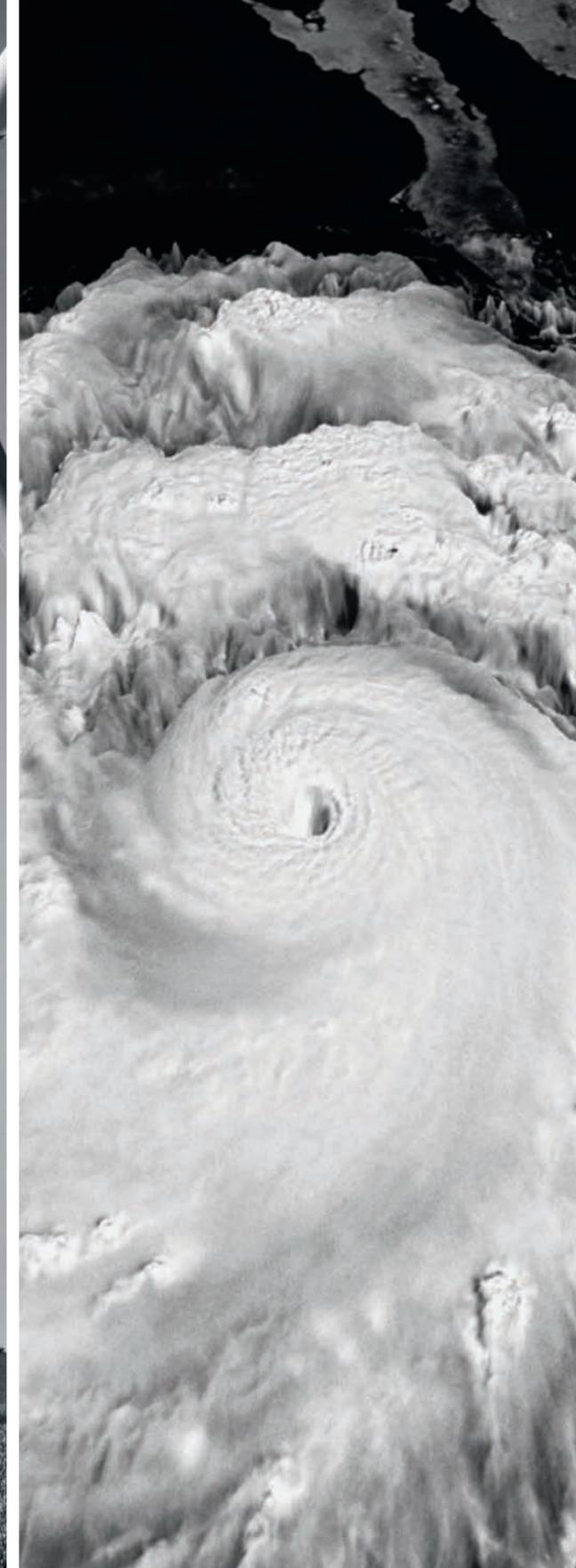


The Columbia School of Mines was established in 1864, at a time when we were anxious to learn ways that Earth could yield its resources for our use. Today, many of our faculty, especially those in the successor Department of Earth and Environmental Engineering, are finding new ways to help our planet endure—working on issues of water, climate, and energy that have impact around the globe.

# SUSTAINABILITY



*Putting a New Spin  
On the Science  
of Electronics*

**WILLIAM E.  
BAILEY**

Associate Professor of Materials Science and  
of Applied Physics and Applied Mathematics

It is often said that there is nothing new under the sun. However, looking more deeply into what is commonly understood can result in surprising new knowledge. Consider the electron, the negatively charged particle on the outer layer of the atom. The electron's charge is responsible for electricity and makes it possible to process data. The electron's spin underlies magnetism and makes it possible to store data. The entire electronics industry has been built on the known utility of this most basic particle.

The electronics industry is now undergoing rapid change, being pushed by a worldwide consumer desire for smaller and more efficient appliances that have increased data processing and storage capability. To meet this demand, engineers are working to lay the stepping stones to new technological breakthroughs in computer, audio, and video storage as well as sensor technology by using the spin as well as the charge of the electron, and by discovering how to transport electrical charge and magnetic spin through single atoms or nanoparticles. This science is leading to the development of magnetic thin films—single atomic layers of magnetic film, layered one upon the other and tested for their response to frequency, electrical resistivity, and their agility in signal processing.

This science could mean a new era defined by increased data processing speed, decreased power consumption and more affordable technology. Imagine an MP3 player that could store hundreds of thousands of songs; a laptop computer that could run on a single battery for weeks; or a cell phone that could store and protect data from degradation for decades. It's all possible, once breakthroughs are made in understanding how to best manipulate the electron's spin via electric and magnetic fields.

William Bailey studies the deposition and properties of magnetic ultrathin films. His research interests include nanoscale magnetic films and heterostructures, materials issues in spin polarized transport, and materials engineering of magnetic dynamics. He investigates novel magnetic properties for application in the emerging field of spintronics, and is particularly interested in designing magnetic materials with reduced energy loss for application in computing.

Prior to joining Columbia Engineering, Bailey held a National Research Council Postdoctoral Fellowship at the National Institute of Standards and Technology (NIST) in Boulder, Colorado. Honors for his research include the National Science Foundation CAREER and Army Research Office Young Investigator awards.

*Sc.B., Brown, 1993; M.S., Stanford, 1995; Ph.D., Stanford, 1999*





## *Assessing Damage in Aging Infrastructure*

# RAIMONDO BETTI

Professor of Civil Engineering and Engineering Mechanics

Assessing potential damage to aging infrastructure is an ever more critical issue every day. One of the areas in which Raimondo Betti, chair of the Department of Civil Engineering and Engineering Mechanics, specializes is damage detection for bridges using data correlation analysis. He and his team are leading the effort to develop a state-of-the-art corrosion monitoring system to be used in main cables of suspension bridges. His research is aimed at finding ways to safely extend the life of existing suspension bridges, focusing on those in New York City.

“New York City has among the oldest suspension bridges in the world,” said Betti. “Many have been in service for over 100 years, in a harsh environment. They have deteriorated and will continue to, if nothing is done. Main cables are the most critical structural element in a cable suspension bridge. If a cable fails, the entire bridge fails and so special attention must be given to such elements.” Replacing a bridge would be prohibitively expensive in a densely populated area as New York City. It is estimated that the failure of one of the city’s suspension bridges could cost billions of dollars.

Over the past five years, Betti has been conducting a unique experiment on the development of a corrosion monitoring system to be applied in main cables of suspension bridges. To test such a system, a mock-up of a bridge cable, 20 feet long, 20 inches in diameter, and made up of nearly 10,000 galvanized bridge wires, has been built inside an environmental chamber and subjected to a one-year cyclic corrosion test.

The cable—one of the largest ever built in the world and the only one subjected to a tensile axial force of 1,200 kips—has been enclosed in an environmental chamber to accelerate deterioration, simulating decades of wear, such as that endured by New York’s Williamsburg, Manhattan, and Brooklyn Bridges. Buried in the cable mock-up are 76 miniature sensors that are measuring corrosion rates, temperature, humidity, acidity, and chlorine content.

Betti and his team are now analyzing the results in order to provide meaningful methods to assess, in real time, the actual conditions of the cable. The answers he finds should help insure a longer life for suspension bridges around the world.

This project—the first systematic study ever done on monitoring the corrosion of suspension cables—is also the first in a series focused on damage assessment in main cables of suspension bridges and is part of a National Center on Aging Infrastructure in Urban Environments created by the Department of Civil Engineering and Engineering Mechanics.

*B.S., University of Rome La Sapienza (Italy), 1985; M.S., University of Southern California, 1988; Ph.D., University of Southern California, 1991*

*Short-Circuiting  
Blackouts*

**DANIEL  
BIENSTOCK**

Professor of Industrial Engineering  
and Operations Research and of  
Applied Physics and Applied Mathematics

**O**n August 14, 2003, an unusual combination of events shut down electrical power for 55 million people in the United States and Canada. The event was what statisticians call a black swan, something so rare that no one plans for it.

Yet major blackouts also occurred—with significant consequences—in 1965 and 1977. Daniel Bienstock believes that by studying these black swans, he can help utilities prepare for and even prevent the next major blackout.

“We’re borrowing ideas from other engineering disciplines,” said Bienstock. “If you design an aircraft wing, you test it by strapping it to a fixture and vibrating it to see what breaks. We do the same thing by using our model of the grid. Our objective is to stress the grid and see where it breaks.”

The 2003 crisis involved a number of unusual events that occurred in different parts of the Eastern United States grid. These included human errors, control room computer bugs, and a plant shutdown. These events put too much strain on several major power lines, causing them to overheat and eventually shut down. This started a process that snowballed until it knocked down much of the Eastern grid.

“One or two things like this can happen frequently and the grid can handle it,” said Bienstock. “But here, the particular combination proved catastrophic. After gathering momentum for several hours, the snowball caused hundreds of lines to fail within 15 minutes.”

His goal is to create software that will let utilities analyze cascading events and react to them before the grid comes down. First, though, he needs to anticipate what combination of events could trigger a blackout. “The traditional way is to enumerate every possible combination of individual lines coming down and determine the consequences,” he said. “There are not enough computers in the world to do this.”

Instead, Bienstock created a mathematical model of the grid and stresses it in different ways. “We can use the model to show us where the grid will break. Then we see what we can do to address those vulnerabilities,” he said.

He also runs what-if scenarios. “It’s a chess game. We look at cascading events and test different strategies to find the best way to react. These become templates that can guide utility responses before these events turn into a major outage,” Bienstock said.

“Imagine,” he concluded. “We would have had at least one hour to do our computations in 2003. We could have calculated the right moves to prevent a blackout.”

*B.S., Brandeis University, 1982; Ph.D., Massachusetts Institute of Technology, 1985*





The solid oxide fuel cell, which runs on hydrogen and oxygen to produce water as exhaust, is seen as a promising technology of the future for transportation. These fuel cells are now used on an experimental basis to power some city buses. But the fuel cells have proved unreliable because the nanoparticles of platinum that serve as a catalyst for the chemical reaction sometimes do not function optimally.

“Scientists want to exploit the nanoparticle in the device but still don’t know that particle’s basic properties,” said Simon Billinge. “Sometimes it works, and sometimes it doesn’t.”

These catalysts, nanoparticles of platinum, are balls one-millionth of a millimeter in diameter. The properties of the metal change when they are so small and scientists have yet to fully characterize them. By determining the nanoparticle’s structure and properties—its electrical conductivity, thermal conductivity, melting point, and stiffness—scientists will be better able to predict a fuel cell’s performance, based on what particular nanoparticle is used as the catalyst.

To help provide a solution, Billinge is developing new methods to characterize the structure of nanoparticles, figuring out the arrangements of atoms in particles that are made up of a few hundred to a few thousand atoms. He uses intense x-ray and neutron source technology, carrying out his research using particle accelerators at the Brookhaven National Laboratory in Long Island, N.Y., the Los Alamos National Laboratory in New Mexico, and the Argonne National Laboratory in Illinois.

In these accelerators, electrons circle at high energy, emitting intense x-ray beams that impinge on the nanoparticles. The scattered x-rays interfere with each other to produce “diffraction” patterns of intensity. Billinge has made important breakthroughs by developing novel Fourier transform methods to analyze the data.

He also has worked on measuring the surface energy of the platinum catalyst. The surface atoms, like those on the meniscus of a water droplet, have higher energy than those inside of the particle. And it’s the surface area of the nanoparticles that provides the reactivity for the hydrogen and oxygen that come together to produce the energy that propels the vehicle.

Earlier this year, Billinge won the J.D. Hanawalt Award for his contribution to the field of powder diffraction. The International Center for Diffraction Data gives the award every three years. Awardees are chosen by the Hanawalt Award Selection Committee, which is comprised of past recipients.

*B.A., University of Oxford (England), 1986; Ph.D., University of Pennsylvania, 1992*

## *Characterizing Nanoparticles for Fuel Cells*

# SIMON BILLINGE

Professor of Materials Science  
and of Applied Physics and  
Applied Mathematics

## ALLEN BOOZER

Professor of Applied Physics and Applied Mathematics

**M**agnetic fusion, a potential long-term source of electricity, occurs when isotopes of hydrogen, deuterium, and tritium combine at temperatures of about 200 million degrees C. At such temperatures, the electrons and the ions separate and form an electrically conducting gas called a plasma, which can be confined by magnetic fields in a chamber, shaped like an inner tube, called a torus. In a symmetrical torus, the electric current that creates the magnetic field runs both through external coils surrounding the chamber, and through the plasma. Helical shaping of the torus allows the confining magnetic field to be produced entirely by currents in the coils.

This shaping in effect forms a cage around the plasma making it more robustly stable as well as eliminating the difficulty of driving currents in the plasma. However, the helical shaping greatly complicates the issue of obtaining adequate plasma confinement. Major issues are the reduction of the power required to sustain the plasma so that power can be supplied by the deuterium-tritium reactions, and the achievement of plasma conditions consistent with engineering requirements, such as robust plasma stability.

Allen Boozer has developed the design principles by which the magnetic field strength in a helically shaped torus could be made consistent with adequate particle confinement. These ideas have been tested in the Helically Shaped Experiment (HSX) at the University of Wisconsin and will be tested in the \$1 billion W7-X experiment under construction in Germany.

Boozer has played a critical role in the understanding of how the detrimental effects on confinement of an asymmetry as small as  $10^{-4}$  can be controlled. He was a co-inventor of a method of driving currents in plasmas, electron cyclotron current drive, which allows the current to be driven in the precise spatial location it is needed. He also showed that thermodynamics implies the power required to drive the current in an axisymmetric torus is sufficiently large to place strong constraints on the plasma performance. Boozer has developed theoretical techniques that are used to enhance the performance of axisymmetric plasmas through feedback.

Boozer was one of two recipients who received the 2010 Hannes Alfvén Prize—the best-known European award in plasma physics. Boozer and his colleague, Jürgen Nührenberg, from the Max Planck Institute for Plasma Physics (Greifswald, Germany) were honored at the June 2010 conference of the Plasma Physics Division of the European Physical Society, which established the award in 2000. The Society cited them for “outstanding work in the formulation of criteria allowing stellarators to improve fast particle and neoclassical energy confinement.” The result of their work is considered important for magnetic fusion energy, in which isotopes of hydrogen (deuterium and tritium) fuse to release energy while confined in a magnetic field at a high temperature.

*B.A., University of Virginia, 1966; Ph.D., Cornell, 1970*





In 1985, Mark Cane and his student, Steve Zebiak, published the results of a model they developed to predict the movement of warm water across the tropical Pacific Ocean in a cyclical phenomenon known as the El Niño Southern Oscillation, or ENSO. When it forms, El Niño's meteorological reach spans the globe, causing a well-known pattern of extreme weather events.

The 2009 El Niño, for example, resulted in deep droughts in India and the Philippines and deadly rains in Uganda. Aside from the regular progression of the seasons, no other phenomenon influences Earth's short-term climate as profoundly as ENSO.

Despite its impact, in the early 1980s there was still no accepted theory for how it worked. "If you're predicting the weather you get to verify your models every three or four days," said Cane. "For El Niño, you have to wait four years to find out if you're right."

The Zebiak-Cane model showed a moderate El Niño developing in late 1986. People in Peru, Australia and elsewhere still had vivid memories of the devastating effects of the powerful El Niño that formed in 1982 and 1983, so many scientists opposed publishing forecasts they didn't yet understand. "People said, 'What if you're wrong?'" said Cane. "I said, 'What if we're right and we don't tell anyone?'"

Cane and Zebiak published their forecast in *Nature* in June of that year, which gave anyone who cared to listen time to prepare. Despite a delay in its formation early in the forecast window, by the autumn of 1986, the predicted El Niño developed, bringing its associated weather patterns to much of the globe.

Most of Cane's work since that time relates to the impacts of human-induced climate change and natural climate variability on people around the world, such as a seminal paper studying the implications of El Niño on maize yields in Zimbabwe. He has also created a highly successful master's degree program in Climate and Society that prepares students to understand and cope with the impacts of climate variability and climate change on society and the environment.

"Science should be more than just an academic exercise," said Cane. "We're not just predicting this thing in the Pacific, we're trying to predict all these consequences around the world that people care about."

*B.A., Harvard, 1965; M.A., Harvard, 1966; Ph.D., Massachusetts Institute of Technology, 1975*

## *Predicting El Niño*

# MARK CANE

Professor of Applied Physics and Applied Mathematics and G. Unger Vetlesen Professor of Earth and Climate Sciences

*Recycling Carbon  
Dioxide for Energy*

**MARCO  
CASTALDI**

Assistant Professor of  
Earth and Environmental Engineering

**M**arco Castaldi, head of the Combustion and Catalysis Laboratory, focuses his research on understanding catalytic and non-catalytic reactions that occur when carbon dioxide is introduced into thermal conversion processes such as the gasification of coal. He recently developed and tested a simple method for converting biomass to fuel in which he added carbon dioxide to the process. When he did, he found that he produced significantly more fuel and less waste.

Humans currently produce nearly 30 billion tons of carbon dioxide each year, almost all of which ends up in the atmosphere. Most strategies to combat global warming focus on reducing the amount of carbon dioxide being emitted or on ways to remove the gas from the atmosphere. Castaldi's aim is to redirect a portion of those emissions to a useful purpose.

Producing energy from biomass is generally done in one of two ways: by burning the material and using the heat to spin a turbine or by extracting the carbon and hydrogen in plant material and using it to produce a hydrocarbon fuel. Of the two, the latter is more efficient and much less harmful to the environment. Synthesis gas, or syngas, is produced by heating biomass in a reaction vessel and injecting steam. It can be used as a stand-alone fuel or, as its name implies, to synthesize other chemicals and fuels. The reaction is an energy- and water-intensive process that can also leave behind large amounts of carbon in the form of unprocessed lignin.

