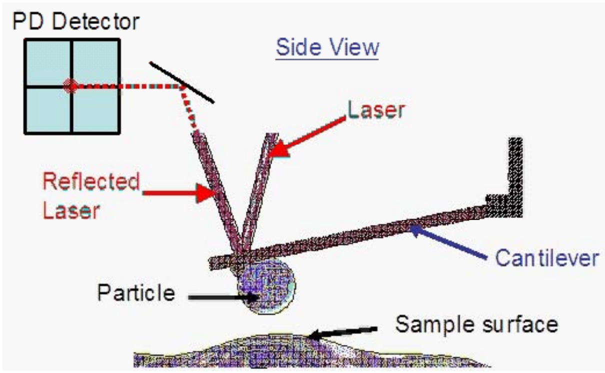

Figure 4. Cohesive force measurement

At the microscale, we identified as critical properties particle size, density, surface roughness (friction), and cohesive interaction. Measurement of size and density was straightforward. The measurement of both interparticle cohesion and friction could be achieved with atomic force microscopy (AFM). We learned that the cohesive force between two particles was obtainable with AFM by attaching one particle to a surface and the second to the cantilever of the AFM (Figure 4).

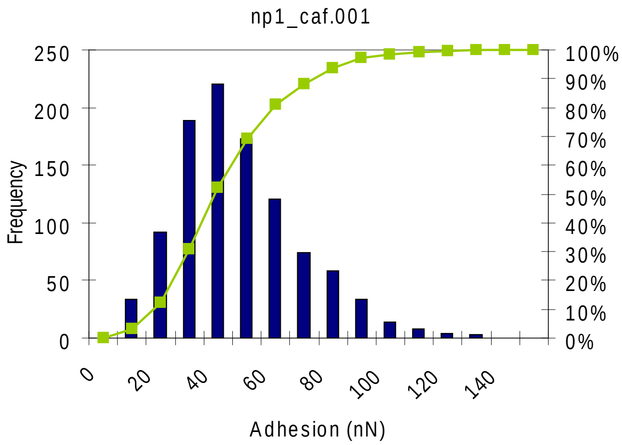

Figure 5. Caffeine particle cohesion

Multiple measurements on sets of particles gave us the frequency distribution for these forces (Figure 5). By using the same setup with AFM to drag one particle across another with variable normal load, we could also obtain the friction interparticle friction coefficient. The third step in this multiscale approach was to predict flow and mixing performance; to do this we employ the discrete element method (DEM) of simulation, which allows us to assign real properties to a set of particles and calculate their dynamic behavior during blending. Although computationally intensive, DEM uses measured properties to predict performance in a manner that can be compared directly with LIF monitoring in a blender. The simulation is easily visualized (Figure 6) and sampled (Figure 7) and leads to estimates of mixing time comparable to experimental observation.

