Research in the Department of Chemical and Biomolecular Engineering encompasses a wide range of fundamental specialties that advance technologies in the chemical, energy, pharmaceutical, semiconductor, biotechnology, and human health industries. The strong, science-based approaches taken by the department’s faculty provide these industries with a solid foundation on which to advance their technologies.

Our faculty members push the boundaries of engineering science. In addition to productive research programs in traditional areas in fluid mechanics, reactor engineering, catalysis, corrosion, control, and optimization, the Chemical and Biomolecular Engineering faculty have established innovative efforts in nanotechnology, biotechnology, cell and tissue engineering, drug delivery, systems biology, microchemical systems, and complex fluids. These activities sustain a leadership position in advancing technologies that affect our standard of living and improve our quality of life.

The department has an outstanding tradition of fundamental research that is well supported by a strong base of corporate, federal, and private funding. Single investigator grants remain an important component of research support, but our faculty members also play central roles in a wide range of multidisciplinary research programs across the campus. These activities are centered at the Beckman Institute for Advanced Science and Technology, the Frederick Seitz Materials Research Laboratory, the Institute for Genomic Biology, the National Center for Supercomputing Applications (NCSA), and the National Science Foundation Nanoscale Science and Engineering Center. Faculty participation in these activities is a testament to the centrality of chemical engineering fundamentals in a broad range of critical technologies. Participation in these multidisciplinary efforts also enable faculty members to leverage funding provided by the Defense Advanced Research Projects Agency (DARPA), Department of Defense (DOD), Department of Energy (DOE), the National Science Foundation (NSF), and the National Institutes of Health (NIH).

Research in Chemical and Biomolecular Engineering results from close, productive collaborations among faculty members, postdoctoral fellows, graduate students, and undergraduate students. Admission to graduate study is an extremely selective process. As part of their doctoral training, students carry out cutting-edge research in university laboratories and some participate in internships at corporate research laboratories. Joint research programs with the National University of Singapore and several research institutes in Singapore give an international accent to departmental efforts. The interdisciplinary and collaborative environment of the department provides an intellectually rich and exciting environment in which to learn and work.

The Department of Chemical and Biomolecular Engineering is in the School of Chemical Sciences in the College of Liberal Arts and Sciences.

Faculty and Their Interests

Richard C. Alkire
Electrochemical engineering

Richard D. Braatz
Multiscale systems and control

Thomas J. Hanratty, Emeritus
Fluid dynamics

Jonathan J. L. Higdon
Fluid mechanics, computational algorithms

Paul J. A. Kenis
Microfuel cells, microreactors, engineered platforms for biology, microfluidic crystallization platforms

Hyun Joon Kong
Biomaterials, tissue engineering, sensors

Deborah E. Leckband
Bioengineering and biophysics
Biochemical and Biomedical Engineering

Modeling and Design of Controlled-Release Drug Delivery Systems
R. D. Braatz,* D. W. Pack,* A. N. Ford, M. Kishida
National Institutes of Health; U.S. Department of Energy

Controlled-release drug delivery systems can provide therapeutic benefits while reducing side effects and reducing the frequency of administrations. However, the design of controlled-release systems can be challenging due to incomplete understanding of the mechanisms that regulate release. We are modeling the effects of polymer particle size distribution, molecular weight distribution, pore size distribution, and the accumulation of acidic degradation byproducts on macromolecule release in biodegradable polymer drug delivery systems. A model-based optimization algorithm will be developed to design drug delivery systems to produce desired release profiles.

Modeling and Simulation of Cancer Progression
R. D. Braatz,* S. Farooq,* K. S. Cheong
Singapore National Science and Technology Board

More than 100 distinct types of cancers can occur in various organs of the human body. Research over the last quarter of a century has revealed cancer to be a disease of the genome—mutations produce oncogenes and tumor suppressor genes, transforming normal cells into cancerous lesions that ultimately invade surrounding tissues and metastasize. We are developing population balance models to adequately account for the age and replicative potential of cells in order to more accurately model the six-step progression of cancer. Sensitivity and uncertainty analyses are being applied to the large numbers of coupled partial differential equations to assess which kinetic parameters have the strongest effect on the cell populations and to quantify the effects of simultaneous uncertainties on cancer progression.

Engineered Platforms to Manipulate Intracellular Redox State
P. J. A. Kenis,* J. A. Henderson, A. Sokolowski, V. L. Kolossov, H. R. Gaskins
National Institutes of Health, PHS 1 R21 EB004513

Intracellular redox status exerts influence on the normal cellular processes of DNA synthesis, selective gene expression, cell cycle progression, proliferation, differentiation, and apoptosis. However, molecular mechanisms mediating redox sensitivity are still poorly defined. We have created electrochemical platforms that enable precise manipulation of intracellular redox state. We have also obtained novel genetic constructs that will enable real-time and extended assessment of alterations in intracellular redox without cellular disruption through FRET microscopy. These cell study platforms and biosensors for visualization are now being used to study the relationship between intracellular redox and density-dependent contact inhibition of cell growth, i.e. the role of intracellular redox in uncontrolled cell growth (tumorigenesis).

Innovative Methods for Membrane Protein Crystallization
National Institutes of Health, PHS 1 R21 GM75930

Membrane proteins play key roles in many biological processes and are thus prime targets for intervention in disease-related processes with pharmaceuticals. Unfortunately, the success of crystallization of membrane proteins, necessary for structure determination via x-ray...
diffraction, lags behind the crystallization of their soluble counterparts. We have created novel microfluidic crystallization platforms and procedures to substantially speed up the process of determining optimal crystallization conditions for membrane as well as soluble proteins. We have shown that precise control of the rate of solvent evaporation (i.e. kinetic control) enables the identification of crystallization conditions for a variety of proteins (e.g., lysozyme, thaumatin, Bacterio-rhodopsin) as well as for the dramatic improvement of crystal quality. Also, we obtained a microfluidic network capable of distributing 48 precipitants in three different protein/precipitant ratios over 144 wells that are each 30 nanoliters in volume, and microfluidic chips to create lipidic mesophases in sub-30-nanoliter quantities for the crystallization of membrane proteins in a more membrane-like environment. Both are presently being tested in crystallization experiments. In addition, a better understanding of the phase behavior of solutions used to crystallize proteins is important to allow crystallographers to set up experiments that will have better chances to result in favorable outcomes. Thus, research is directed to develop experimental protocols to help increase the understanding of the phase behavior of solutions used for protein crystallization.

The Role of Integrins and Cadherins in Tumorigenesis
P. J. A. Kenis, D. E. Leckband,* J. Silvestre
National Institutes of Health, PHS 1 F31CA126500

Cell-surface and cell-cell receptors have been studied extensively to investigate the switch from benign noninvasive to metastatic tumors. However, one of the major limitations has been the lack of studies that explore the effect of the cellular microenvironment on this transition. In this study we use microfluidic platforms to create gradients of surface-bound extracellular matrix (ECM) and N-/E-cadherin proteins, thereby manipulating the microenvironment that the cell experiences. Cell migration studies on these gradients aid in the elucidation of the synergies shared between integrins and cadherins, and thus increase our understanding of the effects of tumor microenvironment on cellular behavior.

Cadherin Lysosilation in Oral Cancer
M. Kukurizinska, D. Leckband, M. Langer
National Institutes of Health

Cadherins are essential for development and tissue organization. Their malfunction is also linked to a variety of different cancers. In some oral cancers, cadherins express an unusually high level of carbohydrate modification. However, whether this is the basis of the disease or a consequence has not been established. The goal of this project is to determine the impact of abnormal cadherin glycosylation on cadherin function, and to determine whether these changes alter the cadherin function and thereby contribute to carcinogenesis.