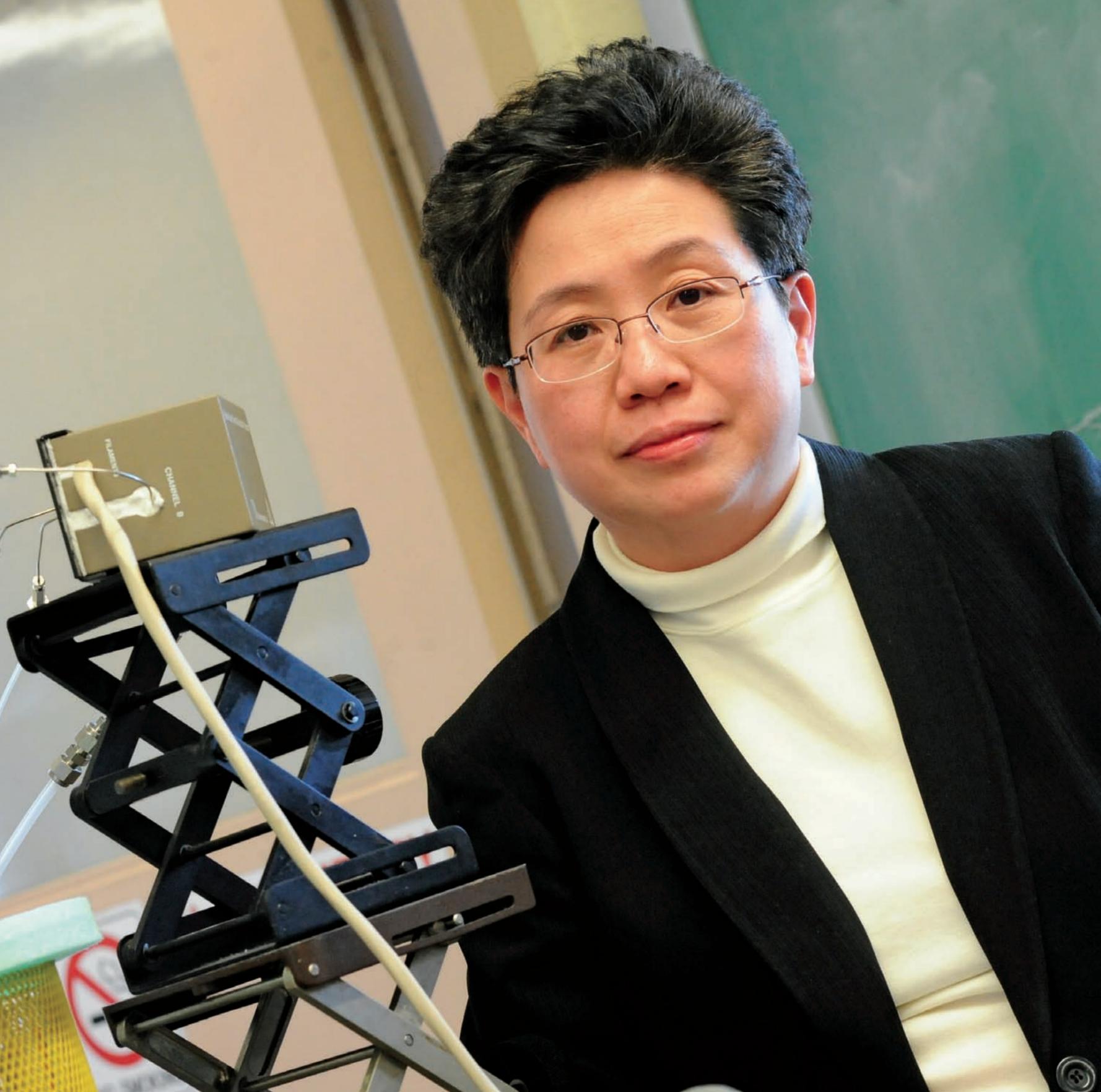
Five years ago, Castaldi began investigating what would happen if he reused some of the carbon dioxide generated during syngas production by pumping it back into the reaction chamber. When he did, he discovered that the carbon dioxide reacted with the biomass resulting in higher efficiency. He also found that replacing about 30 percent of the steam with carbon dioxide reduced water usage and converted all of the biomass to syngas, leaving behind only a carbonless char.

Castaldi estimates that if the biomass were used to replace 20 percent of existing demand for transportation fuels, 1.4 billion tons of carbon dioxide would be kept from the atmosphere. Incorporating carbon dioxide into the fuel-making process would increase this to more than 1.8 billion tons—the same as removing 308 million vehicles from the roads.

“This is what engineering does best,” said Castaldi. “Developing processes that can extract value from unwanted materials—to help make the world a better place.”

*B.S., Manhattan College, 1992; M.S., University of California-Los Angeles, 1994; Ph.D., UCLA, 1997*





Polycrystalline materials are ubiquitous in all engineering structures and devices. Any two misaligned grains in these materials form a planar defect called a grain boundary. Boundaries can trap electrons in certain devices and can also demonstrate novel properties depending on the particular geometric misalignment, such as in superconducting oxides in regard to electrical transport. But that geometric misalignment is not the same between any two grains, even of the same material, making grain boundaries and interfaces among the least understood in materials science.

Identifying boundary types that have similar electrical responses has important relevance for next-generation technology like high temperature superconducting quantum interference devices (squids) for magnetic cardiograms and rare mineral explorations. Also, identifying chemical additions that can improve certain properties at boundaries has important implications; consider how adding manganese to steel in order to abate its brittleness could have changed the story of the Titanic. Already special boundary engineering has enabled zinc oxide varistors as surge protectors; positive temperature coefficient materials for temperature-activated switches; and new thin film transistors.

Siu-Wai Chan has focused on a systematic study of grain boundaries and interfaces relating their geometric structure, chemistry, and energetics with their electrical properties. Her research activities include the study of grain boundaries and interfaces in metals and oxides, particularly the fast ionic conductors and YBCO, a high-temperature oxide superconductor. She has placed emphasis on isolating and examining particular boundaries and their structures via high-resolution transmission electron microscopy (TEM) and measuring electrical properties via scanning squid microscopy. She has also developed methods to increase twin boundary density in superconducting oxide wires pinning magnetic flux lines and increase their super-current capacity.

Current research involves oxide crystallites with special metal additions as catalysts. Many researchers propose that the boundaries and interfaces exist in these catalysts play special roles in stabilizing the nanostructure and promoting reactions. Her early work on grain rotations explains accelerated grain growth in nanoparticles and thus reduced effectiveness as catalysts. These nanocrystals prepared in a single size and shape will be used to investigate optimization of catalytic reactions with crystallites of special shape and size. She investigates certain surfaces as active catalysts using scanning tunneling microscopy and spectroscopy and is exploring new techniques such as in-situ TEM applied to crystallites to look at their reduction and oxidation as they occur to lend insight into catalysis mechanism. She has five U.S. patents.

*B.S., Columbia, 1980; Sc.D., Massachusetts Institute of Technology, 1985*

## *Investigating the Magical Properties of Grain Boundaries and Interfaces*

**SIU-WAI CHAN**

Professor of Materials Science  
and of Applied Physics and  
Applied Mathematics

*Repairing the Microbial  
Nitrogen Cycle*

**KARTIK  
CHANDRAN**

Associate Professor of Earth and  
Environmental Engineering

Not everyone can lay claim to having helped found a new field of study or to having a unit of measurement named after them. Kartik Chandran can, but he tends not to. In fact, he'd prefer not to talk about either, except that the subject is very important these days.

Chandran focuses on the influence of nitrogen on global climate and the biosphere. As  $N_2$ , nitrogen is a largely non-reactive, but crucial, part of Earth's atmosphere. As nitrous oxide ( $N_2O$ ), it is one of the strongest greenhouse gases. As nitric oxide (NO), it plays a role in ozone depletion and, at the molecular scale, in promoting resistance to anti-microbial products. Both can be formed in the process of wastewater treatment.

"We'd ideally like to convert everything to di-nitrogen gas," said Chandran. "But if we don't engineer bioreactors well, we'll just end up impairing air quality and possibly creating robust microorganisms."

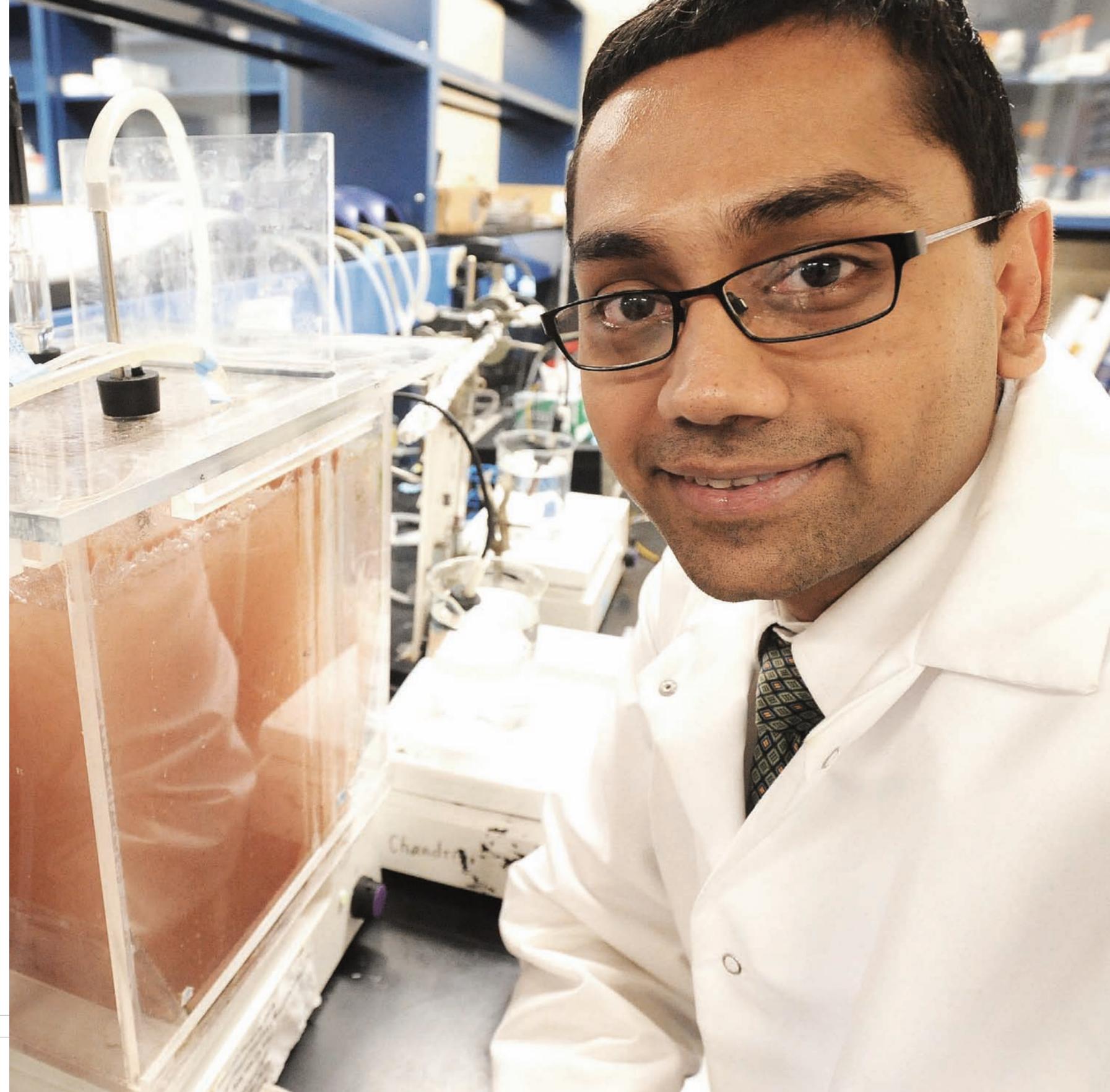
Ideally, household and industrial wastewater is treated to convert nitrogen-containing compounds to  $N_2$ . However, the U.S. Environmental Protection Agency estimates that improper treatment methods lead to the accidental release of 24,000 tons of nitrous oxide in the U.S. alone each year. Because the gas is more than 300 times more effective at trapping heat in the atmosphere, the combined effect is equivalent to having more than one million extra cars on the road.

Nitric oxide is a byproduct of faulty or improper wastewater treatment. In the atmosphere, it converts to nitrogen dioxide, a major component of ground-level smog in cities. It also has the surprising property of helping microorganisms "learn" to become resistant to the human immune system and, potentially, to antibiotics such as tetracycline.

The obvious need for continued treatment of wastewater coupled with increasing concerns over the impacts of improper treatment have led to efforts by Chandran and others to launch the new field of azotomics, which examines the microbial structure and function of the global nitrogen cycle. In addition, Chandran's work has resulted in a new unit of measure, the Chandran number, which describes the propensity of microbes to produce nitrous oxide.

"We are going to be dealing with wastewater treatment and nitrogen pollution for a long time," said Chandran. "By improving understanding of the molecular mechanisms of the microbial nitrogen pathways and coupling that with new engineering tools, we can tackle these issues in a better fashion than we have been thus far."

*B.S., Indian Institute of Technology (Roorkee), 1995; Ph.D., University of Connecticut, 1999*





## *Harvesting Energy Via Nanomechanics*

# XI CHEN

Associate Professor of  
Earth and Environmental Engineering

Every day around the world, an enormous amount of energy is wasted during power generation. The efficiency of fossil fuel power plants is about 40 percent and that of solar panels 25 percent, with the majority of the chemical and solar energies lost as low-grade heat. While scientists work on producing low-cost, efficient “clean” energy, 70 percent of the United States still relies on traditional carbon-based power and it is clear that, over the next few decades, we will still have to live with these traditional energy sources.

One researcher who may have found a way to harvest some of this lost energy through nanomechanics is Xi Chen. He is working with nanoporous materials, including nanoporous carbon, silica, and zeolite, materials that are readily available and low-cost, to convert ambient thermal or mechanical energy to electricity. The ultra-large specific pore surface area provides an ideal platform for energy conversion that yields unprecedented performance.

Chen has coupled nanoporous solids and functional liquids to create a multifunctional nanocomposite. “Depending on the combination of the solid matrix and liquid filler, the thermomechanical and electrochemical processes amplified by the large surface area may enable high efficiency energy conversion among mechanical, thermal, and electrical energies,” he said.

The nanocomposite can simultaneously harvest electricity from the ambient low-grade heat and/or mechanical motions. Significant power output—many times higher than other energy-harvesting materials—has already been successfully demonstrated by his group. Chen envisions that the integration of such a system into existing power plants would be relatively simple, requiring no major change, and the nanocomposite would generate “recovered” power as inexpensively as several cents per watt. He is currently in talking stages with several companies for implementing this technique.

Chen is also looking ahead, “not so far into the future,” he said, to multifunctional nanocomposite materials that could have broad, almost mind-boggling impacts: things like self-powered liquid armor that not only protects soldiers but also alleviates their battery needs, impact/blast-resistant skin for vehicles or aircraft whose shape will also morph to perform optimized functions, self- and wirelessly-powered sensors, among others. With these wide potential applications in aerospace, military, national security, and consumer areas, Chen is at the frontier of generating building blocks of intelligent materials for a smarter and more sustainable planet.

*B.E., Xi'an Jiaotong University (P.R. China), 1994; M.E., Tsinghua University (P.R. China), 1997; S.M., Harvard, 1998; Ph.D., Harvard, 2001*

# PATRICIA CULLIGAN

Professor of Civil Engineering  
and Engineering Mechanics

In 2009, the American Society of Civil Engineers gave the country's water and sewage treatment, energy, and transportation backbone a barely passing grade of D, citing long-overdue maintenance and lack of much-needed upgrades. Patricia Culligan believes she can begin to address some of these inadequacies by changing the way engineers design infrastructure. At the same time, her work may help improve conditions for millions around the world living in rapidly growing urban slums who lack basic services.

Culligan would replace or augment these with smaller, more decentralized systems and facilities that can either meet the needs of a fast-growing population or help take the strain off an existing, aging network. One way is studying the role of small-scale infrastructure projects by examining the effectiveness of green roofs—flat roofs covered in a thin layer of vegetation—to cool buildings and reduce or mitigate storm runoff that flows from buildings into overburdened water treatment facilities.

Despite their growing popularity, Culligan has found that many arguments in favor of green roofs are lacking. "A lot of the claims being made are simply not proven," she said. "If this is going to work, there needs to be a scientific rationale behind it."

Culligan began her career studying the transport of chemical and radioactive contaminants through porous media such as soil, fractured rock, and ocean sediments, and later focused on mitigating contaminated groundwater. Since green roofs contain a thin layer of porous media through which water passes before being taken up by the plants or released, it was a natural segue to quantifying the technology's function and effect.

Old wastewater treatment systems in places such as New York City are routinely overwhelmed by street and building runoff, resulting in millions of gallons of raw sewage being dumped in local waterways each year. Green roofs may help absorb some of the runoff.

Columbia has seven green roofs, many of which Culligan and her colleagues have instrumented to study heat and fluid flows through the system. But the heart of the local green roof movement is the South Bronx, where many neighborhoods, finding themselves politically isolated, have begun to look for their own community-based solutions to such socially complex problems as environmental pollution. For this reason, Culligan has made community partnerships and interdisciplinary research the core of her approach.

"Our work is about giving people a better life," said Culligan. "It's about helping society prosper."

*B.Sc., University of Leeds (England), 1982; M.Phil., University of Cambridge (England), 1985; Ph.D., University of Cambridge, 1989*





**G**autam Dasgupta has been working on a wide range of basic engineering problems that span from analytical formulation and mathematical modeling to practical applications. His work in classical civil engineering focuses on analyses of safe but economical design-analysis, such as the dynamic response of nuclear power plants in conjunction with the outwardly radiating waves generated at the soil interface under the action of earthquake excitation, and the effects of acoustic vibrations created by ocean waves on submerged or floating structures, initiating excessive material degradation and damage. He has also worked with spacecraft engineers, dentists, anthropologists, and historic preservationists. The common thread of his research is to relate the force and deformation of real-world systems. His personal interests are reflected in his research applications in computer music and computer-aided graphics.

Dasgupta focuses on research in engineering mechanics. The major objective is to relate the forces (causes) and changes of shapes and sizes (effects) in the real world of uncertainty. Thus his stochastic (models based on probability and statistics) were used by the NASA Glenn Research Center in Cleveland, Ohio, (then NASA Lewis Research Center) in the 1980s to analyze the damage in the main engine turbine blades of the space shuttles. His high-accuracy finite element formulations have been used since the 1990s to analyze the changes in facial bones, including the shape of teeth, as clinicians perform corrective surgery on patients.

Basic engineering mechanics also focus on material properties that change with time under sustained static loading or dynamic impact. The subsequent shape and size changes, which are studied under viscoelasticity and plasticity, have been adapted to computer simulations. Dasgupta derived important theorems for such changes that can vary with frequency and are different in different directions of deforming bodies. In conjunction with his defect-free (finite element) numerical models (of extremely low error), he proposed very large-scale simulations of crash tests for super computers. In order to minimize computing time, a large part of the calculation is carried out algebraically. This led to Dasgupta's development of symbolic computer programs to derive equations and generate conceptual (elegant) codes for numerical execution in a parallel computing environment.

Dasgupta is working on 3D analyses and computer code generation of incompressible fluids and solid mechanics modeling of complex surfaces and solid objects with zones of mechanical failure to be applied in a wide class of applications ranging from blood flow to the cooling mechanism of wind turbines.

*B.Engr., University of Calcutta (India), 1967; M.Engr., University of Calcutta, 1969; Ph.D., University of California-Berkeley, 1974*

*Relating Forces to  
Real-World Systems*

## GAUTAM DASGUPTA

Professor of Civil Engineering  
and Engineering Mechanics

*Quantifying Uncertainty  
in Infrastructure Studies*

**GEORGE  
DEODATIS**

Santiago and Robertina Calatrava Family  
Professor of Civil Engineering

**D**o you ever wonder, as you drive across a suspension bridge, whether anyone really ever checks the bridge's cables? Or what might happen if you are in a building when the ground beneath it starts to tremble during an earthquake? George Deodatis has made numerous contributions in the general field of probabilistic mechanics: the reliability and safety analysis of structures, risk assessment, and risk management of civil infrastructure systems, earthquake engineering, and hazards analysis.

One of his current research projects deals with the monitoring and prediction of the safety of aging suspension bridge cables, with New York City's Williamsburg Bridge as one of his models. He is using stochastic field theory to deal with the various uncertainties involved in the problem of estimating the strength of the thousands of wires (several of which can be broken) contained within a suspension cable. His results are already helping to assess the current safety and future reliability of suspension bridges around the world.

