ChE at

Tufts University

The atrium of the Tufts Science and Technology Center, home to Chemical and Biological Engineering.

BY NAKHO SUNG AND DANIEL RYDER

Tufts College was chartered in 1852 as the 163rd institution of higher learning in United States. Two years later, its first class matriculated. Today, Tufts University is a diverse ensemble of undergraduate, graduate, and professional schools that includes the Schools of Arts and Sciences, Engineering, the Cummings School of Veterinary Medicine, the Schools of Dental Science and Medicine, the Sackler School of Graduate Biomedical Sciences, the Friedman School of Nutrition Science and Policy, the Tissue Engineering Resource Center, and the Fletcher School of International Law and Diplomacy. Full-time students total 8,830, of which 4,950 are undergraduates.

The School of Engineering includes the Department of Chemical and Biological Engineering as well as the Departments of Biomedical Engineering, Civil and Environmental Engineering, Electrical Engineering and Computer Science, and Mechanical Engineering.

Chemical Engineering debuted at Tufts in 1898 to become only the fifth such program in this country, and accepted its first students in 1900. The department was officially part of the Chemistry Department until February 1949; its undergraduate program was initially accredited three years later. An M.S. program was added in 1962 and a Ph.D. program in 1965.

The first M.S. degrees were granted in 1964 to Dewey Ryu (now a professor in the department of Chemical Engineering and Materials Science at the University of California, Davis) and Wayne Sanborn (who worked for Matheson Gas Products). The first Ph.D. degrees were awarded in 1971 to Donald Merchant, Joseph DelPico (who worked for Polaroid Corporation), and Edward Denk, Jr. (now a consultant at Evergreen Solar).

This year the department will award some 15 graduate diplomas, including five Ph.D.s Though it will award only 20 B.S.ChE degrees, enrollment in each of the continuing undergraduate classes exceeds 30 students.

A perennial high-tech incubation zone, the greater Boston area has long been one of the nation's hubs for biotechnology R&D. Within this community, numerous professionals are Tufts Chemical Engineering alumni. Many remain actively involved with the department, which offers teaching and research programs in biological engineering and has contributed nationally to development of the relevant undergraduate curricula.

For the past 15 years, the department has been assembling a core group of biological engineering faculty. Graduate research is divided within three main areas—biological engineering, energy and environment, and advanced materials. The current plan is to focus on expanding clean energy and environmental sustainability along with systems engineering research and teaching.

TUFTS SCIENCE AND TECHNOLOGY CENTER

The department is currently housed in the Tufts Science and Technology (SciTech) Center, which was constructed in 1989 with major financial support from the U.S. Department of Energy. At that time, the Department of Chemical Engineering was the only academic department housed at the facility. The Tufts High Energy Physics Laboratory, Biotechnology Engineering Center, Electro-Optic Research Center, and Laboratory for Materials and Interfaces (LMI) were also housed at the site. Both the Biotechnology Center and LMI were associated research facilities of the ChBE Department. Later, through the generous support of Raytheon Corporation, the Pollution Prevention Projects Laboratory was established within the department's facilities. In addition to the Department of Chemical and Biological Engineering, the complex currently houses the recently established Department of Biomedical Engineering and the Gordon Institute for Engineering Management.

CHEMICAL AND BIOLOGICAL ENGINEERING

The department has a long-standing history relating to the development of educational programs in bioengineering. In 1986, the then Chemical Engineering Department initiated a Massachusetts-sponsored continuing education program to train technical staff for biotechnology business. The Biotechnology Engineering Certificate program, which began as a series of hands-on, introductory, technical courses and remains a vital link to local industry, has led to the development of a graduate-degree program. Today, the department offers graduate degrees in both chemical engineering and biotechnology engineering, including course-only M. Eng. degrees attractive to working professionals, as well as traditional thesis-based M.S. and Ph.D. programs.