Physical Mechanisms Governing Receptor-Mediated Intermembrane Adhesion
D. Leckband,* A. Prakasham, S. Kim, J. Wieland
National Institutes of Health, RO1 GM51338

In these studies, the research team is determining the molecular basis of protein-mediated biological adhesion. The control of receptor-mediated cell adhesion is important in wound healing, cancer metastasis, and tissue engineering. This work uses a combination of molecular force probe measurements, theoretical modeling, and molecular biology techniques to determine the structural basis of protein-mediated adhesion. This information is used to design biological adhesion molecules and cell attachment substrates.

Smart Materials for Biomedical Applications
D. Leckband,* X. Zhu, C. Mann, T. W. Jensen
U.S. Department of Energy, DEFG02-91ER45439

This work focuses on the design of biologically active materials for targeted drug delivery and cell culture. This program has two main thrusts. The first is to identify the design parameters that control the interactions of pH-responsive polymer coatings with biological macromolecules. This work is particularly relevant to the design of oral drug delivery devices that selectively target cell surface molecules in the gastrointestinal lining at a particular pH in the gut. The research objective is to develop novel microfabrication methods for generating biologically active materials with variable mechanical compliance. These materials will enable the identification of the combination of mechanical and adhesive properties needed to promote the growth and regeneration of damaged neurons in engineered environments.

Cadherins in the Inflammatory Response
A. Malik, D. Leckband,* P. Selvin, R. Minshall
University of Illinois, Intercampus Research Initiative in Biotechnology

Cadherins maintain the mechanical integrity of the junctions between endothelial cells that line the vascular system. During inflammation, compounds released into the bloodstream cause these tight junctions to loosen and become leaky. This allows white blood cells to migrate out of the bloodstream into the surrounding tissues at the site of inflammation. This interdisciplinary program is aimed

* Denotes principal investigator.
at identifying the cellular mechanisms that cause the disruption of these junctions.

Design and Synthesis of Polymeric Materials for DNA Delivery
D. W. Pack,* D. Drake, N. Gabrielson, T.-T. Tsai
American Heart Association; National Science Foundation, BES-0134163

The goal of this project is to design novel polymers capable of safe and efficient delivery of genetic material to mammalian cells. A first step of this research is to elucidate the structure-function relationships of currently available, off-the-shelf gene-delivery polymers. Thus, researchers are developing quantitative assays that will allow the team to probe the various intracellular barriers to transport of DNA from outside the cell into the nucleus. The resulting structure-function database will provide a basis for intelligent design of new materials with improved safety and efficacy.

Design of Materials for Delivery of Small-Interfering RNA
D. W. Pack,* L. Wong
American Cancer Society

RNA interference is an emerging technology in which small, interfering RNA (siRNA) sequences mediate highly specific shutdown of gene expression. Because many cancers are caused by undesirable expression of a specific gene (an oncogene) or abnormally high expression of a normal gene, RNAi holds the potential to become a new class of anticancer therapy. Safe and efficient delivery of siRNA molecules is the highest hurdle holding back the development of RNAi-based therapies. The goal of this project is to learn how to design polymers to efficiently carry siRNA into tumor cells. The research team investigates how specific properties of polymers control cytoplasmic localization and release of siRNA. The physicochemical properties of polymers and their complexes with siRNA are evaluated, and gene knockdown is investigated in cells growing in culture and in animal models.

Engineering of Viruses for Enhanced Gene Therapy
D. W. Pack,* R. Keswani, J. Ramsey, H. Vu
Roy J. Carver Charitable Trust

Viruses have evolved to become extremely efficient agents of gene delivery. Unfortunately, they are not ideal for many human gene therapy applications that require, for example, targeting of the gene delivery vehicle to specific organs and cell types. Researchers are reengineering viruses using a combinatorial approach termed "directed evolution." With this technique, the research team generates a diverse library of randomly mutated viruses and subsequently gleans from that library those mutants that are improved in a defined property, such as infection of a new cell type or improved thermodynamic stability.

Nanoparticles for Brain Drug Delivery
D. W. Pack,* S. Anthony
Parkinson's Disease Foundation

The brain is isolated from the systemic circulation by the blood-brain barrier (BBB), formed by the very tight junctions between brain capillary endothelial cells. As a result, most water-soluble drugs, especially macromolecules, cannot be effectively delivered to the brain from the circulation. Safe and effective delivery systems are desperately needed for brain drug delivery, in particular for novel treatments of neurological diseases (e.g., Parkinson’s and Alzheimer’s diseases) and brain cancer. The overall goal of this project is to investigate biodegradable polymer nanoparticles as vehicles for drug delivery to the brain. Nanoparticles are covalently derivatized with targeting ligands that can be transported across the BBB. The team uses both in vitro models of the BBB and in vivo models to investigate the ability of nanoparticles to provide prolonged delivery of drugs to the brain.

Precision-Release Drug Delivery
D. W. Pack,* N. Varde, K. Stovall, K. Smith
National Institutes of Health

The research team is encapsulating therapeutic compounds in polymer matrices such that the drug can be released at a controlled rate over a prolonged period of time in the body. The approach is unique in that researchers have precise control over particle size, size distribution, and architecture. These characteristics lead to unprecedented control of drug delivery kinetics. Furthermore, the team is pursuing advanced applications, such as passive targeting based on particle size, that have not previously been possible due to the limitations of current fabrication methods.

Bacterial Chemotaxis
C. V. Rao, K. Wu
In collaboration with George Ordal (Biochemistry)

Chemotaxis is the process by which cells sense changes in their chemical environment and move toward more favorable conditions. In this research, we are investigating chemotaxis in the Gram-positive bacterium B. subtilis. The objective is to understand the molecular mechanisms regulating chemotaxis in this organism and also understand
Whenever we have an infection, our body needs to recruit immune cells to fight off invading microbes. Chemotaxis, the process by which cells move in response to chemical gradients, plays a prominent role in this defense mechanism. A number of chemical signals, called chemoattractants, are produced at or proximal to the site of infection. Immune cells use these chemical signals to target sites of infection and inflammation. Aberrant signaling can delay the immune response, lead to excessive inflammation, or delay wound healing. The objective of this research is to understand how white blood cells use these signals to target microbes during the initial phases of infection. The results of this research will aid in development of anti-inflammatory drugs and vaccine adjuvants.

Reprogramming Transcription and Translation
C. V. Rao,* L. Chubiz, T. Desai
National Science Foundation CAREER

The goal of this research is to develop genetic tools for reprogramming cellular function. To achieve these goals, we are developing new approaches for engineering transcription factors and ribosomes with novel DNA and RNA binding specificity. Such tools will greatly facilitate controlled gene expression and the design of synthetic gene circuits in applications ranging from gene therapy to metabolic engineering. These tools will also be useful for dissecting the native gene circuits controlling cellular physiology.

Salmonella Pathogenesis
C. V. Rao,* S. Saini
University of Illinois

* Denotes principal investigator.
estradiol derived synthetic ligand and a human estrogen receptor ligand binding domain mutant. Such a system is an invaluable tool for gene therapy, temporal control of the onset of phenotypes in transgenic animals, regulated expression of genes in plants, and biological study of development and other physiological processes.

Biosynthesis of Thermally Stable Energetic Compounds
H. Zhao,* Y. Choi, W. Zha, Z. Shao, S. Rubin
Department of Defense, Office of Naval Research

The researchers will use rational design and directed evolution approaches to engineer several biosynthetic pathways for the production of triacetic acid lactone (TAL) and phloroglucinol from D-glucose and also investigate the reaction mechanism and structural basis of substrate channeling. TAL and phloroglucinol will be exploited with chemical conversions into novel energetic compounds such as 1,3,5-triamino-2,4,6-trinitrobenzene (TATB), and benzenehexamine. The target biosynthetic pathways include 6-methylsalicylate synthase, 2,4-diacetylphloroglucinol synthase, Type II fatty acid synthase, and Type I fatty acid synthase.