Deodatis is also studying the effect of climate change on the civil infrastructure. "This is a problem of truly major societal significance," he said. "For example, how is sea-level rise—in combination with hurricanes—going to affect densely built coastal megacities?" He is working on this challenging problem, which involves a wide range of difficult-to-quantify uncertainties, with the ultimate objective of estimating the consequences of climate change and suggesting a wide range of mitigation measures.

Another important application of stochastic field theory that Deodatis is working on has to do with soil liquefaction, a destructive phenomenon that occurs during earthquakes, causing major structural damage, and with bearing capacity of soils, another phenomenon with major impact for the behavior of a wide range of structures on relatively weaker soils. "We are hoping to account for the inherent uncertainty of the soil mass," said Deodatis. "Learning more about these phenomena should lead eventually to improved mitigation strategies."

Deodatis is currently finalizing a book with Cambridge University Press about "Simulation of Stochastic Processes and Fields" in which he develops the theoretical foundations as well as the corresponding simulation formulas for a broad array of stochastic processes and fields. There are numerous applications of these theories in various fields of engineering and applied science, including earthquake engineering, wind engineering, micro- and nano-mechanics, offshore engineering, environmental engineering, materials science, atmospheric science, oceanography, finance, and many others.

*B.S., National Technical University of Athens (Greece), 1982; M.S., Columbia, 1984;  
Ph.D., Columbia, 1987*





**M**ining and mineral processing have occurred since the earliest times, producing materials for the manufacture of all types of useful objects, devices, shelter, and infrastructure. Half a century ago, it became paramount to mine and process minerals while protecting the environment and insuring the sustainability of Earth's resources.

Today, the multinational extraction and processing industry is making another step toward sustainability by refining present technologies that often result in waste. This waste can be commercially costly and environmentally hazardous when released into the air, ground, and water; in addition, significant amounts of minerals or metals can be lost to waste. The industry's goal is now to devise new reprocessing, recycling, and protection methods that comply with demands for responsible and sustainable business practice which could also turn hazardous waste into a profit generator.

Paul F. Duby is a prominent researcher in the areas of applying electrochemical principles and technologies to improve and design new mineral processing protocols. Examples of his and his students' work include a patent on fuel-assisted electrolytic metal extraction that lowers energy consumption and carbon dioxide emissions; a process to remove heavy metals and other contaminants like arsenic from sediments or from wastewaters; a recycling method that uses electrolysis on industrial waste to recover heavy metals and solar cell material; and a chemistry modification that improves hydrometallurgical processes.

His contributions to the reduction of energy consumption include the use of more efficient anodes for the production of metals in aqueous solutions and the electrolysis of mixtures of molten chlorides for the production of heavy metals or rare earths. The modeling of a hybrid system consisting of a high-temperature fuel cell and gas turbines that converts about 75 percent of the low heating value of natural gas to electric energy is an example of improvement of the efficiency of a power plant.

Corrosion and the resulting degradation of materials properties are natural processes that affect sustainability. Professor Duby has contributed to a better understanding of corrosion typically found on super alloys used on plane engines and steels for non-traditional power plants, and was part of the consulting faculty engineering team that designed and supervised the testing of and development of a rehabilitation and maintenance program for the Williamsburg Bridge in New York City.

*Ingénieur Civil Mécanicien et Electricien, Free University of Brussels (Belgium), 1956; Ingénieur Commercial, Free University of Brussels, 1958; Eng.Sc.D., Columbia, 1962*

## *Driving Efficiency and Sustainability into Materials Processing and Energy*

**PAUL F. DUBY**

Professor of Earth and Environmental Engineering

*Mathematically Modeling  
the Behavior of the Ocean*

**VINCENT  
DUCHÊNE**

Ju Tang Chu and Wu Ping Chu  
Foundation Assistant Professor of  
Applied Mathematics

The ocean is a vast frontier that has fascinated mankind for centuries. But as much as we think we know about it, much more is mysterious. Consider the phenomena of internal waves. When two or more layers of ocean water—like fresh and salt water, or warm and cold water—rest one on top of the other without mixing, waves form between the two layers. This wave energy forms and dissipates, affecting everything from ships and submarines, drilling rigs and undersea cables, and the ecosystem of the ocean.

Studying waves on the surface of the ocean—where their formation and dissipation can be easily observed—is one thing. Trying to understand what happens below depths at the interfaces of water layers is almost impossible because measurement techniques are limited and available data are sparse.

By developing mathematical models to study the propagation of internal waves, scientists can numerically compute and study the behavior of hidden waves in relation to different parameters like depth and fluids densities. By applying that knowledge to oceanic fluid mechanics, new models can be constructed to improve our understanding of the effects of these waves and the energy they generate.

With that understanding, the design of marine structures and ships can be improved and the results of how pollutants mix and percolate to the depths of the ocean can be better monitored.

Vincent Duchêne develops mathematical models that seek to explain oceanographic challenges, especially those regarding the behavior of density-stratified flows constituted of two immiscible fluids influenced by gravity. He has been successful in producing and rigorously justifying models related to the dead water phenomena by reproducing the phenomena's key aspects which include generation of transverse internal waves at the rear of a body while moving at the surface of stratified flows and the positive drag on a body when an internal elevation wave is located at its stern. These models allow scientists to study the behavior of internal waves in relation to different parameters like the depth of the layers, densities of the fluids, and velocity of a ship.

Duchêne's other research interests include understanding problems related to the propagation of light through photonic crystals and partial differential equations with particular emphasis on hyperbolic equations.

*Ancien élève, École Normale Supérieure de Lyon (France), 2007; M.S.C., Université Bordeaux 1 (France), 2008; Ph.D., Université Pierre et Marie Curie (Paris VI), 2011*





Clean drinking water is something most of us take for granted. But many people around the world do not have access to clean water and the problem is only going to get worse in coming years, as populations increase and the water supply becomes more scarce. Researchers, including Christopher J. Durning, are working on improving the decontamination of water, in particular on developing ways—at lower cost and using less energy—to safely use wastewater and to desalinate sea and brackish water.

A current project Durning is working on is developing better filtration membranes for both the reuse of wastewater and the efficient desalination of sea and brackish water. In a project funded by the Pall Corporation, a leading manufacturer of water purification systems, Durning and his team are modifying the surfaces of ultra-filtration membranes with ultra-thin polymer/nanoparticle coatings to enable nanofiltration (NF) and/or reverse osmosis (RO) performance. “This surface modification method we use, layer-by-layer deposition, is a directed self-assembly process, and provides outstanding control of the surface layer architecture and chemistry,” said Durning, adding that the resulting new NF and RO membranes will expand the range and capability of membranes useful for production of potable water via wastewater treatment and desalination. “Our aim,” he said, “is to contribute relevant technology for the impending ‘water crisis.’”

Durning’s research focuses on exploiting “soft” materials in a variety of new applications through their manipulation at the nanoscale. This requires an understanding of the key factors that control their structure and dynamics. He studies transport and diffusion, surface and interfacial behavior in polymeric systems, and self-assembly processes in soft matter systems. He is particularly interested in nanostructured materials, which he says offer unique advantages in many applications, such as high-capacity magnetic storage media, ultra-small photonic and electronic devices, graded layers and films for super-mirrors and notch filters, and “labs-on-a-chip.”

He and his team are currently working to develop new ways to generate nanostructures, such as well-ordered arrays of nanoparticles and nanorods, via supra-molecular chemistry and self-assembly. They are also working to exploit established self-assembly methods, to provide new materials, such as nanocomposites, nanoporous solids, and structured surface coatings, that help address compelling technological problems, such as natural gas refining, fuel cell development, water purification, and toxin detection.

“It’s very satisfying to see what starts as an esoteric basic finding develop into a practical solution for an important technological problem,” said Durning. “It is especially exciting that our work in membrane science could help supply one of the world’s most basic needs—clean drinking water.”

*B.S., Columbia, 1978; M.A., Princeton, 1979; Ph.D., Princeton, 1982*

## *Using Nanomaterials to Filter Clean Drinking Water*

# CHRISTOPHER J. DURNING

Professor of Chemical Engineering

*Predicting Droughts  
and Floods*

## PIERRE GENTINE

Assistant Professor of Earth and  
Environmental Engineering

Climate change has brought increased concern over the rise of extreme weather events around the globe. Water resources are fundamentally impacted by climate change with more regions of the world affected by extreme weather, such as droughts. Incidents of heavy rain leading to flooding have increased as well.

Such events can have far-reaching effects on human health, the environment, and our society. The growing prevalence of drought conditions increases the risk of water shortages and wild fires as well as water- and food-borne diseases. Heavy precipitation affects the quality of surface and groundwater, can contaminate the water supply, and cause substantial disruption to settlements, commerce, and the infrastructure that sustains these communities.

Pierre Gentine studies the relationship between hydrology and atmospheric science, and its impact on climate change. His research began in Morocco from 2002 to 2004 as an engineer with the French space agency. There, he studied hydrology in a semi-arid region—a transition between the desert and a vegetated region.

Based on the data collected during those years, he has developed simple models to understand the hydrological cycle and the link between water resources and climate change. While other scientists are analyzing huge data sets in supercomputers, Gentine's models are simplified, to explain what's happening in the global climate in broad terms.

Gentine's research focuses on land and atmosphere interactions and the inherent feedback between the two systems. The overall motivation of his work is to improve the estimation of evaporation over land, which in turn improves water resources management, weather, and climatic forecasts.

"The Sahara desert was once green, some centuries ago, and is now totally dry," Gentine said. "We expect these semi-arid regions to evolve in the same way."

His scenarios predict more extreme weather—drier in places now experiencing drought, and wetter in regions beset with floods. In dry regions, increasing temperatures will make the soil even drier, which will stress vegetation, and result in less transpiration into the atmosphere. That, in turn, will lead to less rainfall. "With this feedback loop, the phenomena become worse," he said.

It's just the opposite in areas now experiencing higher than normal rainfalls, which has led to extensive flooding. Warm temperatures will increase humidity, and water from the soil will evaporate, putting more water into the atmosphere, creating the likelihood of even more precipitation.

*B.S.c., SupAéro (France), 2002; M.S., Massachusetts Institute of Technology, 2006; Ph.D., MIT, 2009*





## *Collecting Solar Energy with Nanomaterials*

### TONY HEINZ

David M. Rickey Professor  
of Optical Communications  
and Professor of Physics

The amount of energy from the sun that falls to the earth far, far exceeds our demand for energy. Sunlight would surely be of broad use in today's world if we could capture and convert it into electricity sufficiently, efficiently, and economically. The conversion of light to electricity is carried out in photovoltaic devices or, as they are known more commonly, solar cells.

These devices are typically made from silicon. Silicon, the basis for electronic circuits, is in many ways an excellent material. However, the basic properties of electrons in silicon imply that more than two-thirds of the incident energy will necessarily end up as heat rather than as electricity. Is there a way to avoid this energy loss and increase the efficiency of photovoltaic devices?

Tony Heinz is working to revolutionize our understanding of energy-conversion processes and the practical production of electricity from sunlight. He is exploring a new energy-conversion process, in which a single absorbed photon creates two or more electronic excitations. This process, Multiple Exciton Generation (MEG), is weak in conventional semiconducting materials, but Heinz is convinced that it will work with the right materials—novel nanoscale materials.

Heinz and his collaborators are making such structures—individual nanoscale photovoltaic devices based on carbon nanotubes and other tailored nanoscale materials—in which these ideas can be rigorously tested. He said that both the electrical and optical measurements require experimental advances. The program builds on recent progress in extracting photogenerated charges from individual carbon nanotubes and indirectly measuring the amount of light absorbed by such tiny structures through the use of new laser-based techniques.

“This is a very exciting fundamental scientific issue that goes to the core of understanding how light interacts with electrons in solids,” said Heinz. “At the same time, it is a problem with the potential to have an important impact on addressing the world's needs for sustainable energy.

“As part of the Energy Frontier Research Center recently established at Columbia University with the support of the U. S. Department of Energy, we have the good fortune of being able to pursue these fascinating questions,” he said. “At Columbia, we also benefit from an excellent collaborative research environment. This allows us to bring together the diverse expertise in science and engineering disciplines that is indispensable for progress in attacking these demanding problems.”

*B.S., Stanford, 1978; Ph.D., University of California-Berkeley, 1982*

*Tuning Nanomaterials  
for a Better World*

## IRVING HERMAN

Professor of Applied Physics and Applied  
Mathematics

Nanomaterials are viewed as a key part of 21st century manufacturing, with tiny particles whose properties change, depending on their size and shape, and how they are manipulated during the manufacturing process. Applications have already been seen in electronics, pharmaceuticals, and food products. Nano-sized structures can be built in different ways, with pre-selected properties.

For example, nanocrystals, which are intermediate in size between molecules and bulk crystals, emit more blue light when they are successively smaller, due to quantum mechanical effects. Creating such effects becomes more complex when working with assemblies of various nanocomponents

Irving Herman's research focuses on the fundamental aspects of matter and nano-science. His work involves the assembly of nanomaterials from nanocomponents, as well as the investigation of the optical and mechanical properties of new materials composed of semiconductor and metal-oxide nanocrystals. His work has potential applications in harvesting light for solar cells, improving electrical and optical communications, and manufacturing products containing nanomaterials.

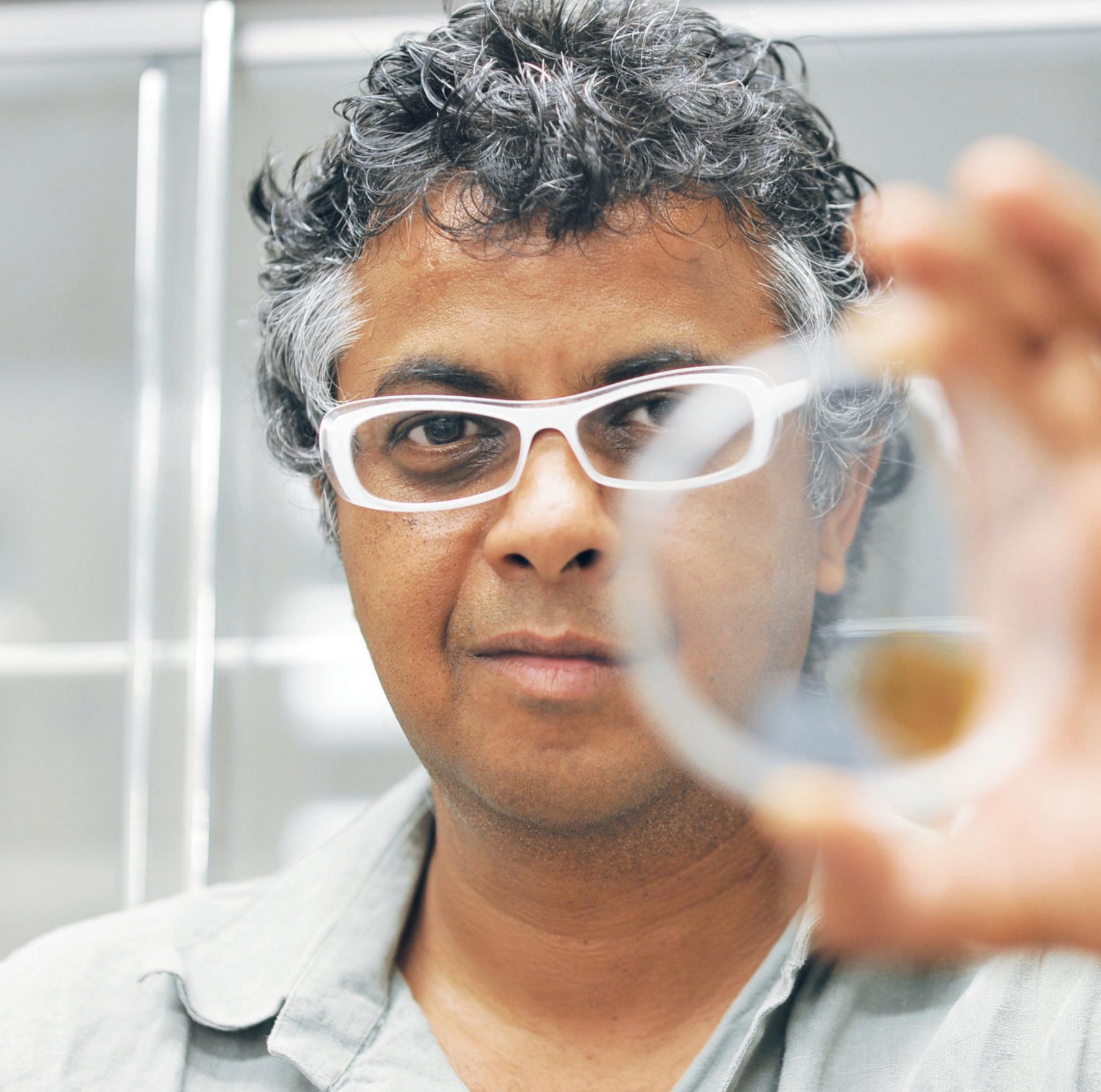
In one project, Herman synthesizes nanocrystals made of cadmium selenide or iron oxide, and assembles them with electrical fields to create materials that have properties in the nanomaterial intermediate-size range. This technique allows scientists to "tune" the materials to have different properties, based on their size, such as optical properties or magnetic properties. In other projects, Herman assembles three-dimensional arrays of nanocrystals, called supercrystals, which are comprised of many layers of ordered nanocrystals. He also assembles hybrid materials composed of nanocrystals and carbon nanotubes.

Herman's research also looks at the optical properties of these materials—how they absorb light or emit light after it is absorbed, which is called photoluminescence. He uses a process known as Raman scattering, in which the wavelength or frequency of light after it hits matter is discerned, to better understand the nanomaterial's properties. This has allowed scientists to couple nanocrystals and other nanocomponents to form nanomaterials. He has used Raman scattering to investigate strain and mechanical properties of nanocrystal films, which helps determine the integrity of products containing nanomaterials.

In addition, Herman teaches a course to Columbia undergraduates, "Physics of the Human Body," which looks at human physiology through the lens of engineering and the physical sciences. His textbook on this subject explains the mechanics of the static body and the body in motion. It also describes the body's materials properties, circulation, breathing, the acoustics of speech, as well as the body's electrical properties.

*B.S., Massachusetts Institute of Technology, 1972; Ph.D., MIT, 1977*





The battery has long been the energy storage device of choice, but limitations persist in life span, storage capacity, and weight. A growing number of researchers—including Sanat Kumar, chair of the Department of Chemical Engineering—are working to make high-energy capacitors (energy storage devices) become a viable replacement in electronics, hybrid cars, and electric power systems.

“Electrical energy is stored by a difference in charge between two metal surfaces, but unlike a battery, capacitors are designed to release their energy very quickly,” he said. Kumar said the objective is to design high-energy capacitors, which would have big impact in industry and the military.

“Such an improvement in the state-of-the-art would have a substantial impact on the Department of Defense, making the move to electrified systems much more practical, for example, for aircraft launchers on ships,” added Kumar. “Further, since we want to use plastics to make these capacitors, it will provide considerable savings in weight, which is highly desirable from a fuel consumption point of view.”

Technological advancements would have an impact on transportation, as well.