In 2004 the department hosted a series of NSF-sponsored workshops focused on the development of chemical and biological engineering curricula. Participants from academia and local bio-industries helped to shape our current undergraduate program (see Table 1), which has evolved to include introductory courses on biology, statistical thermodynamics and molecular structure (Physical Chemistry II), and biochemistry. Simultaneously, the chemical engineering science core has incorporated biological systems and processes, while the upper-level course offerings have been supplemented with applied biology-based electives (see Table 2). We are currently redesigning the senior laboratory courses to comprise industry-sponsored research projects in biotechnology, metabolic engineering, energy sustainability, systems engineering, and advanced materials.

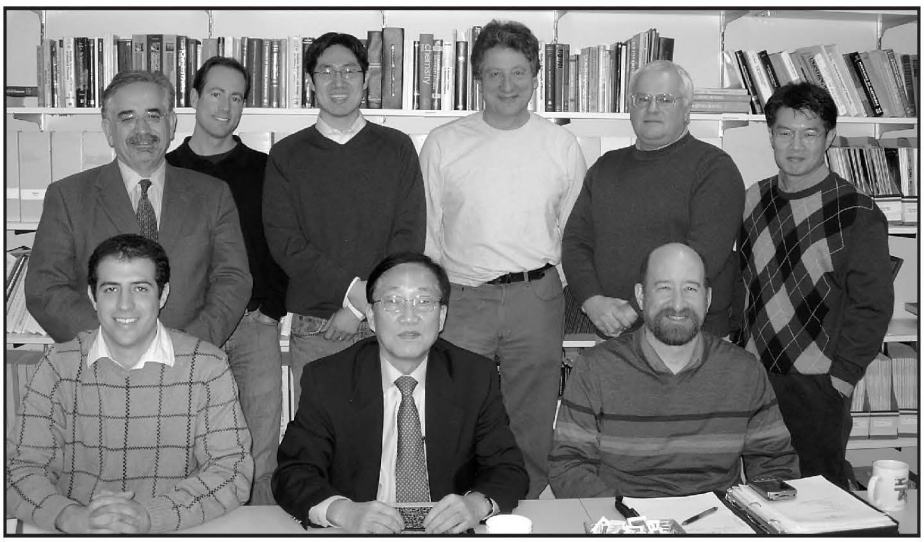
FACULTY

Current Faculty

The current department faculty includes nine tenure-tracked members and two jointly appointed members:

Professor **Linda M. Abriola**, currently dean of Engineering, does research in the mathematical modeling of the transport and fate of organic chemical contaminants in porous media. She developed one of the first mathematical models to describe the interphase mass partitioning and nonaqueous phase migration of organic liquid contaminants in the subsurface. Her recent research involves the use of models and laboratory experiments to examine abiotic and biotic processes influencing the persistence of organics and controlling the effectiveness of aquifer remediation technologies. She is also a member of the Department of Civil and Environmental Engineering, and a member of the National Academy of Engineering.

Faculty member Martin Sussman.



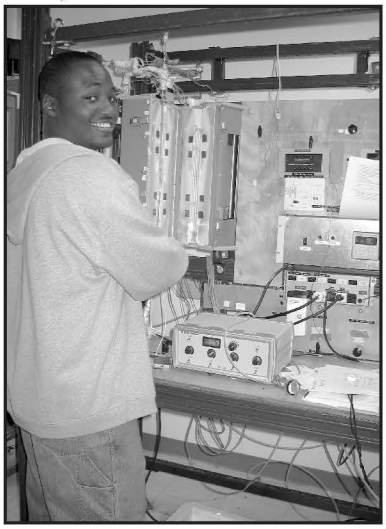
Some of the ChBE faculty. Top, L-R: Christos Georgakis, Blaine Pfeifer, Kyongbum Lee, Jerry Meldon, Daniel Ryder, Hyunmin Yi. Bottom, L-R: Ramin Haghgooie, Nakho Sung, Eric Anderson.