Development of a Novel and Economically Viable Nicotinamide Cofactor Regeneration System
H. Zhao,* R. Woodyer, T. Johannes, R. Sullivan
Biotechnology Research and Development Consortium

In collaboration with research groups of Wilfred van der Donk (Chem.) and William Metcalf (Microbiol.)

Enzyme-catalyzed reactions that require nicotinamide cofactors (NADH and NADPH) have great potential in industrial biocatalysis. The high cost of the cofactors requires in situ regeneration. To this end, the researchers are developing a novel enzymatic system to regenerate the reduced nicotinamide cofactors NADH and NADPH using rational design and directed evolution approaches. The target enzyme is phosphite dehydrogenase, PtxD, which catalyzes the oxidation of phosphite to phosphate.

Computing
Supercomputing Studies of Wall Turbulence
T. J. Hanratty,* Y. Mito
Grant, University of Illinois College of Liberal Arts and Sciences

We are studying the structure of turbulence and are exploring new methods of interpreting turbulent transport of molecular species or particles that describe the field as resulting from a distribution of sources and sinks. These studies are carried out with a supercomputer simulation of turbulent flow in a channel and are made possible by the development of particle tracking routines. Of particular interest is the influence of particles on fluid turbulence.

Fluid Flow, Heat, and Mass Transfer Fundamentals

Effect of Drag-Reducing Polymers on Turbulence
T. J. Hanratty*
Defense Advanced Research Projects Agency, Friction Drag Reduction Program, DARPA Order No. MDA-970-01-C-0029

The influence of drag-reducing polymers on flow over flat and structured surfaces was studied. Of particular interest are the following: influence of aggregation on the effectiveness of drag-reducers, and influence of polymer additives on the structure of fluid turbulence. Attention is being given to the effects of the methods of preparation and delivery of the drag-reducing solution.

Gas-Liquid Flows
T. J. Hanratty,* Y. Mito
Grant, University of Illinois College of Liberal Arts and Sciences

The goal of this work was to relate the distribution of the phases to small-scale interaction. Stochastic methods are being explored to describe droplet dispersion and deposition in annular flows.

Mechanics of Suspensions
J. J. L. Higdon,* K. Higa, M. Bybee, A. Kumar
Mobil Corporation; U.S. Department of Energy

Concentrated suspensions of microscopic particles are encountered throughout the chemical process industry. The goal of this project is to characterize the rheology and sedimentation behavior of these systems, with special attention given to suspensions with nonhydrodynamic interparticle forces and particles of nonspherical shape, such as fibers and platelets. Researchers are developing novel computational algorithms for large-scale, many-body simulations to investigate these systems. The methods follow the basic approach of the well-known Stokesian dynamics algorithm, but yield an operational count $O(N)$ as opposed to the $O(N^3)$ effort of the traditional approach.
Effect of Free Polymer on Protein Interaction Potentials
C. F. Zukoski,* A. Bonner, A. Mirarefi
National Aeronautics and Space Administration, NAG 8-976

Protein crystals are often produced through the addition of soluble polymers to protein suspensions. In this study, the effects of polymer molecular weight and concentration on the strength of protein interactions are investigated. An unexpected minimum in protein solution second virial coefficient is observed. This phenomenon is intimately related to polymer depletion forces and polymer density fluctuations resulting from the proximity of a polymer solution phase boundary.

Materials

Additive Mediated Nucleation and Growth during Electrodeposition: High-throughput Experiments and Multiscale Simulation
R. C. Alkire
National Science Foundation, CTS 04-38356

The objective is to improve understanding of how nucleation and early stages of deposit growth during electrodeposition are influenced by trace quantities of solution additives. The effort integrates experimental studies (carried out with a novel high-throughput method for characterizing nucleation and growth) with multiscale simulations (carried out with new methods that span the stochastic/continuum region). The approach provides new mechanistic insight into complex surface reactions that control shape evolution, and new simulation tools to optimize additives to achieve specific shapes.

Multiscale Simulations of Electrochemical Systems
R. C. Alkire,* J. Alameda, L. Petzold
National Science Foundation; National Resource Allocation Committee, MCA00N016

The physical applications of interest include electrodeposition of copper and degradation of industrially significant metals by corrosion. Numerical simulations of these applications involve phenomena that span over 10 orders of magnitude of scale in time and distance. The computational resources support deterministic (continuum) as well as stochastic (noncontinuum) method separately and, by linking them, enable multiscale investigations of deposition and dissolution processes.

Improved Metal Catalysts with Properties Controlled by Semiconductor Band Engineering
E. G. Seebauer,* G. Chua,
M. Saey (Natl. Univ. of Singapore)
National University of Singapore–University of Illinois Joint PhD Program

Catalysts with metals on semiconducting oxides have proven to be quite useful for applications in fuel cell cathodes and hydrogen production. This project seeks to employ principles routinely used in the design of nanoscale integrated circuits to circumvent these problems. Such devices often use “heterojunctions,” which are structures in which two different kinds of semiconductors are sandwiched together. Such heterojunctions form the basis of laser pointers, but we believe the same principles can be employed with oxides of metals such as titanium, zinc, and iron to make “catalyst heterostructure” devices. In particular, this work seeks to employ principles of semiconductor band engineering to deliberately control the electronic structure of metals in compound catalysts. An entirely new class of catalysts is being created, in which nanoscopically thick layers of metal are deposited atop semiconductor substrates. The substrate type and doping level will be chosen to tune the surface properties of the metal by the “Schwab effect.” Quantum calculations by density functional theory will be used to help predict the type of semiconductor and doping to use for the substrate, as well as the thickness of the metal required. The requisite structures will then be created by deposition methods drawn from microelectronics processing, and the properties of the semiconductor-metal catalysts will be characterized by optical and electron-based methods.

Improved Photocatalysts with Properties Controlled by Semiconductor Band Engineering
E. G. Seebauer,* M. Kratzer
National Science Foundation, DMR 07-04354

The microelectronics industry has developed principles for the design of metal/semiconductor structures to obtain novel and controllable electrical behavior in integrated circuits. Many of these principles should be adaptable to obtain novel and controllable chemical behavior in catalysts. This work seeks to demonstrate how to employ the notion of electronic band engineering in semiconductors to create an entirely new class of catalysts with controllable properties. Since metal oxide catalysts are semiconductors that can support electrical charge distributed in space, it is possible for surface electronic properties to couple to bulk electronic properties. We believe the electronic band structure of the underlying support can be tailored to beneficially affect the electronic

* Denotes principal investigator.
properties (average charge state, reducibility, and so forth) of the free surface. Successful demonstration of such structures would have broad applications in environmental photocatalysis by TiO$_2$.

**Measurement of Illumination Induced Diffusion in Oxide Semiconductors**

E. G. Seebauer,* R. Vaidyanathan  
*Applied Materials*

The present work seeks to develop entirely new forms of defect manipulation in oxide semiconductors, such as titanium dioxide, based on optical stimulation of defect formation and migration. Diffusion measurements have shown that defect mobilities and concentrations can be nonthermally modulated in semiconductors by super-band gap illumination. Specially synthesized structures are used to measure motion of vacancies and interstitial atoms. Quantification is accomplished through detailed continuum modeling backed by characterization of near-surface electric fields through optical photoreflectance.

**New Methods for Defect Manipulation in Semiconducting Oxides**

E. G. Seebauer,* A. Hollister  
*National Science Foundation, DMR 07-04354*

Through experiments and modeling, we seek to develop entirely new forms of defect manipulation in oxide semiconductors using surfaces. Solid-state diffusion measurements have quantified how surfaces react with bulk point defects such as interstitial atoms and vacancies. The chemistry is comparable in richness to the reactions of surfaces with gases. Up to now, little attention has been paid to this alternative form of surface chemistry, even though it can play a primary role in regulating bulk defect concentrations. In semiconductors, bulk-surface coupling occurs through electrostatic and surface bond insertion/generation mechanisms. The science base to be developed here should offer entirely new possibilities for controlling bulk defects in a wide variety of applications. Such defect manipulation might also be helpful for energy production by semiconductors using solar power (e.g., water splitting), where electron-hole recombination rates in the fabricated devices are affected by the concentrations of bulk defects left over from device fabrication.