“Advanced low-voltage capacitors are needed to facilitate more power-efficient and compact, portable electronic devices for communications, medical applications, and high-power electronics,” he said. Applications include implantable defibrillators and power electronics for power conversion and distribution in hybrid electric propulsion systems.”

The present and future needs do not stop there.

“Advanced high-voltage capacitors are needed for reactive compensation of electric power systems, energy storage, and distribution related to the interfacing of renewable energy sources to the power grid,” said Kumar, “and for energy storage for pulsed power applications such as electromagnetic-based pulse power systems.”

To meet the present and future demand, substantial advances beyond the present state-of-the-art in dielectric materials and capacitor technology are required. At the same time, new technologies will be developed for fabricating compact, high-voltage, high-current, high-repetition-rate capacitors that deliver energy in sub-microseconds.

“We will help to model the behavior of new materials that the group will propose as new capacitors,” he said. “The goal is to design better capacitors from the ground up.”

*B.Tech., Indian Institute of Technology, 1981; S.M., Massachusetts Institute of Technology, 1984; Ph.D., MIT, 1987*

*Storing Energy  
More Efficiently*

**SANAT KUMAR**

Professor of Chemical Engineering

*Producing Organic  
Photovoltaics*

## IOANNIS (JOHN) KYMISSIS

Associate Professor of Electrical  
Engineering

Long before the Gulf oil spill and President Obama's call for new efforts to reduce U.S. dependence on oil, Columbia researchers were working to reduce our dependence on the world's rapidly dwindling supply of fossil fuels. Ioannis (John) Kymissis and his team are working on producing organic photovoltaics that are easier and cheaper to manufacture than solar cells currently on the market.

Photovoltaics, which convert energy from the sun into electricity, have been around for more than 50 years. They are currently used in a variety of applications, such as roadside emergency telephones and traffic signs, and recharging batteries in remotely deployed electronics. Such installations potentially present a number of grid-level advantages in both advanced and developing economies. Distributed power generation through photovoltaics can reduce the load on strained distribution systems and provide power to remote locations where it may be cost-prohibitive or environmentally problematic to run power lines.

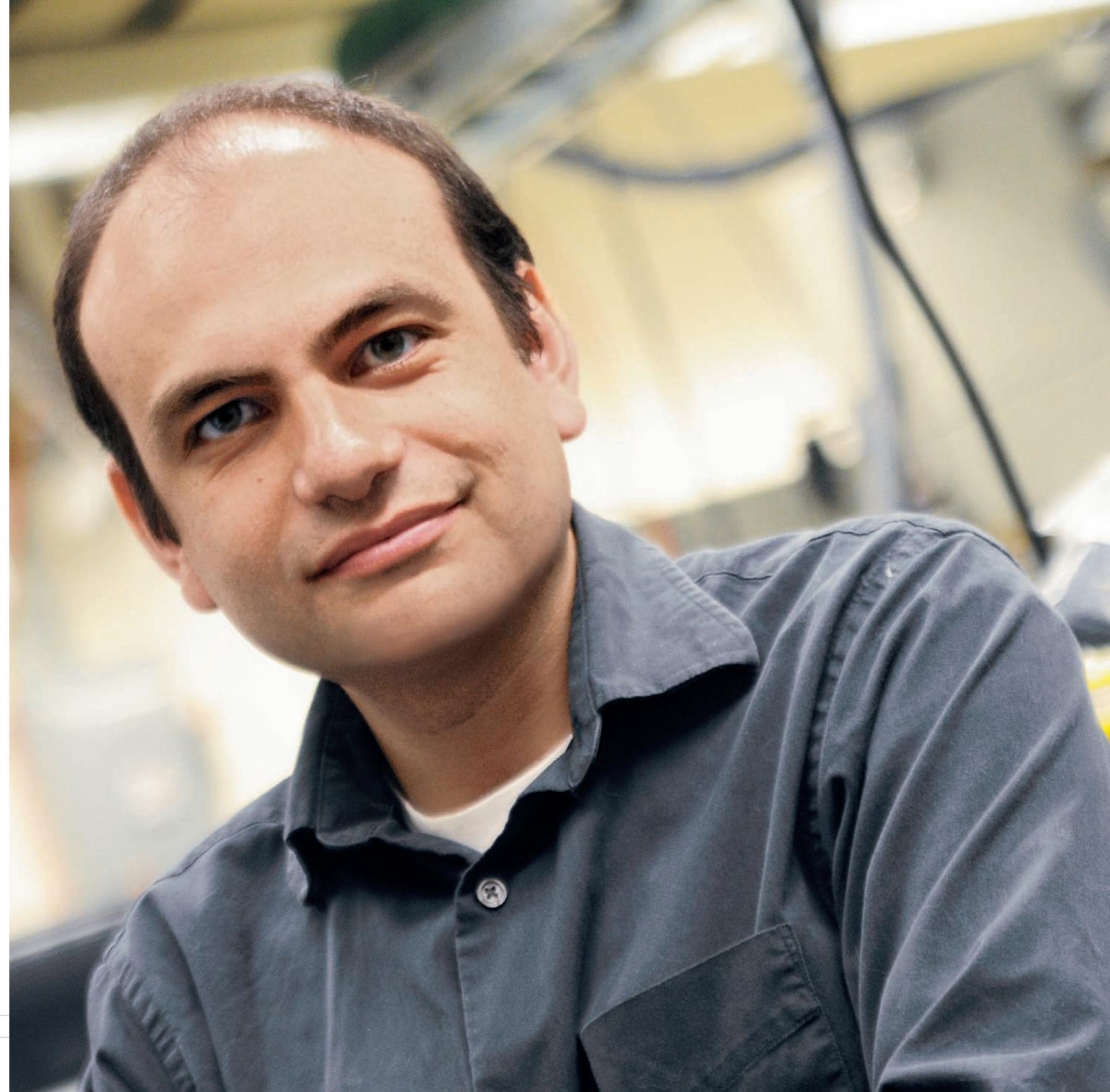
The rate of photovoltaic production has been increasing rapidly—more than 50 percent per year—but photovoltaics are still dwarfed by other sources of energy. Kymissis notes that photovoltaics produced only 0.02 percent of the total energy used in the United States last year; a new approach to photovoltaics is required to meet global energy needs.

Kymissis' team is involved in improving the performance and processability of photovoltaics using organic thin-film semiconductor materials that are elementally abundant, inexpensive to synthesize, and straightforward to deposit in large installations. The team is working on how to improve efficiency, reduce processing costs, improve storage lifetime, and increase the operating lifetime of organic photovoltaic devices.

Kymissis believes that thin-film semiconductors, with their ability to scale to large sizes, can solve a variety of sensing and power conversion problems. His group can fabricate systems that integrate a variety of thin-film devices, including photovoltaics and organic photodetectors, organic field effect transistors, piezoelectric polymer sensors, and organic light-emitting diodes. These integrated devices can be applied to applications in which electronics need to interface with large objects in the real world, such as sensors that can measure sound and airflow over an airplane wing.

"Our children will see the end of petroleum and our grandchildren will see the end of coal," said Kymissis. "It's essential that we start working today to reduce our dependence on finite energy resources to insure a better standard of living for future generations than we have today."

*M.Eng., Massachusetts Institute of Technology, 1999; Ph.D., MIT, 2003*





Engineering and science rely on the ability to make accurate predictions of material behavior in order to create innovative and transforming technological advances. Most properties of materials—such as electric, magnetic, thermal, and optical properties—are sufficiently well understood so that scientists can make meaningful predictions from fundamental principles of physics. Important exceptions to that rule are the mechanical properties of a material. Certain mechanical properties such as stiffness and thermal expansion can be calculated with great accuracy. However, others such as strength, plastic hardening, fatigue limit, ductile-to-brittle transition temperature, and fracture toughness cannot yet be calculated from fundamental principles. Therefore, engineers must rely predominantly on experiments to determine properties when designing new materials for life-critical applications such as those for the aerospace and automotive industries.

The defects of a material determine its interesting mechanical properties. Different types of defects can be idealized as being points, lines, areas, or volumes within a material, and the defect sizes can range from the atomic-length scale to the millimeter-length scale. Further, initial defects in a material create new defects, all of which subsequently move about within the solid and interact with each other in complex and different ways. The conceptual and computational challenges that must be overcome in order to predict the resulting mechanical behavior are daunting. One of the researchers at the forefront of this work to make meaningful predictions of mechanical behavior is Jeffrey W. Kysar.

Kysar's current research is focused on the mechanics and mechanical behavior of materials at multiple scales and under extreme conditions. A second focus is to create new materials that have mechanical properties which interact with other properties, such as optical or electrical, that can be used to make microscale sensors, actuators, and power generation devices.

Kysar was part of the Columbia Engineering team that completed the first strength tests on graphene in 2008, proving it to be the strongest material ever measured. The specimens used in those experiments were sufficiently small so that no defects were present in the material, which is the reason why graphene is so strong. According to Kysar, "The mechanical properties of graphene will enable its use in many new applications that require materials with excellent strength." More practical applications of graphene include use as a transistor that can take the strains of faster microprocessing in computers or as a durable, mechanically operated electrical switch for communications devices, including cell phones and advanced radar.

*B.S., Kansas State University, 1987; M.S., Kansas State University, 1992; S.M., Harvard, 1993; Ph.D., Harvard, 1998*

## *Analyzing Materials Under Extreme Conditions*

# JEFFREY W. KYSAR

Professor of Mechanical  
Engineering

## Creating Artificial Trees

# KLAUS LACKNER

Maurice Ewing and T. Lamar Worzel  
Professor of Geophysics

There are people who think outside the box. Then there are people like Klaus Lackner who throw the box away entirely when they think. While others argue over new ways to reduce greenhouse gas emissions, Lackner has methods process that will, as he puts it, “close the carbon loop” altogether.

“Stabilizing the concentration of carbon dioxide in the air requires reducing carbon dioxide emissions to nearly zero,” Lackner said to a congressional subcommittee recently.

“Think of pouring water into a cup. As long as you pour water into the cup, the water level in the cup goes up. It does not matter whether the maximum level is one inch below the rim or one and a half inches below the rim. In either case, you will eventually have to stop pouring.”

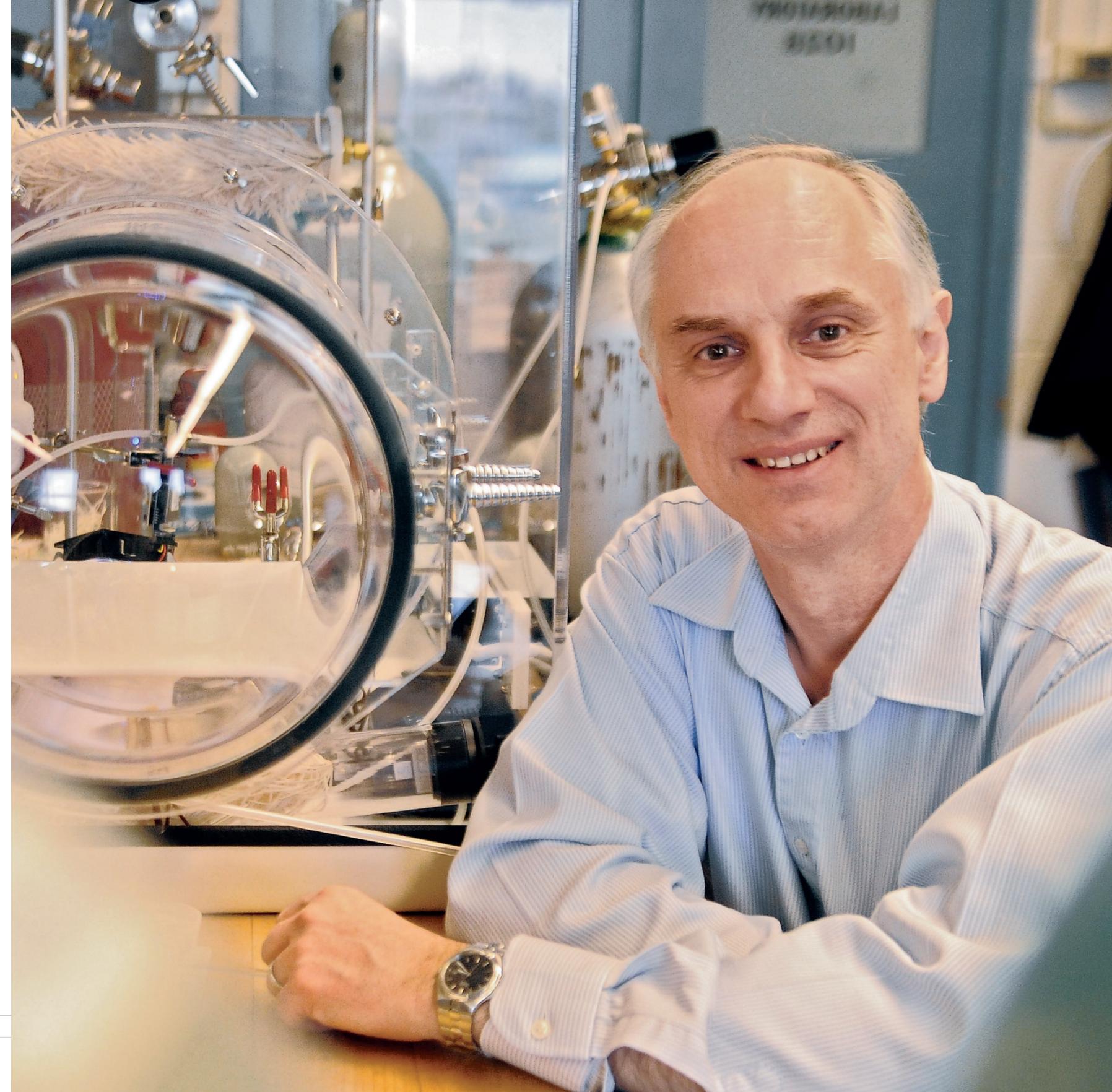
To truly control carbon emissions, we would have to remove carbon dioxide directly from the air. The wind, he calculated, was vastly more efficient at transporting carbon dioxide to a collection device than it is as a means of generating electricity. By capturing the greenhouse gas from the air and locking it away permanently underground as carbonate minerals, it may be possible to fully neutralize the impact of large, concentrated sources of greenhouse gases.

Now Lackner has taken his ideas one step further and is working with Global Research Technologies to create artificial trees that will pull carbon dioxide from the air, just as real trees do. His air capture machines are like giant filters that trap the carbon dioxide that will be later freed and converted into a liquid, such as syngas, synthetic gas that can be used as a fuelstock. Alternatively, it could be disposed of through geologic and mineral sequestration.

Our reliance on liquid hydrocarbon fuels for transportation has led Lackner to search for affordable low-carbon production methods. He and his colleagues at Columbia’s Lenfest Center for Sustainable Energy are looking for ways to apply the benefits of mass production to energy and fuels to drive down costs. In addition, he is taking a serious look at solar power as a way to eliminate carbon emissions from fuel production entirely and bring us closer to achieving a carbon-neutral society.

“Imagine if we decided to solve our garbage problem by putting houses on stilts and raising them a little every year,” said Lackner. “That’s what a lot of geoengineering amounts to, and that’s not a solution to the problem. A real solution will only come by completely rethinking the way we use carbon.”

*B.S., Heidelberg University (Germany), 1974; M.S., Heidelberg, 1976; Ph.D., Heidelberg, 1978*





The *Journal of International Affairs* might seem like an odd place for an engineer to publish, as Upmanu Lall recently did, but this engineering professor is used to addressing big questions with broad reach. Foremost in his mind these days: Will we run out of fresh water in the 21st century?

Since the 1980s, Lall has been focused on how society and water intersect. His interest began when he moved to Texas from his native India in order to study systems analysis and very quickly got involved in one of the most complex systems in the American West: water use. As part of his doctoral thesis, Lall examined the state's future energy and water demands, treating both as parts of one vast, interconnected system with often conflicting parts.

Today, Lall sees a looming global water crisis. In fact, the water crisis, as he sees it, is actually three separate crises—one of access, one of pollution, and one of scarcity—that do not lend themselves to simple solutions. Moreover, each is inexorably linked to the others and to additionally intractable problems like climate change and population growth.

Lall helped found the Columbia Water Center in order to address climate risk management across a range of temporal and spatial scales. “The possibility that North India may run out of groundwater in a decade leading to a collapse of agriculture in India is not viewed as a global problem,” Lall and his co-authors wrote in the *Journal of International Affairs*. “In essence, the global crisis is viewed as a collection of local crises—whether they are related to access, pollution, or scarcity—for which there is a global policy imperative. We rarely address the global elements of these individual problems.”

A key player in the looming water crisis is agriculture, which accounts for 70 percent of global water use on average and more than 90 percent in arid regions. Lall thinks that it should be possible to dramatically reduce regional water use while maintaining food security by improving irrigation systems, irrigation scheduling, and when and where different crops are grown. He also sees room for improving water use by improving food processing, storage, and delivery.

With one-third of the developing world expected to confront severe water shortages in this century, Lall sees a problem that is particularly suited to an engineer's mindset. “The goal of engineering to develop solutions to societal problems,” said Lall, “fits into the domain of engineering better than anything else.”

*B.Tech., Indian Institute of Technology (Kampur), 1976; M.S., University of Texas, 1980; Ph.D., University of Texas, 1981*

## *Solving the Global Water Crisis*

### UPMANU LALL

Alan and Carol Silberstein Professor of Earth and Environmental Engineering and Professor of Civil Engineering and Engineering Mechanics

*Stabilizing the  
Slippery Slope*

## HOE LING

Professor of Civil Engineering and  
Engineering Mechanics

Sometimes the ground beneath your feet isn't as solid as it might seem. For many people living on hillsides and in flood plains or seismically active regions, this can be a deadly fact of life. Hoe Ling literally wants to reengineer the ground to make disasters like the one he surveyed in Taiwan recently a thing of the past.

In 2009 during Typhoon Morakot, more than 450 people died when Hsia-Lin Village in southern Taiwan was wiped off the map by a massive landslide that occurred when rain-weakened hillsides above the village let go.

"When you go to the site of a landslide, you really feel you should do something to help people," said Ling. "There are just too many slope failures."

Every year, nearly 100,000 people around the world die because the ground they are living on or the ground somewhere above them fails. The most common causes are earthquakes and heavy rainfall. In the United States, landslides account for as much as \$2 billion in damages annually.