Professor **Maria Flytzani-Stephanopoulos** spearheads clean energy technology and catalysis research in the School of Engineering. Her work focuses on catalytic fuel processing, including hydrogen generation, for fuel cells; and new materials for air pollution abatement and fuel gas desulfurization. Her group's fundamental research on catalyst structure and function has led to the identification of a family of very active oxidation catalysts based on Au, Pt, and Cu on cerium oxide. An exciting new development in the hot gas cleanup area is the group's recent identification of rare earth oxides that remove hydrogen sulfide to sub-ppm levels via reversible adsorption. Flytzani-Stephanopoulos's research group presently comprises one postdoctoral fellow, seven Ph.D. and four M.S. research assistants, and several undergraduates. Her research is supported by the NSF, the DOE, the Army Research Laboratory, and industry. Since 2002, she has served as the editor of *Applied Catalysis B: Environmental.*

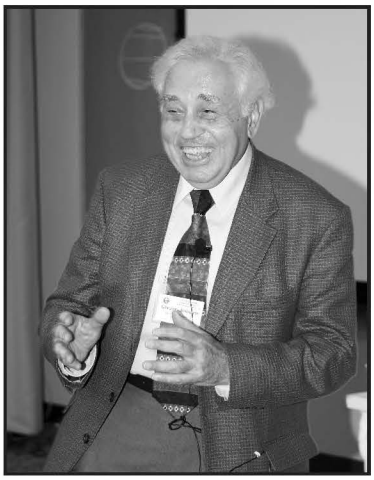
Professor **Christos Georgakis** established the Systems Research Institute for Chemical and Biological Processes in 2005. Modeled on the Chemical Process Modeling and Control Research Center at Lehigh University, the Institute fosters interdisciplinary research in modeling, optimization, and operation of chemical and biological systems and processes in collaboration with leading pharmaceutical and chemical companies. The institute's first initiative—the Industrial Consortium on Batch Manufacturing of Pharmaceuticals and Chemicals (BMPC)—began operation in 2006. The consortium is a cooperative research program that will focus on improving the development, design, and operation of batch pharmaceutical and chemical processes, with the ultimate goal of halfing the time it takes to design new processes. Initial research areas encompass designing batch reactors for multistep synthesis; enantiomeric and polymorphic crystallizations; plant-wide simulations, scale-up, and process sensitivities; and statistical process monitoring and process control that will effectively contribute to the implementation of the FDA's Process Analytical Technology Initiative. The consortium officially launched its research program on Oct. 25, 2006.

Professor **David L. Kaplan**'s group applies biopolymer engineering to elucidate structure-function relationships, including those of fibrous proteins (collagens, silks) and polysaccharides. They apply physiological and genetic engineering approaches to control biopolymer chemistry in order to then explore self-assembly and function from a materials science and engineering perspective. The biopolymer systems are studied for potential biomaterials applications, such as matrices or scaffolds to support cell and tissue growth, for controlled release of pharmaceuticals, and as biosensor platforms. Selective processing, surface chemistry, or genetic engineering redesigns are employed to functionalize biopolymer material surfaces or control morphology and structure, in order to enhance biomaterial interactions with inorganic and biologic interfaces. In combination with human stem cells and complex bioreactor systems, the biopolymer biomaterial systems are employed in the generation of functional human tissues including bone, cartilage, and adipose systems. These systems are studied both in vitro and in vivo for tissue regeneration, as well as to serve as human disease models with which to understand disease progression, and subsequently for pharmaceutical discovery. Transport issues are addressed via vascularization strategies in vitro and in vivo to promote improved functional tissue outcomes. Kaplan's lab collaborates with many colleagues within and outside of Tufts. He also serves as the chair of the Department of Biomedical Engineering.

Professor **Kyongbum Lee**'s research in systems biology, metabolic engineering research in systems biology, and metabolic engineering and tissue engineering is aimed at better understanding the chemical design of living systems through the development and application of analytical platforms, modeling tools, and other enabling technologies. He is especially interested in characterizing and manipulating cellular metabolism for a variety of basic and applied studies. His research is also motivated by the growing need to find and evaluate new therapies for obesity and type 2 diabetes. Current work focuses on the metabolism of liver and white fat cells.