**Surface Diffusion and Ordering Processes Exploited for Directed Self-Assembly Using Amorphous Semiconductors**

E. G. Seebauer,* Y. Kondratenko  
*Intel*

There has long been suspicion that optical illumination may nonthermally influence the diffusion of dopants in semiconductors. We are making the first measurements of the dependence of such effects. Experiments employ specialized structures composed of isotopically labeled Si tracer atoms in an epitaxial Si matrix, or of dopants such as boron or arsenic implanted to shallow depths into silicon. Applications of the results are quite direct in technologies such as millisecond annealing of silicon wafers in the formation of ultrashallow transistor junctions.

**Multifunctional Nanocomposites Based on Single Walled Carbon Nanotubes**

M. S. Strano,* R. Graff, J. Swanson  
*United States Air Force*

Carbon nanotubes are the strongest molecular fibers realized to date. Single nanotube tensile strengths exceed 1 TPa. Our interest is in the synthesis of ultra-strong composites with multiple functionalities, such as embedded electronics, electromagnetic absorption for shielding, and electromechanical modulation. To accomplish this, nanotubes need to be dispersed into a matrix at the single molecule level. We are developing new fabrication techniques that allow unprecedented control of nanoscale interfaces for the next generation of “smart” materials.

**Using 1-D Electron Transfer Chemistry to Control Field Effect Transistor Performance for Flexible-Electronic Applications**

M. S. Strano, M. Usrey, C. Y. Lee, M. Alexander, J. Rogers*  
*Defense Advanced Research Projects Agency*

Single walled carbon nanotubes have electron mobility far in excess of known materials (700,000 cm$^2$/Vs) and hence are ideal for nanoelectronic applications. Flexible circuits and displays are desirable as the basis for new technologies including electronic paper, transportable sensors, robust computer processors and wearable flat panel display projections. Semiconducting carbon nanotubes can operate as field effect transistors for such applications, but metallic impurities short circuit carrier transport and prevent discrete switching. This project seeks to apply knowledge regarding charge transfer to 1-D nanotube systems to selectively rupture carbon bonds of impurity pathways. We seek to map device improvement in terms of on-off ratios.

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* Denotes principal investigator.
to specific chemical pathways, thus providing a useful handle for nanoelectronic control.

**Assembly of Nanoparticles**  
C. F. Zukoski,* E. Mock  
*U.S. Department of Energy, DEFG02-91ER45439  
*In cooperation with the Frederick Seitz Materials Research Laboratory*

Particles with anisotropic interactions are synthesized and used to assemble novel microstructures. Using novel synthesis techniques we control the physical and chemical anisotropy of particles, with the goal of studying how anisotropy affects microstructural arrangements. Links between particle microstructure and macroscopic optical and rheological properties are studied. We are interested in how anisotropy can be used to engineer novel complex particle arrangements.

**Characterization of a Strongly Aggregated Model Gel System**  
C. F. Zukoski,* R. Kramb  
*U.S. Department of Energy, DEFG02-91ER45439  
*In cooperation with the Frederick Seitz Materials Research Laboratory*

A model gel system has been developed in which the dominant force of attraction is van der Waals forces. In this system, solutions of colloidal spheres with diameters from 200nm to 1μm are coated with a nonionic surfactant. The particles aggregate to form gels as the background ionic strength is raised and electrostatic repulsion is screened out. Accurate predictions of strength and range of interparticle attractions are sought using characterization methods including: finding the ionic strength-volume fraction gel line, measuring mechanical properties both near the gel point and deep within the gel, and determining microstructure using light and neutron scattering techniques.

**Flow of Weakly Flocculated Suspensions**  
C. F. Zukoski,* S. J. Yoon  
*U.S. Department of Energy, DEFG02-91ER45439  
*In cooperation with the Frederick Seitz Materials Research Laboratory*

In this investigation, researchers examine the flow properties of weakly flocculated suspensions. A model system has been chosen in which, by solution pH, the suspension can be reversibly gelled. By mapping out a phase boundary in pH/volume fraction space, the research team is able to explore the relationship between flocculation in colloidal suspensions and sol-gel transitions observed in molecular systems. The mechanical properties of the gelled samples are of importance in determining porosity and suspension processibility. Researchers are seeking general descriptions of yielding and flow in terms of the depth of the interparticle attractive potential.

**Microstructure and Mechanics of Filled Polymer Melts**  
C. F. Zukoski,* B. J. Anderson  
*Nanoscale Science and Engineering Initiative of the National Science Foundation, NSF Award No. DMR-0117792*

We explore the effects of polymer molecular weight, nanoparticle volume fraction, and polymer-particle surface affinity on the microstructure and mechanics of filled polymer melts. The design of these materials is often hindered by inadequate particle dispersion resulting in low product performance. Thus, these studies are conducted to understand the stability and behavior of nanoparticles dispersed in high molecular weight solvents. A variety of phases are expected as molecular weight, volume fraction and surface affinity are varied: homogeneous fluid, phase separation, or nonequilibrium gel. Materials are characterized through scattering and rheological techniques.

**Microchemical, Microfluidic, and Nanochemical Systems**

**Cathode Catalysis for Hydrogen/Oxygen Fuel Cells**  
P. J. A. Kenis,* A. A. Gewirth,* R. S. Jayashree, W. P. Zhou  
*Department of Energy, DE-FG02-05ER46260*

In hydrogen-based proton electrolyte membrane fuel cells (PEMFCs), the Nafion membrane separates the anodic and cathodic compartments of fuel cells. The cathode typically limits the cell’s performance due to poor kinetics of the oxygen reduction reaction. In addition, flooding of the cathode often occurs, hampering oxygen in trying to reach the cathode. We have developed a microfluidic hydrogen-oxygen fuel cell with a flowing electrolyte between two gas-diffusion electrodes. This electrolyte stream effectively removes excess water from the cathode side, thus eliminating cathode flooding. A reference electrode in the outlet stream allows for independent analysis of the polarization losses on the anode and the cathode, thereby creating an elegant catalyst characterization and optimization tool. We studied the performance of different catalyst ink compositions on the cathode side, including various nonplatinum based catalysts (e.g. Ag nanoparticles). This microfluidic fuel cell lends itself also

* Denotes principal investigator.
for operation in alkaline media, which is known to enhance reaction kinetics.

**Distributed Nano Fuel Cells Compatible with Transistor Fabrication**

P. J. A. Kenis,* P. O. Lopez-Montesinos, N. Yossakda
Agnitio, 2006-06721

Most present fuel cell technologies use polymer electrolyte membranes such as Nafion to separate the anode and cathode compartments. While these fuel cell technologies hold promise to replace other power sources, most notably batteries, their introduction to the market has been seriously hampered by issues related to these membranes, most notably fuel crossover, catalyst leaching, anode dry-out, and cathode flooding, all leading to reduced performance. Here, we develop silicon-based microfuel cells in which the membrane has been replaced with microfabricated structures, such that it can be fabricated side-by-side with electronic elements, and thus implemented in distributed fashion within electronic architectures.

**High Temperature Microreactors for Fuel Reforming**

P. J. A. Kenis,* Christian, M. Mitchell
Army Research Office, Multidisciplinary Research Program of the University Research Initiative, DAAD 19-01-1-0582

Reforming of liquid hydrocarbons into hydrogen for use in hydrogen fuel cells is an approach that avoids issues related to the storage of hydrogen itself. In this project, we created ceramic microreactors with embedded silicon carbide monoliths as catalyst support structures. These catalyst support structures combine the required properties of high thermal stability, high surface area, and low pressure drop. Using Ruthenium as the catalyst, we were able to show the steam reforming of propane into hydrogen at temperatures between 800°C and 1000°C over hundreds of hours with no loss in structural integrity or catalyst activation. This unique compatibility with high operating temperatures prevents the reactor from coking, the typical cause for the loss in performance in hydrocarbon fuel reforming.