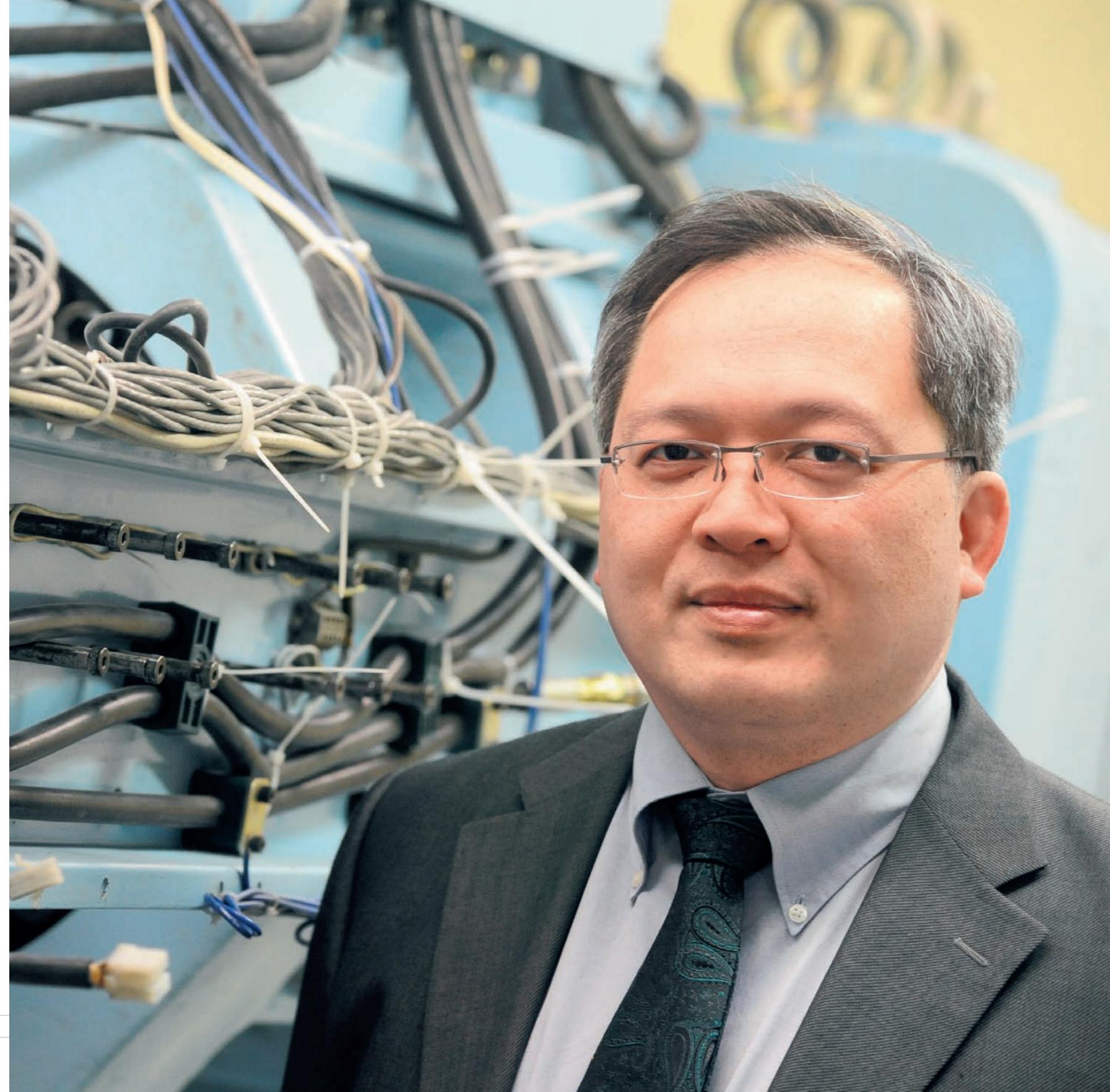
Ling is pursuing two lines of inquiry in order to address the problem. First, he is simulating the effect of heavy rain on soils using the department's geotechnical centrifuge to help model and predict soil and slope failure. Ling has used the instrument, which is one of the largest in the country and can generate a force 200 times that of gravity, to study such things as the failure of New Orleans' levees after Hurricane Katrina.

The other approach Ling takes is to develop geosynthetic materials that help reinforce areas potentially prone to fail. The polymer sheets he has developed are installed between layers of compacted soil to create walls and slopes that stand up to heavy loads and severe shocks such as earthquakes better than soil alone. Because geosynthetic materials don't rot or corrode like wood and metal, they are also more suitable as permanent reinforcing materials.

By combining his work to understand how and under what conditions a particular slope might slip with the application of new materials and techniques, Ling hopes engineers will eventually be able to quickly identify and reinforce high-risk areas. Then perhaps he and millions of others around the world will be able to sleep better knowing that the ground is safe.

Ling received the Career Award from the National Science Foundation in 2001. He has published more than 170 journal and conference papers in the fields of geomechanics and geotechnical engineering.

*B.S., Kyoto University (Japan), 1988; M.S., University of Tokyo (Japan), 1990; Ph.D., University of Tokyo, 1993*





## *Predicting Behavior of Materials*

# CHRIS MARIANETTI

Assistant Professor of Applied  
Physics and Applied Mathematics

**P**redicting the behavior of materials challenges scientists and engineers intent on developing new sources of alternative energy and applications for new materials, such as graphene, the one-atom layer of carbon that researchers say holds promise in a wide variety of applications. The materials used in battery storage are a key part of strategies to exploit renewable resources.

Understanding the behavior of material used in nuclear power and nuclear weaponry is also crucial to their safe storage. Plutonium, an active ingredient in nuclear weapons, has proved particularly challenging. With the international test ban treaty prohibiting experiments, scientists now predict how the materials react with many-body quantum theory, using supercomputers to determine how the electrons within these materials will behave.

“The plutonium in the weapons ages, and we have to be able to predict the properties of plutonium under a variety of conditions,” Chris Marianetti said. “You need the material to be stable and work like you think it will work, and it turns out that it’s difficult to predict.”

Marianetti came to Columbia in 2008. He earned his Ph.D. in computational materials science and engineering at the Massachusetts Institute of Technology, focusing on applying first-principles methods, such as Density Functional Theory (DFT) and Dynamical Mean-Field Theory (DMFT), to energy storage materials.

Marianetti continued on to a postdoctoral position in condensed matter physics at Rutgers University. There, he continued developing/applying DFT and DMFT to strongly correlated electron systems. Following Rutgers, Marianetti moved on to a second post doctoral position at Lawrence Livermore National Laboratory (LLNL) where he utilized LLNL’s world-class supercomputers to apply DFT and DMFT to plutonium.

With an element like plutonium, it can take several weeks to carry out his computations on one of the world’s largest supercomputers. He has made numerous pioneering predictions, including the most accurate computation of the temperature dependence of plutonium’s magnetic properties.

His research has also played a role in understanding the behavior of graphene, the single-atomic layer of carbon whose honeycomb lattice structure is among the strongest ever measured. Graphene, seen as a next-generation material, has many potential uses, from nanoribbons used in integrated circuit connections to transistors that could one day replace silicon, to construction of a tether winding its way through the atmosphere to outer space.

Marianetti’s computations have determined how and why graphene fractures under tension, an important step in determining the limits of the material’s future use.

*B.S., Ohio State University, 1997; M.S., Ohio State University, 1998; Ph.D., Massachusetts Institute of Technology, 2004*

*Containing Hot Plasma  
for Fusion*

**MICHAEL  
MAUEL**

Professor of Applied Physics and  
Applied Mathematics

**S**trong magnetic force fields confine high-temperature ionized gas, called “plasma,” throughout the universe. At the surface of our sun, magnetized tubes of hot plasma, several millions of degrees, are launched with tremendous energy through the solar system. Around the earth, the strong magnetic field that we measure with a compass extends tens of thousands of kilometers into space and forms a protective atmosphere of ionized matter called the “magnetosphere.”

“Scientists have been studying how strong magnetic fields confine high-temperature matter since the dawn of the Space Age,” said Michael Mauel. “Today, a grand challenge of applied physics is to use our know-how of plasma physics to achieve one of the world’s most important technical goals: a source of energy that is clean, safe, and available for thousands of years.”

Fusion energy is the most promising source of energy meeting these requirements. Fusion uses the heavy isotope of hydrogen, called deuterium, to form helium and release huge amounts of energy. Every bottle of water contains enough deuterium to generate the equivalent of a barrel of oil when used in a fusion power source. But a major challenge remains: deuterium must first be heated to the temperature of the stars before fusion energy can be released.

Mauel is building experiments that test whether or not the magnetic fields used to confine high-temperature plasma at the surfaces of stars or in planetary magnetospheres can be used in the laboratory to produce the conditions that will make fusion energy work.

Together with colleagues at Massachusetts Institute of Technology and Professor Gerald Navratil at Columbia Engineering, Mauel builds and operates fusion experiments. These experiments, which have achieved temperatures of more than 100 million degrees, have pioneered numerous techniques for magnetic confinement.

Using these experiments, students and scientists explore how the shape of the magnetic force fields allows the hot plasma to be confined and heated; how the plasma mixes and swirls within the containment vessels; and how sophisticated high-speed control systems maintain the perfect symmetry required to maximize fusion power output.

Mauel has been awarded the Rose Prize for Fusion Engineering and received commendations of appreciation from the United States Department of Energy and Department of State. During the 2006-07 academic year, Mauel was the recipient of a Jefferson Science Fellowship from the National Academies. While at the Department of State, he served in the Office of International Energy and Commodity Policy assisting U.S. diplomatic efforts to promote energy security.

*B.S., Massachusetts Institute of Technology, 1978; M.S., MIT, 1979; Sc.D., MIT, 1983*





As an undergraduate at the California Institute of Technology, Faye McNeill studied the atmosphere for a very personal reason. “The air pollution there was bad,” she said. “I have asthma, so I’m always a little more aware of atmospheric composition just because of the way I feel.”

McNeill is particularly interested in how aerosols affect global climate. Because they are so small, gravity has little effect on aerosol particles and they can remain airborne for several days. Aerosols such as the sulfur compounds and ash emitted by Mount Pinatubo in the Philippines pushed down global average temperatures for two to three years after it erupted in 1991.

Other aerosols can absorb incoming solar radiation or long-wave radiation reflected from Earth’s surface, resulting in a warming effect on climate. The range of direct and indirect, compounding and conflicting effects makes aerosols one of the biggest unsolved problems facing climate scientists.

Aerosols can also have a wide range of chemical compositions, which reflect their diverse origins. Recently, McNeill and her team have focused on understanding the sources and properties of light-absorbing organic material, or brown carbon, in atmospheric aerosols. Often a byproduct of the burning of biomass, it turns out that brown carbon can also form through complex reactions in airborne atmospheric particles.

Brown carbon also interacts very differently with the atmosphere and environment than its inorganic cousin black carbon, and its roles in atmospheric chemistry and climate are just beginning to be understood. For one thing, black carbon tends to absorb radiation across the visible spectrum, but brown carbon preferentially absorbs shorter wavelengths of light and thus can influence the formation of ground-level ozone—the “bad” kind that leads to McNeill’s asthma attacks.

McNeill is focused on the basic chemistry and physics behind the cloud-forming and light-absorbing characteristics of organic aerosols in the lab. She also works with other groups to integrate their piece of the climate puzzle into the big picture, including climate modelers who write the massive, computer-based simulations that attempt to predict how individual parts of the environment interact to govern Earth’s climate.

“A big part of what we do is to communicate the results of our work to modelers,” said McNeill. “The fundamental information we get in the lab will eventually find its way into better climate models.” And that is something that can help us all breathe a little easier.

*B.S., California Institute of Technology, 1999; M.S., Massachusetts Institute of Technology, 2001; Ph.D., MIT, 2005*

## *Understanding Brown Carbon*

# V. FAYE McNEILL

Assistant Professor of Chemical Engineering

## CHRISTIAN MEYER

Professor of Civil Engineering and Engineering Mechanics

One of the world’s most important building materials, concrete, leaves a huge environmental footprint. The production of Portland cement, a basic ingredient of concrete, is estimated to cause the release of one ton of CO<sub>2</sub> into the atmosphere annually. The cement industry alone generates about seven percent of this greenhouse gas across the globe.

But Christian Meyer claims that concrete can be an environmentally friendly material—if, as he puts it, “you use as much concrete with as little Portland cement as possible.” Meyer is at the forefront of the “greening of the concrete industry,” from basic science to commercial production.

He has had great success using recycled materials in concrete, most notably, glass. Early attempts to use post-consumer glass failed because of the alkali-silica reaction, damaging the concrete. Meyer uses various cementitious admixtures as partial substitute of Portland cement, and has shown how colored glass can be incorporated for stunning architectural and decorative concrete applications, including tiles and countertops.

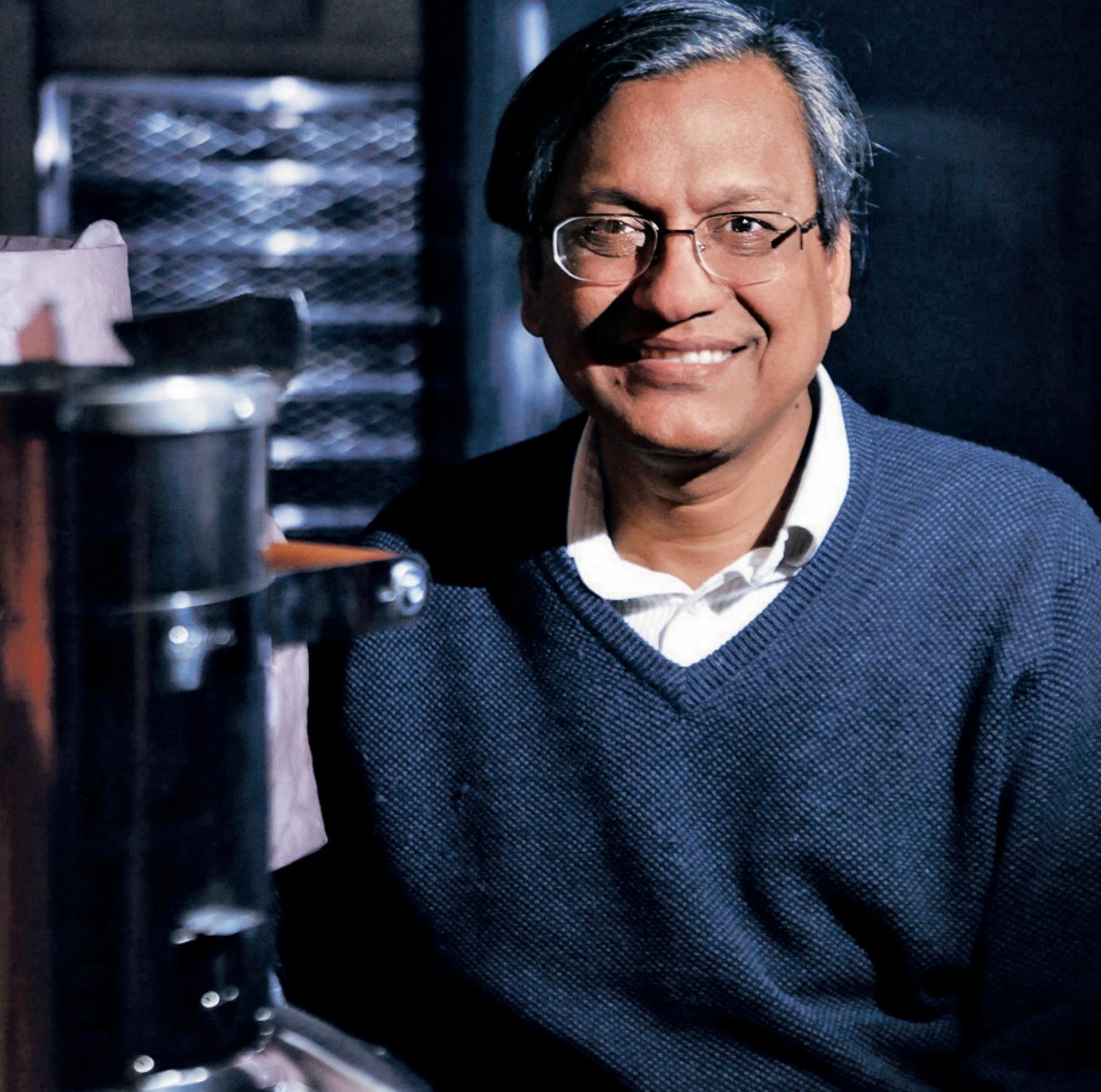
He has added shredded Styrofoam to make lightweight concrete, which has strong insulating and acoustic qualities and is cheaper to transport. He is currently exploring using recycled concrete as aggregate, noting that the United States generates about 150 million tons of construction waste annually and that concrete debris is more than 50 percent of that amount.

Meyer said that a key challenge is to identify special properties intrinsic to recycled materials that can be exploited and thereby generate added value, as in the glass tiles his team has made. He added that the use of recycled materials in concrete is governed by economic factors. “The profit motive is key,” said Meyer. “If people don’t think they can earn a reasonable profit doing something, they won’t do it.” But rather than simply using any waste materials as ingredients of concrete, Meyer prefers to explore how to add value to the various waste stream components and find ways to make better, more useful products while conserving natural resources.

Meyer is also using his expertise in concrete technology to explore ways to safeguard oil wells drilled deep into the ocean floor. He is hoping to develop novel materials that will reinforce the cement slurry with fibers to improve the fracture behavior and energy absorption. A specially developed device to measure the properties of slurries that hydrate under simulated downhole conditions has undergone the first successful tests in the Carleton Laboratory of the Civil Engineering Department.

*Vordiplom, Technical University Berlin, 1965; M.S., University of California-Berkeley, 1966; Ph.D., UC Berkeley, 1970*





Vijay Modi is an engineer in search of problems. That is, he has changed the way he approaches engineering, and in the process, is helping address some seemingly minor challenges that, on further investigation, are extremely complex and can change the lives of a large portion of the world's poor.

"Instead of starting with a particular narrow skill I had and trying to apply it, I'm trying to figure out what the interesting problems are and then seeing how we can bring engineering to bear on them," said Modi. "Sometimes it can be something as simple as creating a solar-powered lighting system that enables people in rural villages to do things after sunset like study or run a small shop."

By taking this bottom-up approach, Modi has discovered that he can categorize the problems he encounters into three groups: those he can make little immediate impact on, those that can have impact but require decades of research to solve, and those he might be able to solve with the help from the right people. It's that last group of problems that has attracted his attention of late.

It wasn't always that way. When Modi arrived at Columbia in 1986, he focused on questions involving fluid flow and heat transfer. Exposure to fellow Columbia Engineering professor Nicholas Themelis, and the Earth Engineering Center soon re-focused his priorities on problems that have fallen through the cracks of the academic community and private sector alike.

"Engineering research carried out in academia has started to lose connection with the profession of engineering, which is about solving problems," said Modi. "What historically separated science and engineering was that science was curiosity driven and engineering was problem driven." But many engineering problems today are inherently multi-disciplinary and require "system" integration.

The key, he believes, lies in assembling people with the diverse skills needed and a desire to apply them. In recent work to understand the problem of electricity access for the two billion who do not have it, Modi's team recognized the importance of allowing a "pay as you go" model for providing electricity from a "system" that did not require long wires from a central power station. The team included engineers who can design low-wattage meters, programmers writing communication, control and payment gateway software, and field practitioners who understand rural needs and capabilities.

Modi has helped design and test solutions to such developing-world problems as the need for a cleaner and more efficient cook stove, and robust IT systems that allow one to access information from remote villages. "These are projects that are not typically driven by large amounts of funding, but they occur in places that are in need of innovation," said Modi. "The key is to figure out how to make innovation happen in a low-tech, low-cost market."