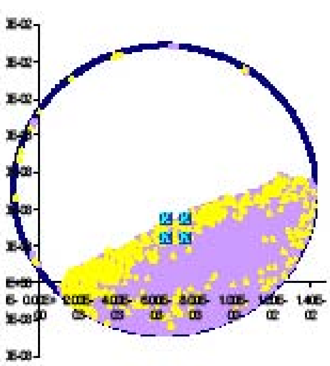

Figure 6. Mixing visualization

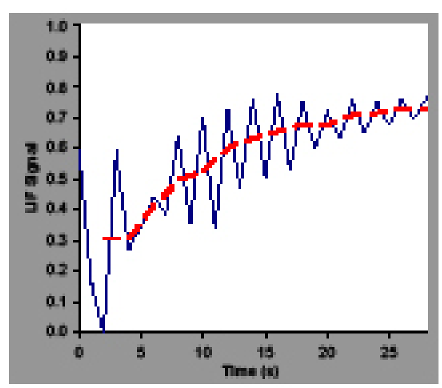

Figure 7. Kinetics simulation

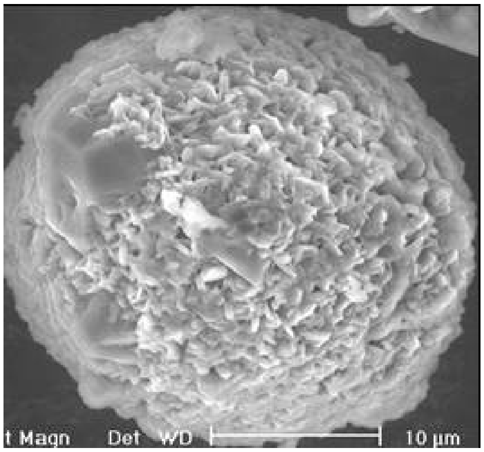

Figure 8. ESEM lactose

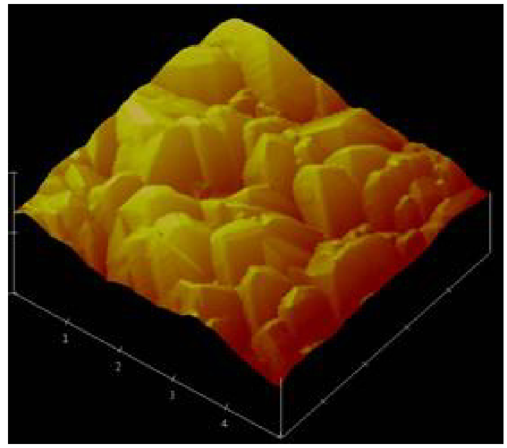

Figure 9. AFM image of lactose

Our current work is to dissect the net cohesion force measured by AFM to understand the component van der Waal's, electrostatic, and capillary forces. The complexity of the problem is seen in electron microscopic (Figure 8) and AFM (Figure 9) images of the particles and their surface structure. With current methods, we have elucidated how particle properties impact the ability to achieve both mixing kinetics and mixture homogeneity. Current work is directed to elucidation of a particle design strategy to facilitate pharmaceutical quality by materials design.

Annual Lectures, Seminars, and Symposia

The Department once again hosted a very successful series of four major annual lectures: the 7th Frontiers in Biotechnology Lecture, delivered by Professor Jay Keasling, director of the Berkeley Center for Synthetic Biology; the 28th Warren K. Lewis Lecture, delivered by Professor Frances Arnold of the California Institute of Technology; the 12th Alan S. Michael Lecture, delivered by Professor David Edwards of Harvard University; and the 20th Hoyt C. Hottel Lecture, delivered by the Honorable Samuel W. Bodman, the US secretary of energy.

Our Departmental Seminar Series featured academic leaders from Advanced Micro Devices, Stanford University, Rutgers University, the University of Illinois at Urbana-Champaign, the University of California at Berkeley, the University of Wisconsin at Madison, Rice University, and the California Institute of Technology.

This year the Department also sponsored two symposia. On Friday, December 9, 2005, the MIT Chemical Engineering Department held a symposium to honor Provost Robert A. Brown for his tremendous contributions through research, education, and service to MIT, to the profession of chemical engineering, and to the fields of fluid mechanics and crystal growth. The symposium featured several reviews and projections about areas in which Professor Brown has worked, given by his colleagues and former students. A symposium was also held in spring 2006 to recognize Institute Professor Daniel I. C. Wang on the occasion of his 70th birthday. He was honored for his research and educational contributions in the profession of chemical engineering and the field of biochemical engineering.

Departmental Awards

The Department Awards Ceremony took place on May 15, 2006, in the Gilliland Auditorium of the Ralph Landau Building. We are pleased to recognize this year's recipients of the Outstanding Faculty Awards: Professor William M. Deen was the graduate students' choice and William H. Green and Kristala J. Prather were selected by the undergraduate students.

The Edward W. Merrill Outstanding Teaching Assistant Award was presented to graduate students Joseph Lowery for his work in 10.10 Introduction to Chemical Engineering and to Sanjoy Sircar for his work in 10.32 Separation Processes.

Chemical Engineering Special Service Awards were conferred to the members of the Graduate Student Council: David Adrian, Nathan Ashcraft, Nathan Aumock, Kevin Brower, Franklin Goldsmith, David McClain, Daniel Perez, Mridule Pore, and Ben Wang. In addition, Nathan Aumock was awarded the Chemical Engineering Rock for outstanding athleticism and Andrea Dooley 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 three recipients of the Award for Outstanding Seminar were Ginger Chao, Kris Wood, and Daniel Pregibon.

Our undergraduates also earned numerous accolades over the course of the year. The Merck Fellowship Award was presented to Chris Tostado and Benjamin Wasserman in recognition of their scholastic excellence. The Robert T. Haslam Cup, which recognizes outstanding professional promise in chemical engineering, went to George Eng. The Department's oldest prize, the Roger de Friez Hunneman Prize, is awarded to the undergraduate who has demonstrated outstanding achievement in both scholarship and research; this year it went to Joshua Michener. The Outstanding Graduate Teaching Assistant Award went to Kristin Mattern for her work in 10.50 Analysis of Transport Phenomena.

The Department is quite pleased to recognize Gwen Wilcox, assistant to professors Jefferson W. Tester and Kristala J. Prather, as the Department's Outstanding Employee of the Year for her dedication and outstanding service to faculty, staff, and students. The School of Engineering Infinite Mile Award went to Department members Gwen Wilcox and Aza Gevorkian from our Administrative Services Office.

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.

Robert C. Armstrong, Department Head and Chevron Professor of Chemical Engineering
Gregory C. Rutledge, Executive Officer and Professor of Chemical Engineering

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