**Membraneless Microfuel Cells**

P. J. A. Kenis,* J. S. Spendelow, R. S. Jayashree, S. K. Yoon, M. Mitchell
National Science Foundation, CTS 05-47617 CAREER award; Army Research Office-INI Power Systems 2005-2374 (STTR Phase 2); SONY Japan; Northrop Grumman Space Technology

In most microscale fuel cells, a proton electrolyte membrane (PEM) separates the anodic and cathodic compartments. Fuel crossover and water management issues (cathode flooding, anode dry out) are the main problems in PEM-related fuel cells. In the membraneless laminar flow fuel cells (LFFCs) studied here, the fuel and oxidant stream are brought together in a channel of microscopic dimensions and continue to flow laminarly in parallel without turbulent mixing while the fuel and oxidant can react at the anode and cathode, respectively, placed on opposite sidewalls. Fuel crossover and water management issues can be minimized in this design by fine-tuning the flow rates and channel dimensions. We optimized the performance of air-breathing LFFCs that are fuel flexible (methanol, formic acid) and media flexible (acidic, alkaline) by the combination of results from simulation (three-dimensional finite-element-method) and experiment. We investigated the impact of different operating conditions (volumetric flow rate, fuel to electrolyte flow rate ratio, oxygen concentration) and of different cell dimensions (electrode-to-electrode distances, channel length) on the maximum power density of individual LFFCs. Fuel utilization in a single pass was improved by hydrodynamic focusing of the fuel as a thin stream on the anode to reduce the fraction of fuel that passes through the channel without reacting. Similarly, we exploited the concept of media flexibility to create bio-LFFCs, where the anode and the cathode operate at different pHs and enzymes were used as anode catalysts.

**Micro and Nanofluidic Systems for Nanomanufacturing**

National Science Foundation, DMI 03-28162, Nanoscale Science and Engineering Center

The overall goal of Nano-CEMMS, the NSF NSEC grant here at Illinois, is the development of fluidic and ionic-based nanomanufacturing technology. We identified the critical parameters that determine the amount of fluid (e.g. ink) transferred from one surface to the next for substrates of different hydrophilicity. Subsequently, we used this knowledge to print droplets as small as 70 femtoliter in a two-step procedure starting from microliter-sized droplets. We also created multiplexed arrays of electric sensors (resistive, capacitive, conductive) to track plugs of fluid (e.g. ink) through a microfluidic network, enabling feedback control of these plugs being routed to a certain nozzle in a multinozzle nanomanufacturing toolbit. The multiplexing concept dramatically reduces the number of leads required to monitor events in an mxn sensor array, specifically from 2xmn to m+n+1; so for a 10x10 array, from 200 to 21 leads. In addition, we integrated novel

* Denotes principal investigator.
microfluidic networks comprised of nanoliter-sized wells with photonic crystal-based biosensors for the combinatorial synthesis and screening of drug leads.

**Microfluidic Tools for Pharmaceutical Crystallization**
P. J. A. Kenis,* V. Bhamidi, G. He, C. F. Zukoski, R. Tan
3M Corporation; Institute for Chemical Engineering Sciences–A*Star Singapore

Pharmaceuticals are often manufactured as microcrystals, ideally in the most stable polymorph. We have shown the selective, direct crystallization of the gamma polymorph of glycine, a well-known model compound for polymorphism of pharmaceuticals, in an evaporation-based crystallization platform that enabled kinetic control over the process. In addition, we are developing microfluidic methods to identify all possible polymorphs of novel pharmaceuticals, and to identify the most robust crystallization procedures for the selective crystallization of the thermodynamically most stable polymorph, for example as a salt.

**Fuel Cells for Portable Power**

The objective of this project is to develop novel fuel cell systems for micropower generation. Parts of the work include developing formic acid fuel cells for micropower generation, catalyst development, construction and testing of silicon fuel cells, development of novel membrane materials, and spectroscopic investigations to understand how micropower systems are different than systems on the macroscale.

**Micro-Gas Chromatographs**
Defense Advanced Research Projects Agency, FA8650-04-1-7121; United States Air Force

The objective of this project is to construct chip-scale gas chromatographs for hazardous gas detection. The work includes developing MEMS pumps and valves for gas sampling and flow control; a fast preconcentration technology using silicon nanograin and selective adsorbents to suppress unwanted species; a fast, ultrahigh resolution, separation technology using high-aspect ratio DRIE columns and nanoengineered stationary phases; microscale thermal isolation using components suspended on polyimide films; and a three-mode orthogonal micro detection system.

**Microreactors for Hydrogen Production**
R. I. Masel,* M. A. Shannon,* V. Subramanian, D. Kim, L. Zhu, N. Ndiege
Defense Advanced Research Projects Office, DST 200700299513-000;

Microreactors are being designed and built to produce hydrogen for small-scale fuel cells using novel chemistries and microfluidic control systems.

**Multiscale Systems**

**Computational Toolbox for the Investigation of Multiscale Surface Processes**
R. C. Alkire, L. Petzold,*
T. Yang (University of California, Santa Barbara)
National Science Foundation, ITR 04-28912

The physical system under study is electrodeposition of metallic nanoclusters with use of additives to achieve specific shapes. Key issues are to understand how small-scale surface interactions guide spontaneous self-organization, how to extract insight from noisy data and uncertain fundamental understanding, and how to ensure quality control at multiple scales in manufacturing. The algorithms and software developed for multiscale simulation and sensitivity analysis are generic over a broad class of problems and will contribute well beyond the applications used in their development.

**Analysis and Design of Multiscale Simulation Codes**
R. D. Braatz,* R. C. Alkire,* T. O. Drews, E. Rusli, X. Li, M. Karulkar
Intel; National Science Foundation, CTS-0438356, NRAC MCA 01S022, DGE-0338215

Chemical reacting systems involve phenomena that span several orders of magnitude in time and length scales, from the molecular to the macroscopic. Many papers have adopted a simulation architecture that employs dynamically coupled simulation codes, in which each code simulates the physicochemical phenomena for a different range of length scales in the reacting system. We use nonlinear systems theory to design coupling algorithms that modify the dynamic information passed between stochastic and deterministic codes to numerically stabilize
their coupling and increase the numerical accuracy of the simulation results. The methods have been used to guide the design of a multiscale simulation code for copper electrodeposition, which is the process used to manufacture the sub-micron interconnects in various electronic devices. The multiscale simulation couples a (2 +1)-dimensional kinetic Monte Carlo simulation code that tracks the motion of molecules on the copper surface with a level set code that tracks the position of the moving solid-liquid interface and a finite volume code that simulates the diffusion and migration of chemical species in the electrochemical solution.

Multiscale Systems Theory with Applications to Nanostructured Materials
R. D. Braatz,* R. C. Alkire,* E. Rusli, T. O. Drews, X. Li, M. Karulkar
Intel; National Science Foundation, CTS-043856, NRAC MCA 01S022, DGE-0338215

New applications in materials, medicine, and computers are being discovered where the control of events at the molecular and nanoscopic scales is critical to product quality, although the primary manipulation of these events during processing occurs at macroscopic length scales. This drives research in the creation of tools for the design and control of multiscale systems that have length scales ranging from the atomic to the macroscopic. Our approach includes stochastic parameter sensitivity analysis, Bayesian parameter estimation applied to ab initio calculations and experimental data, hypothesis mechanism selection, and multiscale optimal design and nonlinear control.