*B.Tech., Indian Institute of Technology (Bombay), 1978; Ph.D., Cornell, 1984*

## *Engineering in the Developing World*

### **VIJAY MODI**

Professor of Mechanical Engineering

*Tailoring Thermal  
Transport*

## ARVIND NARAYANASWAMY

Assistant Professor of  
Mechanical Engineering

Everyone knows that electronic devices can overheat and fail. This is becoming more of an issue as the devices used in our daily lives, from cell phones to laptops, get smaller—the influence of the size-scale effect becomes increasingly important. The ability to extract heat rapidly and efficiently is critical for electronic and optoelectronic devices. Arvind Narayanaswamy is one of the leading researchers studying energy transport in nanoscale structures and devices.

Shrinking a device's size greatly impacts its ability to transport energy, due to classical as well as quantum size effects. Fourier's law of heat conduction, which describes heat transfer well at macroscopic scales, breaks down at nanoscales. So does Planck's theory of radiation, when objects get much closer than a few microns. Recently, researchers, including Narayanaswamy, have discovered that the enhancement in thermal radiative transfer at nanoscale gaps can be utilized to increase the power density of thermophotovoltaic energy conversion devices.

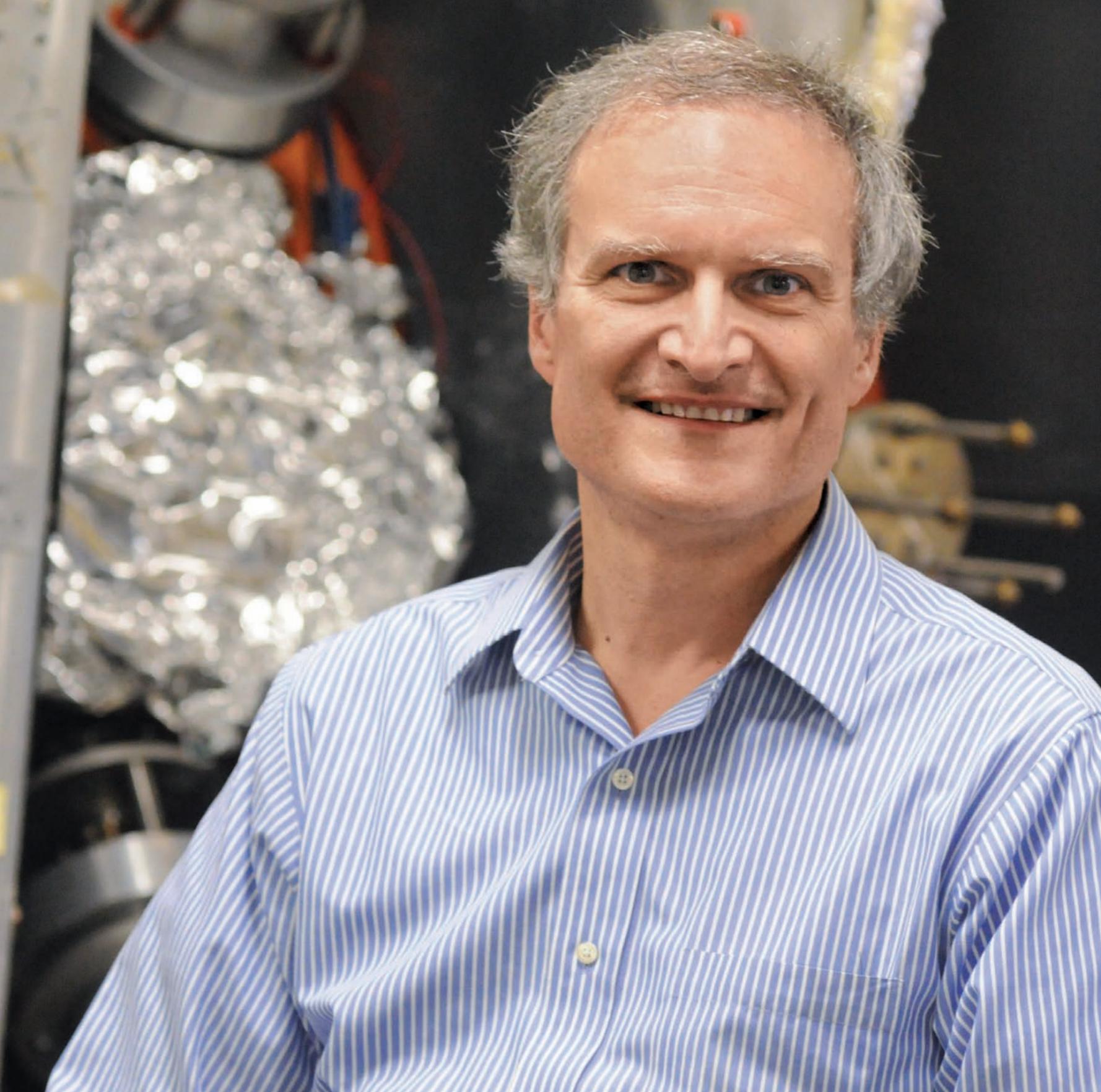
Narayanaswamy's team is addressing two broad areas of thermal transport: nanoscale effects on thermal radiative transfer and thermal transport in nanoscale polymeric materials. His work in radiative transfer focuses on understanding photon transport between nanostructures, and he has shown that by choosing appropriate materials, it is possible to overcome the limit on radiative transfer imposed by Planck's law by a significant amount. While this phenomenon may seem esoteric—most often, heat transfer in nanoscale devices is by thermal conduction—it could have an important impact on hard-disk drive technologies. Narayanaswamy is working with industrial collaborators to ensure that nanoscale thermal radiation does not have a deleterious effect on the performance of magnetic recording devices.

While nanoscale effects on thermal transport in solid-state materials have been well investigated, their influence in polymeric materials is less clear. Polymers are used everywhere, from credit cards and plastic bottles to organic optoelectronic materials. Thermal transport in polymers becomes especially important since they are poor conductors of heat; any means of improving heat conduction through polymers will improve device performance. Narayanaswamy's work focuses on understanding thermal transport in polymeric nanowires synthesized in his lab by different techniques. An important component of his research is technique development to enable measurement of heat transport through single nanowires.

"Our work on nanoscale thermal radiation is very exciting," said Narayanaswamy. "While it will be some time before we can translate our research into applications, the tools we've already developed are helping us start examining thermal transport in polymers. Our discoveries will have immediate engineering implications, especially in electronics cooling."

*B.Tech., Indian Institute of Technology (Madras), 1997; M.S. University of Delaware, 1999; Ph.D., Massachusetts Institute of Technology, 2007*





## *Stabilizing Plasma for Fusion Energy*

# GERALD NAVRATIL

Thomas Alva Edison Professor of Applied Physics and Applied Mathematics

Gerald Navratil is among the world's leading researchers in the field of fusion energy. His findings have been incorporated in the design of ITER, the \$12 billion international experimental fusion reactor project now under construction in France, which is expected to generate up to 500 MW of fusion power after completion of construction by 2018.

"It's a carbon-free way to provide energy, where the fuel sources are unlimited, and there's minimal long-term radioactive waste," said Navratil. "It could be an important part of our energy profile by the turn of the next century."

He conducts his experiments at three tokamaks—a donut-shaped machine that confines the super-hot plasma with magnetic fields. Ideas for experiments on his major projects are generated out of small-scale HBT-EP experiment in Columbia's Plasma Physics Laboratory. He then collaborates with teams of fusion researchers at larger tokamaks, like the DIII-D National Tokamak Facility in San Diego, Calif. and the National Spherical Torus Experiment in Princeton, N.J.

In 2010, his Columbia team on DIII-D was awarded \$1.1 million and his team on HBT-EP was awarded \$3.3 million to continue their work on these projects for three more years. Both projects are supported by grants from the United States Department of Energy.

A crucial issue in fusion energy research involves creating magnetic fields to contain the plasma at high pressure and at temperatures hotter than the interior of the sun. If the confined plasma become unstable, it comes in contact with the cold tokamak walls, loses its energy, and the fusion plasma is extinguished.

Navratil's experiments have focused on understanding the pressure limits of fusion systems. His team has created ways to increase the pressure—and the production of energy in future fusion power plant designs—while keeping the plasma stably contained. His team on DIII-D has been able to double the pressure in fusion systems, which quadruples the fusion-energy output. That's done by rapidly rotating the magnetically confined plasma. This important result was recognized in 2007 with the award to Navratil and his colleagues of the John Dawson Award for Excellence in Plasma Physics Research by the American Physical Society.

Another strategy for extending plasma pressure limits involves developing advanced forms of active feedback-control of the instabilities. That technique was pioneered on the HBT-EP experiment at Columbia, and is now being used in demonstration projects at the DIII-D tokamak in San Diego. Ultimately it will be employed in the operation of ITER in the next decade.

*B.S., California Institute of Technology, 1973; M.S., University of Wisconsin, 1974; Ph.D., University of Wisconsin, 1976*

*Looking at Light*

## RICHARD OSGOOD

Higgins Professor of Electrical Engineering  
and Professor of Applied Physics and  
Applied Mathematics

Sometimes, to solve big problems, you have to think small. Richard Osgood thinks very small. One of the biggest energy questions today is how to make solar cells more efficient and more affordable. This is particularly important for the billion or so people who live in poverty and, in most cases, entirely off the grid.

Osgood and the other members of the Surface Group in his Research Laboratory for Fundamental and Applied Science study the basic processes that allow some materials to convert light to electricity. It is a phenomenon that makes photovoltaic cells and fuel cells possible and that lays at the foundation of many hopes for a more sustainable future. But for all its promise, the process is surprisingly not well understood.

“This is a very basic question we’re trying to address,” said Osgood. “We need to know more about the fundamentals that limit the efficiency of charge transfer.”

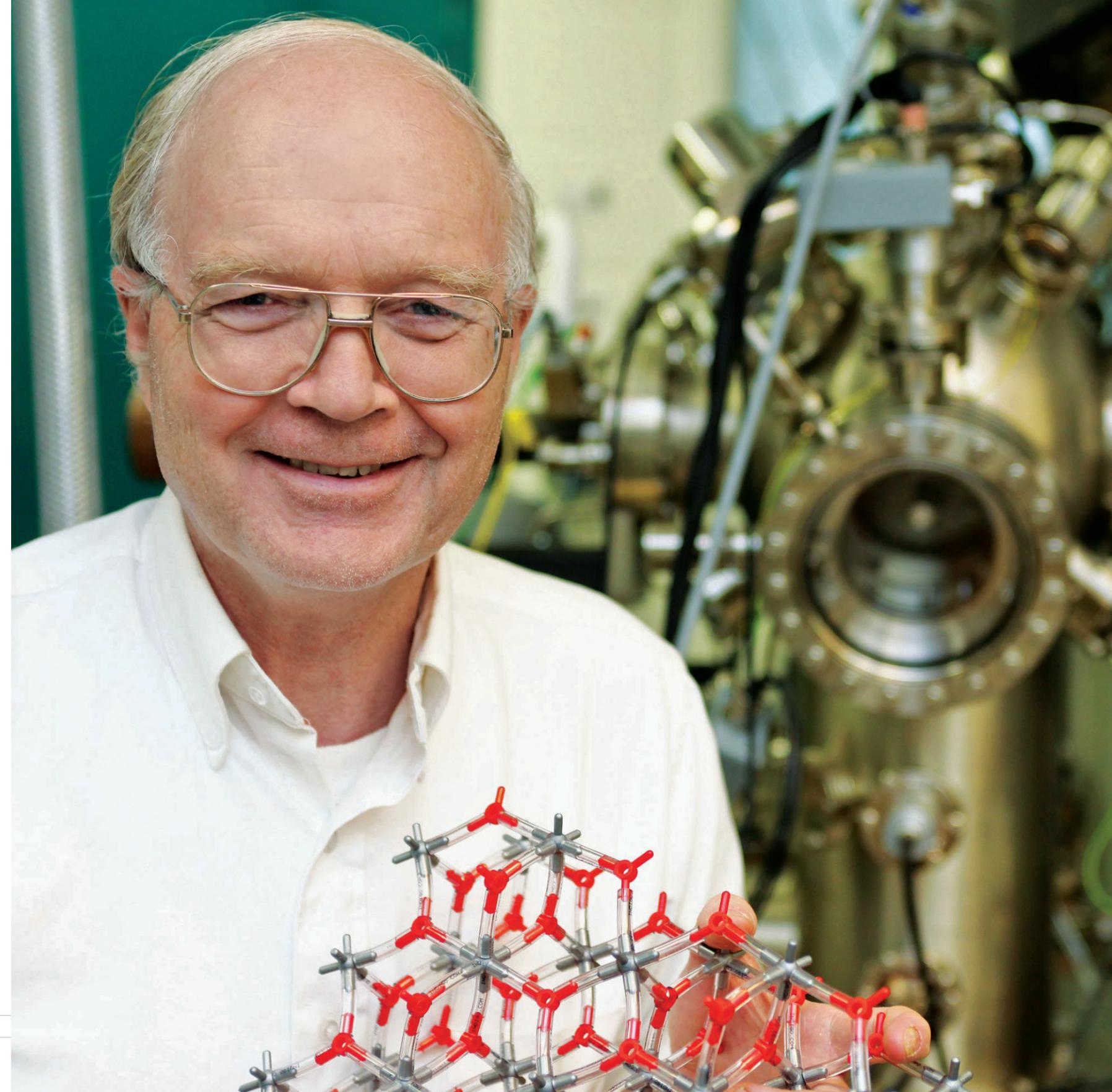
He and his team use ultra-short bursts of laser light to watch individual molecules of titanium dioxide accept or reject electrons. They also have made some of the first studies of titanium dioxide nanoparticles using the atomic-level resolution of a scanning tunneling microscope (STM) to understand how these novel structures can be used to improve solar cells.

Titanium dioxide is of particular interest because it is used in Graetzel cells, a type of low-cost photovoltaic cell that is easy to manufacture from readily available materials. Most low-cost cells are sensitive to only a narrow band of sunlight. The Graetzel cell, however, contains a layer of organic dye that produces free electrons from a wide spectrum of sunlight, much like chlorophyll does in plants.

The trouble is, Graetzel cells are only about seven to 10 percent efficient, meaning that, at best, only one out of 10 free electrons produces a current. Osgood and others would like to improve on this, but the reasons why one electron is captured and another is not remain elusive. Observing short bursts of laser light at a titanium dioxide crystal with an STM, Osgood and his team are nearing the ability to observe individual electrons being taken up or rejected by the crystal matrix.

Osgood hopes that, by focusing on the small stuff, answers to the big questions are not far off. “The world is changing in the way things are done,” he said. “The number of people doing interdisciplinary work is growing every day. It’s an exciting time.”

*B.S., U.S. Military Academy, 1965; M.S., Ohio State University, 1968; Ph.D., Massachusetts Institute of Technology, 1973*





Ah-Hyung (Alissa) Park has been called the “Carbon Lady” for good reason. She is one of the leading experts in the many forms that carbon takes as humans transform the environment, and her path-breaking work may help pave the way to a future in which society obtains energy and materials from a wide range of sustainable sources and deals with its excess carbon in surprising ways.

“The future of humanity depends on our ability to use energy and materials with an eye towards environmental sustainability,” said Park, who is also the associate director of the Lenfest Center for Sustainable Energy. “This will inevitably have to include efficient extraction of energy and materials from fossil resources, biomass, and municipal solid wastes.”

Park studies the ways that carbon circulates through industrial and environmental processes. “The reason we take so much carbon out of the ground is because of our needs for energy and materials,” said Park. “If we can find a way to keep the carbon circulating above ground while providing energy and materials, we won’t have to take so much out of the ground.”

More than seven billion tons of carbon produced by human activity around the world ends up in the atmosphere each year, primarily in the form of the greenhouse gas, carbon dioxide. Being able to manage our role in the global carbon cycle is an important step in the future of our society. Park is investigating novel ways to integrate carbon capture and storage (CCS) technologies with those that synthesize hydrogen and liquid fuels from coal, biomass and municipal solid wastes including non-recyclable plastics.

Today, Park is also working to advance efforts to capture carbon dioxide from emissions and lock it away permanently and economically. To do this, she is exploring the use of nanoparticle organic hybrid materials (NOHMs), a new class of organic-inorganic hybrid materials that consist of a hard nanoparticle core surrounded by functionalized corona. NOHMs are essentially solvent-free, particle-based fluids that provide a large number of capture sites for CO<sub>2</sub>. By imposing frustration onto the corona structure, CO<sub>2</sub> capture can be enhanced via not only enthalpic but also entropic effects.

Park is also looking for ways to safely and permanently dispose of the captured carbon dioxide as mineral carbonates or to convert it to other useful materials such as paper or plastic fillers. The key to achieving sustainability is to take a more holistic view of the systems that process carbon.

“In the past, engineering has mainly focused on optimizing the individual unit of a process,” said Park. “Today, we need to look at the big picture and add environmental sustainability to our equations.”

*B.S., University of British Columbia (Canada), 1998; M.S., University of British Columbia, 2000; Ph.D., Ohio State University, 2005*

## *Capturing Carbon for Sustainable Energy*

# AH-HYUNG (ALISSA) PARK

Lenfest Junior Professor in Applied Climate Science

*Re-evaluating the  
Ozone Layer*

**LORENZO  
POLVANI**

Professor of Applied Physics and  
Applied Mathematics

**W**e don't hear much about the hole in Earth's ozone hole these days, and for good reason. Collective international action has been successful in reversing a decades-long deterioration of the protective layer in the stratosphere. The hole, which grows and shrinks seasonally over Antarctica, is expected to close by sometime mid-century.

Now, however, models and observations of Earth's atmosphere are showing that the ozone hole might have an effect on global climate patterns that may be masking the full impact of global warming. "The ozone hole has been ignored for the past decade as a solved problem," said Lorenzo Polvani. "But we're finding it has caused a great deal of the climate change that's been observed."

Polvani, who also holds an appointment in the Department of Earth and Environmental Sciences, has studied atmospheric dynamics from the surface to the upper stratosphere and from both poles to the equator. In the last few years, he has focused on understanding the effects that ozone depletion, and its eventual recovery, have on Earth's climate.

Ozone—a molecule made up of three atoms of oxygen—absorbs much of the sun's UV-B radiation. In the mid-1980s, it was discovered that chlorofluorocarbons, a chemical used as aerosol propellants, were breaking down the planet's ozone. In 1987, world governments signed the Montreal Protocol to ban chlorofluorocarbons.

Ozone warms the stratosphere when it absorbs UV radiation. Its relative absence over Antarctica for the past 40 years has had a cooling effect on the upper atmosphere over the South Pole that is as much as 10 times as strong as the warming effect associated with increasing carbon dioxide concentrations.

The effects of this cooling already appear to be affecting the location of the Southern Hemisphere's mid-latitude jet stream. Cooling of the upper troposphere—the highest part of the lower atmosphere—has been connected to a shift of the southern jet stream towards the south by a few degrees.

This shift has resulted in precipitation patterns moving south as well, and in the tropical dry zones expanding. Polvani's next task is to find out what will happen as the ozone hole closes and the full brunt of global warming is felt throughout the atmosphere.

"These next couple of decades are going to be interesting times," said Polvani. "We're going to see these climate changes play out in our lifetimes."

*B.Sc., McGill University (Canada), 1981; M.Sc., McGill University, 1982; Ph.D., Massachusetts Institute of Technology, 1988*





Any one of Peter Schlosser's three jobs could be a full-time undertaking. First, he studies Earth's hydrosphere as Vinton Professor of Earth and Environmental Engineering and professor of earth and environmental sciences. Second, as senior staff scientist at Lamont-Doherty Earth Observatory, he is involved in an array of large scientific programs. Finally, he is the associate director and director of research at the Earth Institute.