Left, one of several students in the senior projects lab who got hands-on experience when the department's distillation column needed repair. Below, Danny Pierre, a graduate student in Professor Flytzani-Stephanopoulos's catalysis lab.



Above, Gregory Botsaris gives a presentation at the 2005 symposium in his honor.

There is increasing evidence that the functions and structural features of a biochemical network are intertwined. Thus, a useful approach to studying the design of these complex systems has been to characterize their layout, or "wiring." Lee's research aims to develop a modeling framework to integrate the analysis of the structural and functional layout of biochemical networks. For example, he has recently developed and applied a series of algorithms for the rational decomposition of metabolic networks based on experimentally derived reaction activity data.

In the context of metabolic engineering, Lee's group uses mathematical models of metabolic pathways in conjunction with experimental biochemistry techniques to quantitatively study the metabolic basis of adipose tissue development and growth. In addition to fundamental insights into adipocyte metabolic regulation, they seek to obtain: 1) novel drug targets, for example enzymes that catalyze the key controlling steps in adipocyte lipid accumulation; and 2) robust, sensitive, and easily measured metabolite biomarkers for diagnosis of obesity-related diseases and efficacy assessment of therapeutics. To these ends his group has performed in silico and in vitro studies characterizing the metabolic flux profiles of de novo adipocyte formation, identified target pathways for metabolic intervention, and demonstrated the feasibility of achieving a global shift in lipid accumulation through the forced expression of a single protein.

Lee also uses tissue engineering to design, build, and optimize model systems whereby important cellular functions may be studied under well-controlled conditions while maintaining a high degree of physiological relevance. The primary focus here is on engineering the cellular component and its medium (as opposed to the materials or reactor housing). Current projects leverage developments in micro-fluidics and stem cell biology to generate flow-through incubators that afford spatial control over the chemical environment of the cultured cells. This incubator is used for a number of on-going studies involving heterogeneous cell components (*e.g.*, adipocyte-preadipocyte co-culture) and solution gradients of exogenously added chemicals (*e.g.*, drug transformation by hepatocytes).

Professor **Jerry H. Meldon**'s research interests are in mass transfer and separation processes, particularly when reversible chemical reactions control the rate and selectivity of a diffusional separation. His primary focus is on membrane processes, gas scrubbing, and mathematical modeling of mass transfer with chemical reaction. Recent work includes theoretical and experimental investigations of hydrogen transport in palladium membranes and its role in catalytic membrane reactors for the production of pure hydrogen. One Ph.D. student is building and modeling a novel spinning disk system for reaction and separation; another is modeling NOx scrubbing.

Professor **Blaine A. Pfeifer**'s research group seeks to influence genetic, metabolic, cellular, and process events in the synthesis of therapeutic products. For example, they apply molecular and process engineering in conjunction with molecular biology, microbiology, analytical chemistry, and bacterial genetics to develop microbial bio-processes and products that can potentially target cancer, bacterial infections, diabetes, and other diseases.

Pfeifer's group also seeks more efficient and economical ways to generate biological products. One approach is to

Left, Zheng Zhou, a graduate student in Professor Flytzani-Stephanopoulos's catalysis lab. Right, graduate student Lisa Schupmann works with a multi-reactor system in Professor Georgakis's Systems Research Institute.

transplant genetic material responsible for an important therapeutic product into a convenient and process-friendly bacterial microorganism (such as Escherichia coli) for eventual product scale-up and development. Current projects include: 1) cellular and metabolic optimization for production of the antibiotic erythromycin; 2) production of new and established anticancer agents; 3) development of new biological vaccine systems; and 4) modeling and experiments to identify and elucidate cellular bottlenecks in natural product biosynthesis.