Optimization and Process Systems Engineering

Branch-and-Reduce Algorithms for Global Optimization
N. V. Sahinidis*
ExxonMobil Upstream Research Company

Realistic treatments of physical and engineering systems frequently involve nonlinear models in which optimization requires escaping from local minima traps. This project develops global optimization methodologies. The algorithms solve sequences of convex underestimating subproblems obtained by evolutionary subdivision of the search region. Novel features include optimally based and feasibility based range reduction, new branching rules, new bounding schemes, and efficient heuristics to accelerate convergence. The project addresses applications in engineering design, molecular structure determination, and economics. Special classes of problems are also considered, including minimization of concave functions over convex sets, minimization of products of convex functions, bilinear programs, integer programs, and factorable programs.

Combinatorial Problems in Computational Chemistry
N. V. Sahinidis*
National Science Foundation

The enumeration of large, combinatorial search spaces presents a central conceptual difficulty in many problems in combinatorial chemistry, chemometrics, and molecular design. This research develops novel and mathematical models and algorithms to address such combinatorial challenges. In one application area, we are developing models and algorithms for interpreting FTIR spectra. In another application area, they are developing a systematic methodology for the design of environmentally benign alternative refrigerants. This has led to the identification of several novel potential alternatives. We are developing molecular design techniques with an emphasis on minimizing the environmental impact over the entire life cycle of the new compounds.

Processing

Experiments for Control of Transient-Enhanced Diffusion in Transistor Fabrication
E. G. Seebauer,* S. H. Yeong,
M. P. Srinivasan (Natl. Univ. of Singapore),
B. Colombeau (Chartered Semiconductor),
L. Chan (Chartered Semiconductor)
Chartered Semiconductor Manufacturing

Formation of extremely shallow pn junctions with very low electrical resistance is a major stumbling block to the continued down scaling of microelectronic devices. Recent work in our laboratory has shown that the behavior of defects within silicon can be changed significantly by controlling the chemical state at the surface. Certain chemical treatments of the surface induce it to act as an active “sink” for point defects that removes Si interstitials selectively over impurity interstitials, leading to less dopant diffusion and better electrical activation. The present work demonstrates such effects experimentally for several dopants such as boron, arsenic, and phosphorus in both crystalline and Ge pre-amorphized silicon wafers. Moreover, such active surfaces dramatically reduce the number of end-of-range defects observed after annealing.
Modeling for Control of Transient-Enhanced Diffusion in Transistor Fabrication

E. G. Seebauer,* R. D. Braatz, C. T. M. Kwok
American Chemical Society Petroleum Research Fund, 43651-AC5

Transient-enhanced diffusion (TED) during annealing after ion implantation limits how the shallow junctions can be made in next-generation transistors. Models for TED in current commercial process simulation software do not incorporate surface effects adequately. We are incorporating these new aspects of physics through systems-based methods such as Maximum Likelihood estimation and Maximum A Posteriori estimation, and testing the results experimentally in the ion implantation of boron into silicon. Two-dimensional simulations based on this model indicate that the beneficial effects of active surfaces in the source-drain region extend laterally to the surface toward the channel region of a device as well as perpendicularly to the surface into the bulk.

Separation of Single Walled Carbon Nanotubes According to Electronic and Geometric Structure

M. S. Strano,* M. Usrey, D. Heller
Dupont; Ocean Optics Inc.

Carbon nanotubes are a diverse class of electronic and optical materials. Depending on their diameter and helical twisting, nanotubes can be metallic, semimetallic or semiconducting. All currently known synthesis methods create random mixtures of all types, but to use these materials as nanoelectronic circuits and sensors, one needs to isolate and control one particular type. We are developing robust methods to sort and separate carbon nanotubes into distinct fractions for electronic applications.

Systems and Control

Control of Crystal Size and Shape Distribution in Pharmaceutical Crystallization

National Science Foundation, ESI-0426328; Merck & Co., Inc.

Most pharmaceutical compounds are produced in crystalline form. An integrated approach is being created to control pharmaceutical crystallization that incorporates first-principles simulation models, optimization theory, nonlinear feedback control, and state-of-the-art analysis. This includes simulating the nucleation, growth, and aggregation of crystals with multiple characteristic length scales, designing algorithms for constructing crystal size and shape distributions from in situ video microscopy and laser backscattering, analyzing the sensitivity of the states and product quality variables to model uncertainties, and designing algorithms to control the properties of the product crystals.

Economic Design of Maintenance Policies for Deteriorating Systems

R. D. Braatz,* J. Isom
United Technologies Corporation Fuel Cells

When an alarm is used to initiate an action on a stochastically deteriorating system, the economic impact of a maintenance policy can be assessed with a reliability model, cost model, and process model of the stochastic system. We are investigating three methods for developing the stopping region for such maintenance policies. Direct search over subsets of the measurement space is practicable only in simple cases. Search of the feasible stopping probability boundary yields optimal results through global minimization. The likelihood ratio method solves a simpler minimization to produce results that are nearly globally optimal.

Journal Articles

Biochemical and Biomedical Engineering


* Denotes principal investigator.


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**Fluid Flow, Heat, and Mass Transfer Fundamentals**


### Materials


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**Microchemical, Microfluidic, and Nanochemical Systems**


**Processing**


**Book Chapters**

Biochemical and Biomedical Engineering


**Fluid Flow, Heat, and Mass Transfer Fundamentals**


**Microchemical, Microfluidic, and Nanochemical Systems**


**Papers Presented at Conferences and Symposia**

**Biochemical and Biomedical Engineering**


Leckband, D. E., Bayas, M., Kearney, A., and van der Merwe, P. A. **Chemistry at biological interfaces.** Probing Molecules at the Biological Interface, American Chemical Society 231st National Meeting (Atlanta, GA, Mar. 2006).

Leckband, D. E., Plunkett, K., Xi, Z., and Moore, J. **MW and density dependence of the temperature-dependent collapse of grafted PNIPAM.** Biomolecular and Polymeric Nanostructures and Interfaces, American Chemical Society 231st National Meeting (Atlanta, GA, Mar. 2006).


Sahinidis, N. V. and Xie, W. **An exact algorithm for the contact map overlap problem in protein structural alignment.** International Symposium on Mathematical Programming (Rio de Janeiro, Brazil, Aug. 2006).


Wongand, L. and Pack, D. W. **Efficient siRNA delivery with acetylated polyethylenimine.** American Institute of Chemical Engineers Annual Meeting (San Francisco, CA, Nov. 2006).

**Fluid Flow, Heat, and Mass Transfer Fundamentals**

Anderson, B. J., and Zukoski, C. F. **Nanoparticle stability and structure in polymer melts.** American Institute of Chemical Engineers Annual Meeting (San Francisco, CA, Nov. 2006).


Zukoski, C. F. **States of colloidal aggregation: Progress and challenges.** American Institute of Chemical Engineers Annual Meeting (San Francisco, CA, Nov. 2006).

**Materials**


**Microchemical, Microfluidic, and Nanochemical Systems**


Kenis, P. J. A. Air-breathing laminar flow fuel cells operating in alkaline or acidic media. American Institute of Chemical Engineers Spring National Meeting (Orlando, FL, Apr. 2006).


Kenis, P. J. A. Microfluidic fuel cells. American Institute of Chemical Engineers Annual Meeting (San Francisco, CA, Nov. 2006).

Kenis, P. J. A. Mixing in the formulation of screens for drug leads or crystallization conditions in microfluidic systems. American Institute of Chemical Engineers Annual Meeting (San Francisco, CA, Nov. 2006).


Masel, R. I. Formic acid fuel cells—New possibilities for portable power. Purdue University School of Chemical Engineering Seminar (West Lafayette, IN, Apr. 2006).


Monty, C., Oh, I., and Masel, R. I.  **Detection of organophosphorus compounds using an acetylcholinesterase-based biosensor.** American Institute of Chemical Engineers Annual Meeting (San Francisco, CA, Nov. 2006).


Oh, I., Monty, C., Shannon, M. A., and Masel, R. I.  **Electrochemical sensor for toxic chemicals based on nanodeposit and enzyme.** American Institute of Chemical Engineers Annual Meeting (San Francisco, CA, Nov. 2006).