Rather than keeping them separate in his mind, he tackles all three together. "They all retain some distinct character," said Schlosser. "But in my daily life, they are all intertwined." Not only are they intertwined, but they also speak to the way Schlosser has always approached his work.

As an undergraduate student in his native Germany, he chose to study physics at a university with a long tradition and broadly-based research and teaching, because, he said, he wanted to see science as a holistic part of the entire university. Physics, he felt, gave him the opportunity to acquire a set of skills that would be useful for studying a wide range of scientific problems with societal relevance.

He eventually ended up in environmental physics, in part because of a natural curiosity in the world around him. Since arriving at Columbia in 1989, Schlosser has continued to feed his omnivorous curiosity about his surroundings by fostering connections with faculty members from departments across campus.

That broad perspective has helped him become a key part of efforts to establish and expand the Earth Institute. Schlosser has been integral in guiding the Institute's research agenda, which focuses on developing practical solutions to the problems that humankind faces in designing a sustainable future. At the same time, he recently founded the Columbia Climate Center, a part of the Earth Institute that specifically addresses society's needs for strategies to mitigate and adapt to climate change.

"Whether we can turn the world from a non-sustainable to a sustainable path has been on my mind a lot," said Schlosser. "I don't think we have a real answer yet, but the important thing is that we can see a path forward that is supported by technological innovation."

Schlosser emphasizes the need for communicating the messages of science clearly and accurately to a public that is often charged with deciding how to allocate resources to achieve a sustainable future. Exactly how to do that is a difficult question, but he feels it is possible with involvement from many different fields across campus.

"That, to me, is enough motivation to continue working and to look for solutions," he said.

*B.S., Heidelberg University (Germany), 1981; M.S., Heidelberg University, 1981; Ph.D., Heidelberg University, 1985*

## *Sustaining the Environment*

# PETER SCHLOSSER

Vinton Professor of Earth and Environmental Engineering and Professor of Earth and Environmental Sciences

*Harnessing Fusion:  
The Ultimate Green Energy*

## AMIYA SEN

Professor of Electrical Engineering  
and of Applied Physics and Applied  
Mathematics

World demand for more efficient energy production is colliding with the need for environmental responsibility. Finding and harnessing a sustainable energy source is a paramount universal goal. If the nuclear fusion which occurs naturally in the sun can be replicated by science here on Earth, it will be possible to turn the heavy hydrogen that is available in abundance in seawater into a powerful, nearly inexhaustible source of energy.

However, while thermonuclear fusion has great potential as an efficient and environmentally friendly energy source, harnessing that power is hampered by fusion plasma's instabilities, fluctuations, and turbulence. The large variety of instabilities and fluctuations drain energy out of their core and vitiate the success of fusion devices.

An important tool in identifying and studying these instabilities is the Columbia Linear Machine. It was developed, repeatedly redesigned, and appropriately tailored with striking ingenuity for the physics requirements of each instability by Amiya Sen. His efforts, extending over many years, led to the very first production, identification and detailed parametric studies of trapped particle, ion, and electron gradient instabilities and their transport consequences.

With his sustained pioneering theoretical and experimental efforts in the relatively new field of feedback control of plasma instabilities, Sen has established himself as a leader in this critically important area. These efforts include the Lyapunov stability of plasmas, the observability, controllability, and feedback suppression of most plasma instabilities.

Recently, Sen has pioneered a new paradigm for plasma transport, which challenges the 50-year-old gold standard of Bohm/gyro-Bohm scaling. This finding promises to have a great impact on the quest for fusion.

By far the most prestigious archival journal in physics and applied physics is *Physical Review Letters*. Sen and his students have published 17 papers in this, and in numerous other publications.

Sen has been a consultant and advisor to the Lawrence Livermore National Laboratory, the Princeton Plasma Physics Laboratory, the United States Department of Energy, and the National Science Foundation. He is a fellow of the American Physical Society and the Institute of Electrical and Electronics Engineers, and is a member of Sigma Xi and the American Geophysical Union.

*Dipl., Indian Institute of Science, 1952; M.S., Massachusetts Institute of Technology, 1958; Ph.D., Columbia, 1963*





## *Modeling Monsoons*

# ADAM SOBEL

Professor of Applied Physics and Applied Mathematics and Professor of Earth and Environmental Sciences

Adam Sobel once bought a plane ticket to the city of Darwin in Australia's tropical north based on a colleague's weather prediction. That in itself is nothing new—people do it all the time. But the prediction he followed was for the start of the monsoon rains three weeks hence, a prediction that was virtually unheard of just a decade earlier for the length of its foresight. When he got off the plane, no one was happier to see the sky open up and the rain begin right on schedule.

"We had half a meter of rain in 10 days," said Sobel. "It was exciting."

For more than one billion people, the seasonal monsoons are both a life-giving annual event and a potential disaster. Although much is known about how the monsoons occur, very little is understood about how they vary.

Monsoons are an atmospheric circulation pattern that develops in the tropics at fairly well-defined times of year. The sun warming the surface of the earth draws moisture from ocean waters and forms the iconic, seasonal rains of South and Southeast Asia or sub-tropical Africa and South America. The people who live in these regions, particularly the rural poor, rely on the monsoon rains to water crops and recharge aquifers.

When the monsoons are weak, drought and famine can result; if they come with too much gusto, flooding and disease occur. The fine line between life and death makes monsoon forecasting one of the most important topics within climate modeling these days. Sobel is trying to develop models to predict the variations within a monsoon season, known as "active" and "break" cycles, which have so far been beyond the ability of climate modeling. Recently, he helped demonstrate the central importance of heat stored in the oceans on the formation of active and break cycles.

The atmospheric patterns that drive the monsoon are also responsible for spawning tropical storms in distant ocean basins and may influence the formation of El Niño and La Niña cycles in the western Pacific. As a result, Sobel's work may one day have an impact on people who live well beyond the reach of the monsoon rains.

"We need a central theory that can be stated simply that explains the variations we see," said Sobel. "Weather prediction can look two weeks in the future, max. Climate models can give us the probability for a strong or weak monsoon a year in advance. This is in between. It's kind of the Holy Grail right now."

*B.A., Wesleyan University, 1989; Ph.D., Massachusetts Institute of Technology, 1998*

*Fostering New  
Ways to “Green”*

## PONISSERIL SOMASUNDARAN

LaVon Duddleson Krumb  
Professor of Mineral Engineering

Ask Ponisseril Somasundaran to say something in Hindi and he will jokingly beg ignorance aside from “a few common bad words.” Ask him what he thinks “sustainability” means, though, and he will quote the Hindu tenet of *nishkam karma*, or selfless action, that entails making sacrifices today for the sake of the future.

A world leader in surfactant science, Somasundaran has used his expertise to take on problems as wide-ranging as the enrichment of scarce minerals from ultra-lean ores, to the impact of cigarette smoke on lungs, to the behavior of nanoparticles. His current mantra, however, is sustainability.

“Sustainability has several different meanings,” said Somasundaran. “It is like the four blind men describing an elephant.” In that Sufi tale, four blind men each disagree about the true nature of an elephant because each feels a different part of the animal. Like those men, but with his eyes wide open, Somasundaran is approaching sustainability from several perspectives.

“There is a fundamental disconnect in the sustainability movement when it comes to consumer products,” he said. “An increasing number of people are choosing products based on third-party green certification, but many of these labeling programs give little weight to the full scope of a product’s lifecycle, from manufacture and shipping, to use and disposal.”

An example is liquid soaps and detergents, which contain large amounts of water. Somasundaran’s approach has been to reduce the amount of water in these products to lower the amount of packaging they require and the amount of fuel needed to ship them. He has applied a similar water-saving approach to mineral processing and mine tailing treatment by developing chemicals that require less water consumption.

More recently, Somasundaran has begun to focus on agriculture, which is notorious for its enormous demand for water. Even modest savings in agricultural water use could translate to huge gains globally. Using cellulose nanoparticles, which naturally curl to trap droplets of water, he is trying to develop a targeted release mechanism to water just the roots of crops and only when the soil is too dry or when high temperatures threaten crops.

His next target may be the carbon footprint. Somasundaran is convinced that focusing solely on carbon is far too narrow. “We need to broaden our notion of what is sustainable,” he said. Then, perhaps, we will all be able to see the entire elephant.

*B.Sc., University of Kerala (India), 1958; B.E., Indian Institute of Science, 1961; M.S., University of California-Berkeley, 1962; Ph.D., UC Berkeley, 1964*





Growing up, Marc Spiegelman dreamed of one day being the next Jacques Cousteau. The only problem was he enjoyed hiking more than diving and he excelled at math and physics rather than oceanography. Two summers spent working as a ranger for the United States Forest Service and the discovery that the planet often reveals its secret inner workings through calculus sealed his future.

Spiegelman now studies the interior of the planet using the tools of a computational physicist to understand how Earth's crust and mantle behave in tectonically active regions of the world. More recently, he has begun considering a problem that has traditionally attracted scientists with a more airy focus: what to do with all the carbon dioxide in the atmosphere.

Spiegelman's principle expertise involves applying theories that describe the migration of magma and fluids in the solid earth, and the behavior of solid materials under the immense heat and stress of the deep earth. His efforts are helping create a more general understanding of the interactions between solids and fluids in the mantle and crust. This work has applications to understanding the behavior and output of volcanoes around the globe like Eyjafjallajökull, the volcano in Iceland that erupted in early 2010 and shut down air travel over much of Europe for nearly one month. His work also provides insights into such problems as the interactions between reactive fluids and a variety of minerals found in the earth.

His expertise is attracting attention from new circles because it turns out that one of the more promising ideas for dealing with excess carbon emissions involves the solid earth. Geological carbon sequestration, a problem that Spiegelman's colleagues at the Lamont-Doherty Earth Observatory are actively investigating, entails injecting carbon dioxide into certain mineral formations found in many places around the world.

Spiegelman's ability to work between the worlds of observation and modeling may one day prove crucial in understanding what happens when carbon dioxide under immense pressure reacts with mineral formations containing magnesium. Such reactions produce extreme heat, which cracks the rock, and form solid magnesium carbonate, locking the carbon dioxide away safely and permanently.

It is this ability to model unobservable interactions between solids, fluids and heat deep underground that gives him a leg up on his old hero, Jacques Cousteau. Instead of a view into the depths of the ocean, Spiegelman has been able to see through his equations and models into the deepest recesses of the upper Earth.

*B.A., Harvard, 1985; Ph.D., University of Cambridge (England), 1989*

## *Studying Earth's Mantle and Crust*

# MARC SPIEGELMAN

Professor of Applied Physics and Applied Mathematics and Professor of Earth and Environmental Sciences

*Keeping Wind  
Turbines Turning*

**ELON J.  
TERRELL**

Assistant Professor of  
Mechanical Engineering

**A**round the world, communities are increasingly utilizing wind power because it is a clean, sustainable source of renewable energy, is fast to deploy, creates jobs, uses very little water, and is economically competitive. In fact, wind power is the fastest-growing source of energy production, having grown from zero production in the early 1980s to more than 120,000 megawatts worldwide as of 2008. But as wind turbines are increasingly being installed, their power systems are being challenged by a number of issues, especially exposure to harsh operational and environmental conditions, as well as the effects of contamination from the environment.

Elon J. Terrell is an expert in tribology, the science of friction, lubrication, and wear within sliding and contacting interfaces. He uses analytical, numerical, and experimental techniques to analyze the interfacial interactions and the wear between sliding surfaces in either dry sliding or lubricated contact. Since friction and wear are challenges for devices that contain moving components, his research interests include power generation, energy conversion, energy harvesting, microelectromechanical systems (MEMS), and health sciences.

One of Terrell's current projects is focused on the multiphysics analysis of contaminated cyclic rolling-sliding contacts to gain a better physical understanding of the behavior of an interface between two lubricated surfaces. His primary testbed involves particulate contaminants in a lubricated gearbox system, such as those used in wind turbines. A vital aspect of his research is the combined modeling of the various physical interactions that take place within this interface, including lubricant fluid flow, particle motion, particle-surface contact, and the resultant abrasive wear experienced by both surfaces.

To better understand the lubrication of contaminated gear trains, Terrell's group is using mesh-free particle methods, wherein the lubricant flow, the contacting surfaces, and the particles are all represented by virtual particles that interact with one another and move dynamically with time. Although studies have involved the use of these methods for fluid mechanics and solid mechanics, Terrell's group is seeking to be the first to use them to integrally connect fluid mechanics, solid mechanics, and particle dynamics into a single predictive simulation.

His other research interests include the study of crack initiation, propagation, and agglomeration under low-amplitude cyclic loading, work that will help to better explain why the bases of gas turbine blades fail after a given amount of use. Terrell is also exploring the possibility of applying electrokinetics to thin film lubrication, a project that is mostly applicable to devices such as MEMS and magnetic data storage devices.

*B.S., University of Texas (Austin), 2002; M.S., University of Texas, 2004; Ph.D., Carnegie Mellon University, 2007*





**A**ging infrastructure is of great concern to all of us on the planet—no one wants to drive over a bridge that may collapse or live or work in a building whose structure is failing, but oftentimes it is difficult to predict catastrophe. Rene Testa is an expert in structural mechanics and materials, and has focused his research on the deterioration and failure of materials and structures of all kinds, especially buildings and bridges.

Testa, who is also the director of research for the Carleton Laboratory at Columbia Engineering, has extensive experience in infrastructure assessment and rehabilitation, including work on New York City’s Whitestone, George Washington, Brooklyn, and Triborough bridges. He has also done testing on the Manhattan, Walt Whitman, Verazano Narrows and Throgs Neck Bridges, as well as on high- and low-rise buildings. He has formulated an optimal maintenance and repair strategy for management of a system of bridges like the one developed for, and used by, the city. His current research focuses on the use of vibration monitoring to detect damage in structures, the characterization of damage in materials, and the management of bridge maintenance.

Many of Testa’s projects dealing with material and structural performance are conducted in the Carleton Lab. Research on sustainability of aging urban infrastructure is being greatly advanced by the development of a new accelerated-aging test facility in the lab. Testa notes that “this will provide far greater capability for research relating to aging infrastructure by both senior and junior members of the civil engineering faculty.”

Testa’s research has also included the analysis of failed structures, mechanical systems, and components of metallic and cementitious materials. He has worked on composite materials, the inelastic response of concrete, and modeling of the mechanical response of structural fabrics for which he holds a patent for a stress transducer.

“Much of my work over the years has involved real structures, especially when there is a failure—its cause must be determined to provide an opportunity for learning,” said Testa.

“In fact, a failure is only a total failure if nothing is learned from it. While research that focuses purely on fundamental theory of structures and continuum mechanics is elegant and valuable in propagating knowledge and gives me much satisfaction, it is the research that is driven by actual application that is the most gratifying.”

*B.E., McGill University (Canada), 1959; M.S., Columbia, 1960; Eng.Sc.D., Columbia, 1963*

## *Maintaining Aging Urban Infrastructure*

# RENE B. TESTA

Professor of Civil Engineering and Engineering Mechanics

*Building Single-Molecule Circuits*

## LATHA VENKATARAMAN

Associate Professor of Applied Physics and Applied Mathematics

As electronic devices become ever smaller, and the demand for ever tinier components grows, understanding how current flows through these materials at the nanometer (billionth of a meter) scale is becoming increasingly important. Latha Venkataraman conducts research on the molecular level, where she focuses on probing, manipulation, and control of single molecules as active elements in electrical circuits. “I am working to understand the interplay of physics, chemistry, and engineering at the nanometer scale,” she said.

By probing and understanding electronic structure and properties at this scale, her research findings will not only influence the design of molecules as active electronic components; they will also enhance the understanding of charge transport across metal-organic interfaces, with impact on the fields of organic electronics, photovoltaics, catalysis, and biological processes, including respiration and photosynthesis. “These experiments provide a deeper understanding of the fundamental physics of electron transport, while laying the groundwork for technological advances at the nanometer scale,” she said.

To fabricate circuits with a single molecule, a physical connection has to be made between the single molecule at the nanoscale and the metal electrodes, in microscale. Building such circuits with atomic precision is beyond the capabilities of top-down approaches; indeed, one of the main challenges has been to figure out how to measure the resistance of electronic components that consist of a single molecule. Although there are a number of techniques that have been used, the large variations in the experimental results produced by these techniques had made it difficult to predict how individual molecules will behave as electronic devices.

Venkataraman’s pioneering research has made possible these measurements by using a bottom-up approach to form single-molecule circuits where a molecule self-assembles into a gap between two metal electrodes. The ability to create devices with known structure is then controlled by the chemistry at the metal-molecule interface, which can be tuned.

In her lab, these device fabrications and their characterizations are carried out using state-of-the-art scanned-probe microscopes, which are built inhouse to have sensitivity to small currents and forces, as well as to have the required mechanical stability. In her group, these instruments are then used, for example, to measure electronic conduction or single bond breaking forces. They show that these properties relate not only to the molecular structure, but also to the metal contacts and linking bonds.

“A single-molecule circuit is the ultimate limit one can achieve,” says Venkataraman. “Understanding how to control and transfer charges on this scale allows us to push the frontier.”

*B.S., Massachusetts Institute of Technology, 1993; M.S., Harvard, 1997; Ph.D., Harvard, 1999*





## HAIM WAISMAN

Assistant Professor of Civil Engineering  
and Engineering Mechanics

The I-35 bridge collapse in Minneapolis, Minn. in 2007 killed 13 people and resulted in untold economic disruption for the Upper Midwest. It also brought to stark relief a problem with the nation's infrastructure: it is old and getting older every day.

Haim Waisman is developing computational techniques to help understand how and why things fall apart, and how this may be predicted and prevented. "Fractures govern our lives," he said. "Everything is connected by fractures."

Waisman is refining computational methods known as extended finite elements and multiscale modeling to design high-strength, nanocomposite materials that might one day shore up aging structures, such as pipes and bridges, in corrosive environments. He also has developed a non-invasive method of detecting fractures in things such as an airplane wing using measurements from only a few common stress sensors.

In particular, he has been using his methods to study how suspension bridge cables age. The main cables are made of thousands of wires clamped and wound together. When a wire breaks, the loads it carries are redistributed to neighboring wires. Understanding and predicting the fracture response of the entire cable considers as many as 50,000 wires wound into a tightly compressed bundle more than two miles long, and requires a supercomputer.

He has found that, when a wire breaks, friction between the remaining wires can effectively transfer the strain throughout the cable bundle without compromising the entire bridge. That's a relief for the millions of people who daily cross the graceful, but aging, bridges that lead into and out of Manhattan.

Fractures also play a role in nature and Waisman has recently turned his attention to a dramatic example—the collapse of ice shelves in Greenland and Antarctica. As the climate warms, water from melting ice seeps to the bottom of glaciers, allowing them to slide more easily over bedrock and forming networks of cracks in ice shelves.

In 2002, 1,250 square miles of the Larsen B ice shelf in West Antarctica shattered, sending icebergs into southern shipping lanes. Since then, several other shelves have collapsed, threatening sea-level rise around the world. Understanding how things like ice shelves and bridges break and fail is a necessary first step to understanding the inevitable changes going on all around us all the time.