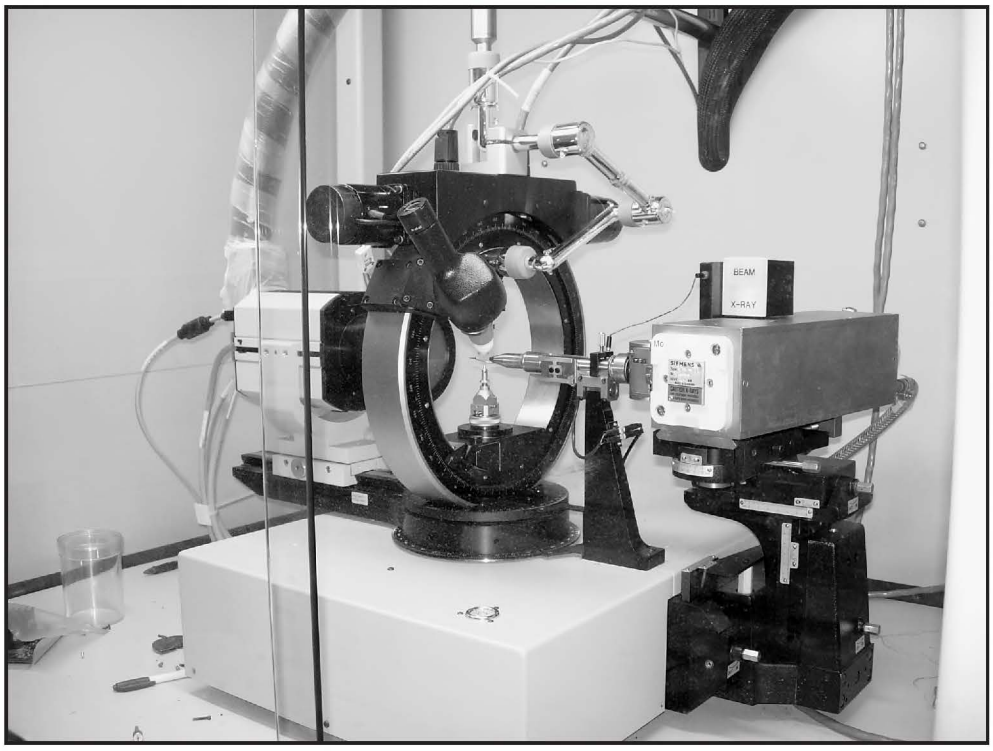
Professor **Daniel F. Ryder**'s primary research lies in the processing and characterization of ceramic and organically modified ceramic materials for electronic and optical applications. Specific areas of study include: Sol-gel processing of PLZT ceramic thin films for applications in ferroelectric memories; chemical processing of hexagonal ferrite thin films for application in high frequency devices; chemical processing of superconducting oxide materials; the development of organically modified ceramic materials for abrasion resistant and antireflective coatings on optical polymeric substrates; and chemical vapor deposition methods for III-V nitride semiconductors.

Professor and Chair **Nakho Sung**'s research in the area of structure-property-processing relationships of polymers and composites includes development of in situ monitoring techniques for characterization of reactions in polymers and composites via fiber-optic fluorescence and UV reflection. Both extrinsic and intrinsic reactive fluorophores are developed for various matrix polymers for advanced composites to follow cure reactions as well as water uptake using distal-end and evanescent fiber optic probes. UV reflection spectroscopy, coupled with bifurcated fiber-optic probes, is also developed to characterize reactions in composites that are fluorescence-insensitive, such as those based on polyimides, epoxies, and unsaturated polyesters; this technique complements fluorescence monitoring.

Another area of research has been to develop a methodology for tailor designing composite interphases. Using a low-temperature plasma of various monomers and inert gases, interfacial structure is modified to enhance such properties as adhesion strength and long-term stability against temperature and moisture-induced degradation. Sorption/diffusion behavior of organic molecules in multiphase polymers is investigated using a model composite consisting of glassy and rubbery domains where morphology is systematically varied. These model composites facilitate elucidation of complex diffusion behavior and development of a predictive diffusion model. Recently, Sung's group has been developing low-cost membranes for fuel cell application and hydrogen purification. Current focus is on anionic membranes suitable for low-temperature direct methanol fuel cells.