Oh, I., Shannon, M. A., and Masel, R. I.  **Electrochemistry at fuzzy interfaces and micro electrochemical systems.** American Institute of Chemical Engineers Annual Meeting (San Francisco, CA, Nov. 2006).

Oh, I., Shannon, M. A., and Masel, R. I.  **Microfabricated electrochemical organophosphate sensor based on oxime chemistry.** American Institute of Chemical Engineers Annual Meeting (San Francisco, CA, Nov. 2006).

Prakash, S., Armijo, A., Yoshitomi, D., Masel, R. I., and Shannon, M. A.  **Transient flame dynamics within submillimeter combustors.** Institution of Mechanical Engineers (Chicago, IL, Nov. 2006).

Radadia, A. D., Shannon, M. A., and Shannon, M. A.  **Dispersion effects of microchannel configurations and turn geometries.** American Institute of Chemical Engineers Annual Meeting (San Francisco, CA, Nov. 2006).


Rusli, E., Lee, H., and Braatz, R. D.  **Optimal distributional control of crystal size and shape.** 5th World Congress on Particle Technology (Orlando, FL, Apr. 2006).

Schudel, B. and Kenis, P. J. A.  **Controlling microfluidic arrays for combinatorial chemistry using multifunctional valves.** American Institute of Chemical Engineers Annual Meeting (San Francisco, CA, Nov. 2006).


Spendelow, J. S., Goodpaster, J., Kenis, P. J. A., and Wieckowski, A.  **The different roles of defects in CO oxidation, methanol oxidation, and oxygen reduction on Pt(111) in alkaline solutions.** 210th Electrochemical Society Meeting (Cancun, Mexico, Nov. 2006).


Strano, M. S. Understanding and exploiting the chemistry of single-walled carbon nanotubes. Brown University, Department of Chemical Engineering (Providence, RI, Apr. 2006).

Strano, M. S. Understanding and exploiting the chemistry of single-walled carbon nanotubes. Massachusetts Institute of Technology, Department of Chemical Engineering (Cambridge, MA, Apr. 2006).

Strano, M. S. Understanding and exploiting the chemistry of single-walled carbon nanotubes. University of Oklahoma, Department of Chemical Engineering (Norman, OK, Sep. 2006).


Optimization and Process Systems Engineering


Xie, W. and Sahinidis, N. V. Optimal combinatorial library design from a computational complexity perspective. American Institute of Chemical Engineers Annual Meeting (San Francisco, CA, Nov. 2006).


Processing


Theses

Biochemical and Biomedical Engineering


Fluid Flow, Heat, and Mass Transfer Fundamentals

Microchemical, Microfluidic, and Nanochemical Systems


Awards and Honors

Richard C. Alkire
Member, National Academy of Engineering
Fellow, American Association for the Advancement of Science
Fellow, Honorary Member, and Past President, The Electrochemical Society
Teaching Excellence Award, University of Illinois School of Chemical Sciences, 1982
Research Award, Electrochemical Division, The Electrochemical Society, 1983

Carl Wagner Memorial Award, The Electrochemical Society, 1985
Professional Progress Award, American Institute of Chemical Engineers, 1985
Director, American Institute of Chemical Engineers, 1988-1991
G. W. Kidd Outstanding Alumnus Award, Lafayette College, 1988
E. V. Murphree Award, American Chemical Society, 1991
Technical Achievement Award, National Association of Corrosion Engineers, 1992
Lifetime National Associate, U.S. National Academies, 2002
Vittorio de Nora Award and Gold Medal, Electrochemical Society, 2004
Fellow, International Society of Electrochemistry, 2006
Invited Lecture Series, Waseda University, Tokyo, Japan, 2006
Ralph Peck Memorial Lecture, University of Illinois Chicago Institute of Technology, 2006
Distinguished Speaker Series, University of California, Riverside, 2006

Richard D. Braatz
Doctoral Thesis Prize, Hertz Foundation, 1994
DuPont Young Faculty Award, 1995
Teaching Excellence Award, University of Illinois School of Chemical Sciences, 1997
Advisors List for Advising Excellence, University of Illinois College of Engineering, 1999, 2002
Xerox Award for Faculty Research, University of Illinois College of Engineering, 1999
Donald P. Eckman Award, American Automatic Control Council, 2000
Council of Outstanding Early Career Engineers, Oregon State University, 2000
Ernest W. Thiele Lectureship, University of Notre Dame, 2001
Beckman Associate, University of Illinois Center for Advanced Study, 2002
University Scholar, University of Illinois, 2003
CAST Director's Award, American Institute of Chemical Engineers, 2003
Curtis W. McGraw Research Award, American Society for Engineering Education, 2004
Outstanding Paper Award, IEEE Transactions on Control Systems Technology, 2005
CAST Outstanding Young Researcher Award, American Institute of Chemical Engineers, 2005
Antonio Ruberti Young Researcher Prize, Institute of Electrical and Electronics Engineers, 2005
Lindsay Distinguished Lecturer, Texas A & M University, 2005-2006
Millennium Chair of Chemical and Biomolecular Engineering, University of Illinois, 2006
Excellence in Process Development Research Award, American Institute of Chemical Engineers, 2006
Fellow, Institute of Electrical and Electronics Engineers, 2007

**Thomas J. Hanratty, Emeritus**
Member, National Academy of Engineering
Member, National Academy of Sciences
Fellow, American Academy of Arts and Sciences
Fellow, American Institute of Mechanics
Fellow, American Physical Society
Honorary Doctorate, University of Toulouse
Honorary Doctorate, Villanova University
Allan P. Colburn Award, American Institute of Chemical Engineers, 1957
Curtis W. McGraw Award, American Society for Engineering Education, 1963
William H. Walker Award, American Institute of Chemical Engineers, 1964
Professional Progress Award, American Institute of Chemical Engineers, 1967
Senior Research Award, American Society for Engineering Education, 1979
Shell Distinguished Chair in Chemical Engineering, University of Illinois, 1981-1990
Distinguished Engineering Alumnus, Ohio State University, 1984
Ernest Thiele Award, Chicago Section, American Institute of Chemical Engineers, 1986
University Scholar, University of Illinois, 1987
J. W. Westwater Professorship, University of Illinois, 1989-1997
Lamme Medal, Ohio State University, 1997
International Prize for Research in Multiphase Flow, 1998

**Jonathan J. L. Higdon**
Presidential Young Investigator Award, National Science Foundation, 1984
Teaching Excellence Award, University of Illinois College of Liberal Arts and Sciences, 1988
Teaching Excellence Award, University of Illinois School of Chemical Sciences, 1984, 1986, 1990, 1994
Stanley Corssin Lectureship in Fluid Mechanics, Johns Hopkins University, 1993

**Paul J. A. Kenis**
Akzo-Nobel Graduate Fellowship, 1993-1997
TALENT Postdoctoral Fellowship from NWO, Dutch Science Foundation, 1998
3M Young Faculty Award, 2001-2004
Collins Scholar, Academy for Excellence in Engineering Education, University of Illinois College of Engineering, 2001
Faculty Early Career Development (CAREER) Award, National Science Foundation, 2005-2010
Xerox Foundation Award for Faculty Research, University of Illinois College of Engineering, 2006
Excellence in Teaching Award, University of Illinois School of Chemical Sciences, 2006
Beckman Fellow, University of Illinois Center for Advanced Study, 2007-2008
Helen Corley Petit Scholar, University of Illinois College of Liberal Arts & Sciences, 2007-2008

**Hyun Joon Kong**
International Fellowship, Hanyang University, 1995-1997
Honored Student, 1992
Fellowship Award, Samnam Foundation, 1990-1991
Fellowship Award, Hanyang University, 1988-1989