*B.S., Technion Israel Institute of Technology, 1999; M.S., Technion Israel Institute of Technology, 2002; Ph.D., Rensselaer Polytechnic Institute, 2005*

*Using Optoelectronics  
for Chemical and  
Environmental Sensing*

## WEN WANG

Thayer Lindsley Professor of Electrical  
Engineering and Professor of  
Applied Physics and  
Applied Mathematics

The human body naturally emits trace amounts of about 500 chemicals. Likewise, the atmosphere contains hundreds of chemicals that, in trace amounts, do not adversely affect our breathing or health. When these chemicals become out of balance—such as from illness, chemical weapons, or hazardous waste—often only complex chemical testing can diagnose their presence.

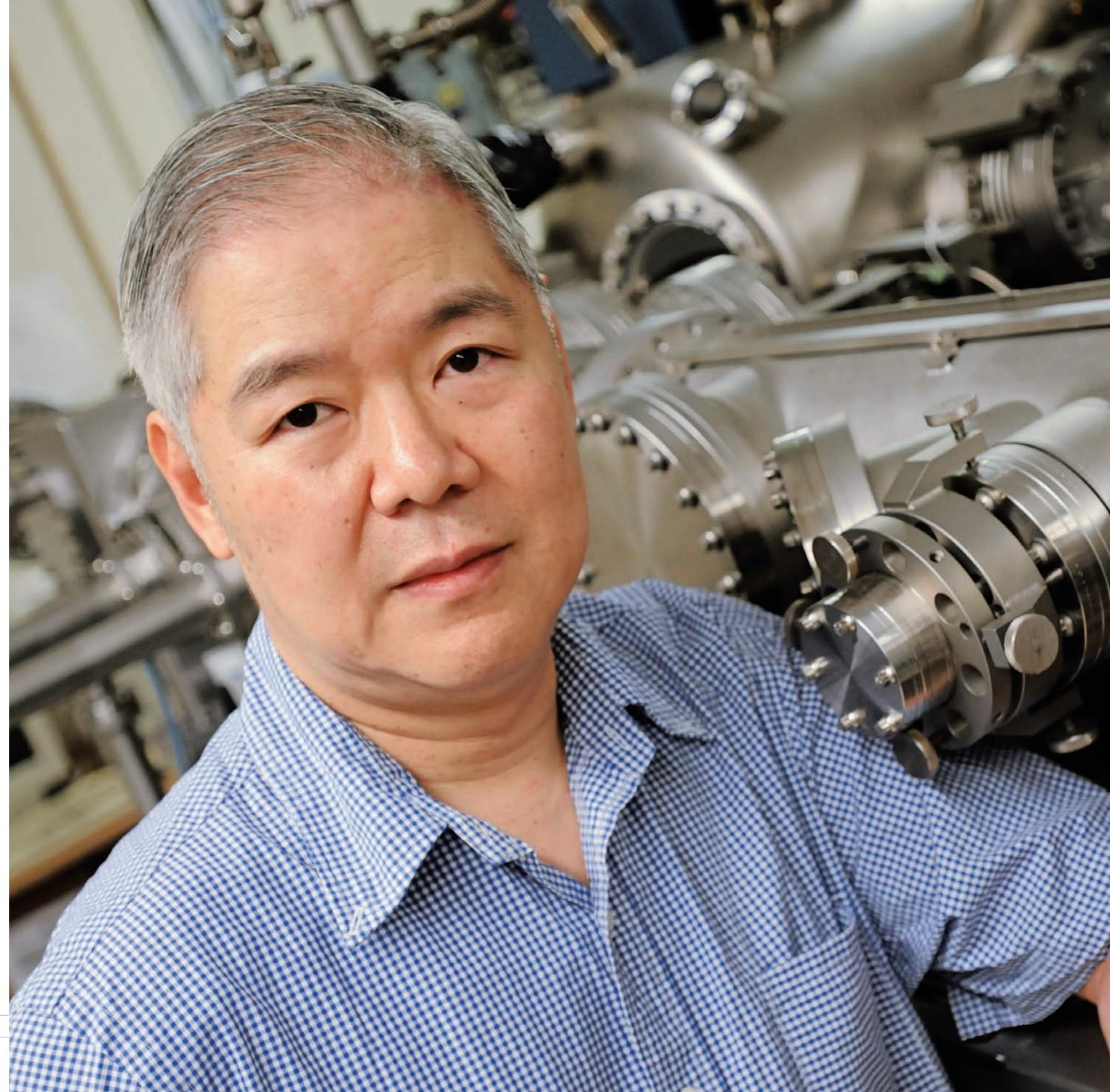
Because every molecule has a unique absorption signature, optoelectronic devices hold the promise of providing effective identification of chemicals, by analyzing a molecule's absorption. For example, light from a semiconductor laser could pass through the molecules in a person's breath, the absorption could be measured and determination made—within minutes—about what chemicals are present and in what amounts. By providing fast and effective trace gas detection, this technology has application in environmental sensing (measuring the atmosphere for pollutants), industrial process control (chemicals and food products) and medical diagnostics.

Wen Wang is an eminent researcher in optoelectronic materials, devices, and molecular beam epitaxy. He focuses his research on creating knowledge that can be applied to real-world problems. His current projects include nano and heterostructure material properties, optoelectronic devices, infrared lasers, detectors, and photovoltaics.

He has contributed some 250 papers and published extensively in this area, e.g. Type-II InAs/GaSb superlattices for mid- and long-wavelength applications (Quantum Structure Infrared Photodetectors International Conference, 2010, Istanbul, Turkey); High detectivity InGaAsSb photodetectors with cutoff wavelength up to 2.6  $\mu\text{m}$  (J. Crystal Growth, 2009); Interface and optical properties of InGaAsNSb quantum wells (very low threshold 1.3  $\mu\text{m}$  lasers, J. Vac. Sci. Tech. 2007); Mid-infrared InGaAsSb quantum well lasers with digitally grown tensile-strained AlGaAsSb barriers (J. Vac. Sci. Tech. 2007); Strain-compensated InGaAsSb quantum well lasers emitting at 2.43  $\mu\text{m}$  (environmental and glucose sensing, IEEE PTL, 2005); Invention of a new quinary dilute nitride InGaAsSbN for mid-infrared optoelectronic devices (JAP 2003 and APL 2001).

Wang is a fellow of the Institute of Electrical and Electronics Engineers, the American Physical Society, John Simon Guggenheim Foundation, and is an Electron Device Society distinguished lecturer.

*B.S., National Taiwan University, 1975; M.E.E., Cornell, 1979; Ph.D., Cornell, 1981*





Imagine genetically engineering a microbe to produce a biofuel by growing on ambient carbon dioxide from the atmosphere and ammonia from wastewater or generated electrochemically. This carbon-neutral bio-electrochemical process is being developed to produce butanol, a biofuel compatible with today's vehicles, and is just one of many projects that Alan West is working on with his colleagues.

West's research focuses on a large number of problems that he says are often characterized as belonging to "electrochemical engineering." He and his team have studied applications of electrochemistry to the production of advanced electronic devices. For example, the "wiring" used to make integrated circuits in logic and memory chips used in personal computers is made through the process of electroplating.

West works on electrochemical application for energy storage (i.e., batteries) and conversion (fuel cells). Working closely with Scott Banta of the Department of Chemical Engineering and Lt. Col. Robert Bozic from the USMA, he has also developed bio-electrochemical sensors that can be employed in a range of applications, including environmental monitoring of potential toxins in groundwater and assessing the safety of drinking water.

West notes that electrochemical technologies will play a key role in sustainable energy, and he and his colleagues have increasingly turned their attention to studies of batteries that can be economically scaled for use in conjunction with large-scale renewable energy production and with a smarter electrical grid. Energy storage such as that provided by batteries accommodates variations in energy production by renewables. For some applications, it may be better to store excess electrical energy in the form of a fuel by using electrolysis (think of a fuel cell running in reverse). In such a technology, a fuel cell is used to oxidize the fuel to produce electricity. West has also been collaborating with Klaus Lackner of the Department of Earth and Environmental Engineering on developing these electrochemical conversion systems.

"We continue to be fascinated by our studies of electrochemical systems because we collaborate with colleagues from a wide variety of disciplines," said West. "It is very gratifying that our work is directly applicable to industrial interests, while addressing long-term environmental and energy needs. We particularly enjoy working with industrial colleagues, in part to keep our ideas grounded in reality and also to provide job opportunities for our students."

*B.S., Case Western Reserve University, 1985; Ph.D., University of California-Berkeley, 1989*

## *Applying Electrochemical Technologies for Sustainable Energy*

### **ALAN C. WEST**

Samuel Ruben-Peter G. Viele Professor of Electrochemistry

*Controlling Light with  
Nanostructures*

## CHEE WEI WONG

Associate Professor of  
Mechanical Engineering

Quantum physics has come a long way, and the advent of nanostructures has enabled researchers to observe experiments once relegated to textbooks. Chee Wei Wong is at the forefront of examining the control of light with nanostructures, with interesting results.

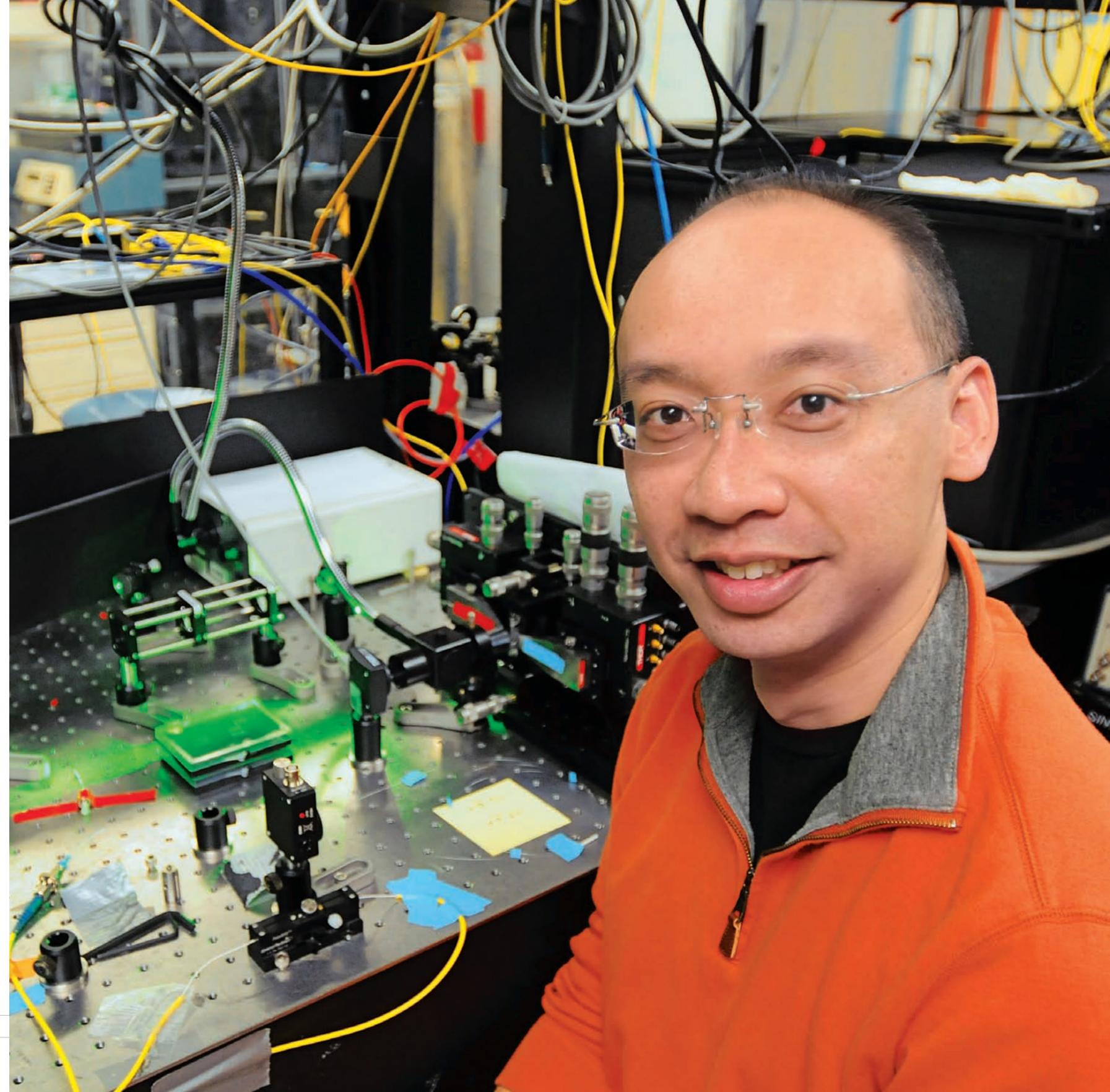
“When you can trap light in a confined space and bounce it back-and-forth for a time equivalent to one million optical cycles, its intensity gets really strong,” said Wong. This intensity, when tuned to resonances, such as atomic transitions or mechanical radio-frequency vibrations, can speed up or cool down the other process. An exciting subset is laser cooling of nanomechanical beams to its fundamental quantum mechanical ground state, “the coolest state of its eigenmodes,” he said. With the discovery of nanostructures and coherent lasers, researchers can now explore mechanics of quantized structures, “where it’s mind-boggling that so many atoms can act in such a coherent way.”

Wong focuses on the physics and engineering of nanoscale optics, e.g. optical interconnects and ultrafast lasers for infrastructures, and photovoltaics for sustainability. His team can not only trap light in a small box, but also use nanostructures to slow light down, forcing increased interactions with its surroundings. Wong is compressing light pulses at 100-femtosecond timescales and generating new frequencies for next-generation optical networks.

Wong notes that even the single photon has many properties not yet fully understood. It can encode much information in its many degrees-of-freedom (vortices, timing, polarization, etc.). It can interact with a single quantum dot for new computational ways. It can interact with, or generate, another photon in non-classical distributions. It can interact with a phonon for metrology purposes. Trapped in a confined nano-space for one million cycles, many of these effects are enhanced. These have fundamental security implications because, Wong observed, “with the newly discovered ability to artificially engineer materials for negative refraction, people are fantasizing that one day we can cloak objects, hiding objects from the enemy’s electromagnetic radar.”

Understanding photon-material interactions has implications for next-generation photovoltaics. “The sun is our most abundant energy source and in an hour floods our planet with sufficient energy for one year, if we know how to collect it efficiently,” said Wong. “We used to think each photon gives one electron (or less), and hence there is a glass ceiling on the performance and cost effectiveness of photovoltaics. It turns out that, with new materials and a better understanding of the dynamical processes, we can develop photovoltaics that are better and cheaper, trapping light longer for more electricity. This is our challenge.”

*B.S., University of California-Berkeley, 1999; M.S., Massachusetts Institute of Technology, 2001; Ph.D., MIT, 2003*





## TUNCEL YEGULALP

Professor of of Earth and Environmental Engineering

“Extreme” is perhaps the last thing that comes to mind when talking to Tuncel Yegulalp. “Orderly” and “soft-spoken” seem more appropriate. Nevertheless Yegulalp was the last student of Columbia Professor E.J. Gumbel, who helped found the field of extreme value statistics.

Today, Yegulalp is a leading expert in the field, which is used to analyze and predict statistical outliers of common events, such as large earthquakes and severe floods, as well as the failure strength of rocks. In addition, his career has recently come full circle, returning him to the fields of mining and geology, only this time he’s trying to figure out how to put something into the ground—namely, carbon dioxide—rather than remove it.

Yegulalp arrived at Columbia in 1963 to continue his studies of uranium mining. It was during that time he discovered “there was more to the world than just uranium,” he said. That world included a graduate course in extreme value statistics—a class for which students had to be interviewed and handpicked by Gumbel. Yegulalp tried to use extreme value analysis to develop a statistical model of large earthquakes, but gaps in the seismic record made it impossible to create accurate forecasts.

Yegulalp eventually devised a new method to allow for the data gaps, but it wasn’t until 1999 that he was able to verify his work. While on vacation in Turkey, he experienced the magnitude 7.6 Izmit earthquake. The quake fit squarely into the range of what might be expected, given its magnitude and the time since the region’s last large event.

These days, Yegulalp is teaching extreme value methods to an entirely new group of students who are interested in understanding and predicting extremes of climate that might arise in the wake of global warming. At the same time, he is applying his expertise in geology and mining to projects focusing on geologic sequestration of carbon dioxide. The idea is that pumping carbon dioxide into minerals that contain magnesium will form magnesium carbonate, a stable solid that will keep the greenhouse gas out of the atmosphere permanently.

The only problem, he said, is the sheer volume of the carbon dioxide we will eventually have to sequester and the large amount of magnesium carbonate rock that it will result. “If we want to maintain coal as a major contributor of energy, we will have to mine at least six billion tons of rock per year and learn to dispose of an even greater weight and volume of magnesium carbonate,” said Yegulalp. Spoken like someone with a mind for extremes.

*M.S., Istanbul Technical University (Turkey), 1961; Eng.Sc.D., Columbia, 1968*

## HUIMING YIN

Assistant Professor of Civil Engineering  
and Engineering Mechanics

If Huiming Yin has his way, solar panels will one day all but disappear from view on rooftops—and from a builder's bottom line. Yin is working on a prototype for an inexpensive photovoltaic (pv) cell that produces both electricity and hot water. He is also attempting to integrate his new design into roofing materials, perhaps one day eliminating the need for both solar panels and roofing shingles.

Sunlight spans a wide range of the electromagnetic spectrum—from nearly 120 to 20,000 nanometers, but the typical pv cell can only convert a narrow sliver of this to electricity. The rest is wasted or converted to heat—the enemy of many pv cells. In particular, the most inexpensive silicone-based cells virtually stop producing a current above 85 degrees Celsius, but rooftop solar cells often reach temperatures exceeding 100 degrees Celsius, making them all but useless in most parts of the world.

“As civil engineers, we want to produce something that really changes peoples’ lives,” said Yin. His design incorporates a functionally graded material (FGM), a relatively new type of material made up of two components that, instead of meeting in an abrupt transition, change gradually in composition from one to the other. This allows designers to take advantage of the physical properties of both components without having to create a physical bond between them—often the weakest point in any composite.

The FGM that Yin uses in his solar panels helps both draw heat from the base of the photovoltaic cell and insulate the roof. Water-filled tubes embedded in the thin FGM layer carry that heat away to be used in the building. By cooling the cell, Yin is aiming to improve the efficiency of existing silicone pv cells.

His earlier research focused on improving the wear and durability of roads using FGMs to prevent buckling and heat stress. The shingled roof, which is essentially another asphalt-covered surface, seemed like the next obvious focus of Yin's attention—particularly when that surface is forced into double duty as both a shelter and an energy producer. Installing solar panels on an existing roof, he says, is a quintessential civil engineering problem, one that involves structural dynamics, wind loading, and heat dissipation.

The next step is to fashion his cells into durable roofing elements that can take the place of shingles. Yin envisions a day when any building will be able to convert sunlight to electricity and hot water for less than the cost of a conventional roof. Until that time, he will continue trying to change the world, one rooftop at a time.

*B.S., Hohai University (China), 1995; M.S., Peking University (China), 1998; Ph.D., University of Iowa, 2004*