Professor **Hyunmin Yi**'s research interests lie in biochemically driven nanometer scale fabrication (nanobiofabrication) of high throughput biosensors, biophotonic devices, and nanocatalysts for biomedical, environmental, and energy applications using smart biopolymers and viral nanotemplates. His primary research areas are nanobiofabrication with genetically modified viral nanotemplates, and biophotonic device fabrication with smart biopolymers.

Yi's group has developed nucleic acid hybridization-based surface assembly strategies of genetically modified tobacco mosaic viruses through their own genomic mRNA. These biologically derived nanotubes—with the precise dimensions of 300 nanometer (nm) length,18 nm outer diameter and 4 nm inner channel—can serve as nanotemplates for covalent coupling of functional nanoparticles. Building upon these facile assembly strategies of these potent nanotemplates, his group is working toward the development of high-throughput biosensors and BioMEMS devices for environmental and biological threat detection. In closely related collaboration with Flytzani-Stephanopoulos, they are also developing na-



A close-up of the Tufts Chemical and Biological Engineering Department's X-ray diffractometer.

noscale gold particle-based catalysts for energy applications using the viruses as nanotemplates with high capacity and precise nanoscale spacing.

In his second research area, Yi seeks to develop biocompatible high-throughput biosensing platforms and implantable biophotonic devices for biomedical and environmental applications. They exploit the stimuli-responsive properties of smart biopolymers to fabricate nanoscale patterns and waveguides with high spatial, temporal, and orientational control. Example biopolymers include structural proteins such as gelatin and silk as well as polysaccharides such as agarose and chitosan. Recently his research group has shown that the thermo-responsive morphology transition of common biopolymers such as gelatin and agarose can lead to efficient means for consistent manufacturing of nanometer-scale surface diffraction gratings under mild processing conditions. They are currently working on building all-biopolymeric implantable waveguides, photonic bandgap crystal fiber-based biosensors and nanoimprinted biopolymeric gratings.

Research Professor **Aurélie Edwards**'s research falls broadly in the domain of biological transport phenomena, developing theoretical models of transport in the renal medullary microcirculation, both at the macroscale and the cellular scale. The microcirculation in the renal medulla plays an essential role in the regulation of fluid and electrolyte excretion and in the long-term maintenance of arterial blood pressure. Understanding how medullary blood flow is regulated and how it influences in turn arterial blood pressure is the main objective.

Specifically, a detailed mathematical model of transport in the tubular and microcirculatory systems of the renal medulla is in development in order to examine how interactions between oxygen, nitric oxide (a potent vasodilator), and superoxide affect tubular sodium reabsorption, medullary blood flow, and blood pressure.

Mathematical simulations of ion concentration changes within the bulk cytoplasm and microdomains are under development to elucidate contractility of resistance vessels, such as medullary descending vasa recta, regulated by variation of intracellular Ca2+ concentration ([Ca2+]cyt) in both endothelium and smooth muscle. This model accounts for the characteristics of the channels and transporters that exchange ions between the plasma membrane, SR stores, and cytosol. Edwards's group is investigating which factors are most likely to serve as principal determinants of [Ca2+]cyt and delineate the mechanisms through which the bulk cytosol, microdomains, and SR communicate. Their goal is to ultimately relate local medullary NO concentrations to [Ca2+]cyt changes and to blood vessel diameter variations.

Emeritus Faculty

The early transition years of any department present a series of challenges that require the selfless dedication, vision, and determination of its faculty. The accomplishments of these early efforts are often taken for granted with the passage of time, but whatever level of success that this department presently enjoys is due in large part to a small group of faculty that has served Tufts throughout their professional career.

Martin V. Sussman joined the department in 1961 and served on the faculty for 37 years before retiring due to illness in 1998. His popular "Technology as Culture" course, which offered liberal art students insights into the world of technology, made him a household name across the Tufts community. He earned his doctorate in chemical engineering from Columbia University and was a Fellow of both the American Institute of Chemical Engineers and the American Chemical Society. He was the author of two books on thermodynamics as well as numerous technical articles. Martin's

research interest spanned the fields of materials science and biotechnology. He was author to some 20 patents that included the "Incremental Draw Process" for the processing of synthetic fibers and the "Fibra-Cel" tissue culture matrix.