**Deborah E. Leckband**
Fellow, American Institute of Medical and Biological Engineering (AIMBE)
Fellow, American Association for the Advancement of Science (AAAS)
National Science Foundation Research Initiation Award, 1993-1996
FIRST Award, National Institutes of Health, 1993-1998
Faculty Early Career Development (CAREER) Award, National Science Foundation, 1995-1999
Amoco Lectureship, Stanford University, 1998
Xerox Faculty Research Award, University of Illinois College of Engineering, 1998
Helen Petit Professorship, University of Illinois College of Liberal Arts and Sciences, 1999-2000
Fellow, University of Illinois Center for Advanced Study, 1999-2000
University Scholar, University of Illinois, 2001-2004
Plenary Speaker, American Chemical Society Colloids and Surface Science Symposium, 2001
Keynote Speaker, University of Virginia Bioengineering Symposium on Biomechanics of Adhesion, 2002
Provost's Distinguished Lecture Series, University of Texas, Austin, 2003

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<tr>
<th>Name</th>
<th>Awards/Prizes</th>
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<tr>
<td>Richard I. Masel</td>
<td>Distinguished Lecturer, Cell and Molecular Biology, Boston University School of Dental Medicine, Boston, 2003</td>
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<td></td>
<td>Britton Chance Distinguished Lecturer in Engineering and Medicine, University of Pennsylvania, 2004</td>
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<td></td>
<td>Alumni Achievement Award, Liberal Arts College, 1996-1997</td>
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<td>Postdoctoral Fellow, NATO, 1977</td>
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<td></td>
<td>Exxon Faculty Fellowship in Solid-State Chemistry, American Chemical Society, 1982</td>
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<td></td>
<td>Presidential Young Investigator Award, National Science Foundation, 1984</td>
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<td>Innovation Discovery Award, 2005</td>
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<td>Walter G. May, Emeritus</td>
<td>Member, National Academy of Engineering</td>
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<td>Fellow, American Institute of Chemical Engineers</td>
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<td>Tau Beta Pi Eminent Engineer, 1988</td>
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<td></td>
<td>Award in Chemical Engineering Practice, American Institute of Chemical Engineers, 1989</td>
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<td>Teaching Excellence Award, University of Illinois School of Chemical Sciences, 1989, 1991</td>
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<tr>
<td>Daniel W. Pack</td>
<td>Excellence in Teaching Award, School of Chemical Sciences, University of Illinois, 2000</td>
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<td></td>
<td>Selection to Frontiers of Engineering Symposium, National Academy of Engineering, 2002</td>
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<td>Faculty Early Career Development (CAREER) Award, National Science Foundation, 2002</td>
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<td>Excellence in Teaching Award, School of Chemical Sciences, University of Illinois, 2003</td>
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<td>Beckman Fellow, Center for Advanced Study, University of Illinois, Urbana-Champaign, 2004-2005</td>
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<tr>
<td>Christopher V. Rao</td>
<td>National Science Foundation CAREER Award, 2007</td>
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<tr>
<td>Nikolaos V. Sahinidis</td>
<td>DuPont Young Faculty Research Initiation Grant, University of Illinois, 1991</td>
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<td></td>
<td>Faculty Early Career Development (CAREER) Award, National Science Foundation, 1995</td>
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<td>Fellowship, National Science Foundation/Lucent Technologies Industrial Ecology, 1998</td>
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<td>CAST Director's Award, American Institute of Chemical Engineers, 1999</td>
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<td>INFORMS Computing Society Prize, Institute for Operations Research and the Management Sciences, 2004</td>
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<td>Center for Advanced Study Associate, University of Illinois, 2005</td>
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<td>University Scholar, University of Illinois, 2005</td>
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<td>Beale-Orchard-Hays Prize Mathematical Programming Society, 2006</td>
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<td>Edmund G. Seebauer</td>
<td>Dow Teaching Excellence Award, 1988</td>
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<td>Presidential Young Investigator Award, National Science Foundation, 1988</td>
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<td>DuPont Young Faculty Award, 1989</td>
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<td></td>
<td>Fellow, Alfred P. Sloan Foundation, 1994-1996</td>
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<td></td>
<td>Inventor Recognition Award, Semiconductor Research Corp., 1995</td>
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<td>Teaching Excellence Award, University of Illinois School of Chemical Sciences, 1996</td>
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<td>Fellowship for Study in a Second Discipline, University of Illinois, 2000</td>
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<td>Fellow, American Vacuum Society, 2000</td>
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<td></td>
<td>Distinguished Lecturer, Institute of Electrical and Electronic Engineers Electron Device Society, 2004-2006</td>
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<td>Beckman Associate, Center for Advanced Study, University of Illinois, 2004</td>
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<td>James W. Westwater Professor, 2007-</td>
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<td>Michael S. Strano</td>
<td>Sidney A. Savitt Award for Academic Excellence in Chemical Engineering, Polytechnic University, 1997</td>
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<td>Garrett Reed Cantwell Graduate Scholarship, University of Delaware, 1998</td>
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<td></td>
<td>Annual Research Award, Philadelphia Catalysis Society, 1999, 2001</td>
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<td>Graduate Award, American Institute of Chemical Engineers Separations Division, 2001</td>
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<td>Honorable Mention, Graduate Award, American Institute of Chemical Engineers Environmental Division, 2002</td>
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<td>Young Investigator Award, Dupont, 2004</td>
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<td>Top Young Innovator Award, MIT Technology Review, 2004</td>
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<td>Faculty Early Career Development (CAREER) Award, National Science Foundation, 2005</td>
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<td>Top 1% of Highly Cited Researchers, Essential Science Indicators/Web of Science, 2005</td>
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<td>Young Investigator Award, Nanoscale Science and Engineering Forum, American Institute of Chemical Engineers, 2005</td>
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<td>Coblentz Award for Molecular Spectroscopy, 2006</td>
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<td>3M Nontenured Faculty Award, 2006</td>
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<td>Beckman Young Investigator Award, 2006</td>
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Collaboration Success Award, Council of Chemical Research, 2006
Presidential Early Career Award for Scientists and Engineers (PECASE), 2006

Huimin Zhao
Dow Special Recognition Award, 1999-2000
Collins Scholar, University of Illinois College of Engineering, 2001
Faculty Early Development (CAREER) Program Award, National Science Foundation, 2004-2009
Excellence in Teaching Award, University of Illinois School of Chemical Sciences, 2004
Beckman Fellow, University of Illinois Center for Advanced Study, 2005-2006
Xerox Award for Faculty Research, University of Illinois College of Engineering, 2005
Dupont Young Professor Award, 2005
Helen Corley Petit Scholar, University of Illinois College of Liberal Arts and Sciences, 2006

Charles F. Zukoski
Presidential Young Investigator Award, National Science Foundation, 1987
Everitt Award for Teaching Excellence, University of Illinois College of Engineering, 1992
Fulbright Teaching/Scholar Fellowship to visit the University of Melbourne, 1992
Robert W. Vaughan Lectureship in Chemical Engineering, California Institute of Technology, 1993
Alumni Professor, University of Illinois Department of Chemical Engineering, 1994-1999
Thiele Lectureship in Chemical Engineering, Notre Dame University, 1994
University Scholar, University of Illinois, 1994-1997
Plenary Lecture: 13th Symposium on Industrial Crystallization, Toulouse, France, 1996
Moulton Medal, Institute of Chemical Engineers, 1997
Publication Award, Society of Rheology, 1997
Ralph K. Iler Award, American Chemical Society, 1997
Alcoa Plenary Lecture, Symposium on Particulate Fluids, Melbourne, Australia, 1998
William H. and Janet G. Lycan Chair, School of Chemical Sciences, University of Illinois, 2000-2001
Wilheim Lectureship, Princeton University Department of Chemical Engineering, 2001
Engineering Council Award for Excellence in Advising, University of Illinois, 2002
Alpha Chi Sigma Award for Chemical Engineering Research, American Institute of Chemical Engineers, 2002
Member, National Academy of Engineering, 2007