The department was saddened by his passing in 2005, but his legacy and connection with Tufts survive through the generous funding of the Jeanne and Martin Sussman Endowed Fellowship.

Gregory D. Botsaris joined the department in 1965 immediately after earning his Ph.D. in chemical engineering at M.I.T. He officially retired in 2004 after 39 years of service, but remains on campus to continue his research in crystallization processes. He is the author of numerous technical articles in that field and other separation processes. His contributions to crystallization technology were recognized by his peers through the establishment of the Gregory Botsaris Lecture series.

Ken Van Wormer is the newest emeritus faculty member. Van Wormer joined the department as an instructor in 1954 while completing his doctoral studies at M.I.T. His continuous service to the department for an impressive 53 years—including 10 years as chair—is a testament to his dedication to the profession.

TABLE 1
Chemical & Biological Engineering Curriculum at Tufts University

First Year	
Fall Term	Spring Term
EN 1 (Intro. to Computers in Engineering)	EN 2 (Intro. to Engineering Communication)
Math 11 (Calculus 1)	Math 12 (Calculus 2)
Chem 1 (Chem. Fundamentals w/ Lab)	Chem 2 (Chem. Principles w/ Lab)
English 1 (Expository Writing)	Humanities/Social Sciences Elective
EN Elective1 (Intro. to Engineering)	Physics 11 (General Physics w/ Lab)
Second Year	
Fall Term	Spring Term
ChBE 10 (Thermo & Process Calc I)	ChBE 11 (Thermo & Process Calc II)
Math 13 (Calculus 3)	Math 38 (Differential Equations)
ES 11 (Intro. to Biology)	ChBE 39 (Appl. Math and Numerical Methods)
ES 10 (Intro. to Materials Science)	Chem 32 (Physical Chemistry II)
Chem 33 (Physical Chemistry Lab I)	Humanities/Social Sciences Elective
Third Year	
Fall Term	Spring Term
ChBE 21 (Fluid Dynamics & Heat Transfer)	ChBE 22 (Mass Transfer)
Chem 51 (Organic Chem I)	ChBE 102 (Reactor Design)
Chem 53 (Organic Chem Lab I)	Bio 152 (Biochemistry & Cellular Metabolism)
ES 3 (Intro to Electrical Engineering)	Advanced Chemistry Elective
Humanities/Social Sciences Elective	ChBE Concentration Elective
Free Elective	—
Fourth Year	
Fall Term	Spring Term
ChBE 45 (Separation Processes)	ChBE 60 (Chemical Process Design)
ChBE 51 (ChBE Unit Ops Lab)	ChBE 52 (ChBE Projects Lab)
ChBE 109 (Process Dynamics & Control)	ChBE Concentration Elective
ChBE Concentration Elective	Advanced Chemistry Elective
Humanities/Social Sciences Elective	Humanities/Social Sciences Elective

ACKNOWLEDGMENTS

Sources for this feature article came primarily from the ChBE Department archives, the Tufts Office of Institutional Research, and the Tufts Office of Alumni Relations. Professor Kenneth Van Wormer's "Speech on the Occasion of the 85th Anniversary of Chemical Engineering at Tufts, April 1986" was an especially valuable source for the department's early history. His speech contained references to **Russell F. Miller**'s Light on the Hill: A History of Tufts College (Boston: Beacon Press, 1966). Authors acknowledge the help from **Joanna Adele Huckins** in drafting this article. ❐

TABLE 2
Biological Engineering Electives

ChBE 160	Biochemical Engineering
ChBE 161	Protein Purification
ChBE 162	Introduction to Biotechnology
ChBE 163	Recombinant DNA Techniques Laboratory
ChBE 164	Biomaterials & Tissue Engineering
ChBE 166	Principles of Cell and Microbial Cultures
ChBE 167	Metabolic and Cellular Engineering
ChBE 168	Biotechnology Processing Projects Laboratory