

ENGenious



A PUBLICATION FOR ALUMNI AND FRIENDS OF THE DIVISION OF ENGINEERING AND APPLIED SCIENCE
of the California Institute of Technology

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Cool Earth Solar—pages 38–41

Briana Ticehurst—page 8 (Blanquart)

Feedback

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The Caltech Division of Engineering and Applied Science consists of seven Departments and is home to more than 90 faculty who form an interconnected web of researchers creating the frontiers of modern science and engineering. Their students and postdoctoral colleagues have access to world-renowned educational resources, as well as unparalleled opportunities for both basic and applied research.

We invite you to learn more about the Division through our website
<http://www.eas.caltech.edu>

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Cover Image: *Montage created from photos and research images highlighting the three eras of Electrical Engineering at Caltech: power, computing, and communications. The front cover shows a power arc created by a 1,000,000 volt testing transformer in the High Voltage Laboratory, as well as the corrugation of a semiconductor distributed-feedback (DFB) laser. The corrugation or grating was constructed to reflect only a narrow band of wavelengths. This unique feature of the DFB laser is the reason it is widely used in optical communication. The back cover shows a variety of computer chip designs in reference to the computing era and its great impact.*

*Ares J. Rosakis, Theodore von Kármán
Professor of Aeronautics and Professor of
Mechanical Engineering; Chair, Division of
Engineering and Applied Science, standing
in the recently renovated Von Kármán
Conference Room.*



The “impact out of proportion to our size” theme continues to resonate at Caltech. We have been ranked as the number one Engineering and Technology university in the world by the Times Higher Education World University Ranking, despite our modest size (300 faculty at the Institute, with roughly 90 of those in the Division of Engineering and Applied Science). And our stellar faculty, students, and alumni continue to win praise and recognition from all quarters. The White House, as we go to press, just named Amnon Yariv, Martin and Eileen Summerfield Professor of Applied Physics and Professor of Electrical Engineering, a recipient of the National Medal of Science; John Dabiri (MS '03, PhD '05), Associate Professor of Aeronautics and Bioengineering, was awarded a MacArthur “Genius” grant; and Chiara Daraio, Assistant Professor of Aeronautics and Applied Physics, has been recognized by Popular Science magazine as one of the “Brilliant 10” in their annual compilation of America’s young science geniuses. These are but three of the hundreds of recognitions and awards that our faculty receive each year and attest to the broad spectrum of achievement that exists in the Division.

I became Chair in May of 2009 and, since then, have enjoyed working with this truly amazing group of faculty to reorganize the Division into seven Departments that collectively offer fourteen graduate and seven undergraduate degrees. What has been the impetus? To create a structure that allows larger groups of faculty, with related intellectual interests, to efficiently articulate their vision for engineering at Caltech in seven key areas: Aerospace; Applied Physics and Materials Science; Bioengineering; Computing and Mathematical Sciences; Electrical Engineering; Environmental Science and Engineering; and Mechanical and Civil Engineering. A clear vision for education and research in each of these areas is instrumental in continuing to attract donors and foundations to support our goals, retaining and attracting the best faculty, and attracting and recruiting the very best and brightest students—who of course become the best and brightest alumni!

Also during the past year, the Resnick Institute, founded with an initial \$20 million gift from Stewart and Lynda Resnick and a \$10 million gift from the Gordon and Betty Moore Foundation, has begun its mission to foster transformational advances in energy science and technology through research, education and communication. Vinod Khosla, co-founder of Sun Microsystems and “greentech” investor, gave the inaugural Resnick Institute lecture on

October 26. Plans to renovate the Jorgensen Laboratory as the new headquarters for this center have begun. Joining the Resnick Institute in the Jorgensen Lab is the Joint Center for Artificial Photosynthesis, a \$122 million DOE energy “hub” that aims to do no less than decisively move us away from a fossil fuel economy by developing revolutionary methods to generate fuels directly from sunlight.

Also established this year is the Terrestrial Hazard Observation and Reporting Center (THOR), whose research seeks to find ways to minimize the damage caused by natural hazards such as carbon emissions, earthquakes, floods, and wildfires. THOR has been endowed with \$6.7 million from Foster and Coco Stanback and with \$3.3 million from the Gordon and Betty Moore matching program and will provide a focal point to unify efforts and allow investigators to focus on critical societal issues. This interdivisional center is jointly managed by our Division and the Division of Geological and Planetary Sciences. Another related example of interdisciplinary research at Caltech is the newly established Community Seismic Network (CNS). By combining the algorithms and analysis from Computer Science with simple, cheap accelerometers employed on a massive scale, this project seeks to enhance our community’s capability to respond to major earthquake disasters.

Our focus in this issue of ENGenious is on the “electrifying century” of Electrical Engineering at Caltech, and I invite you to enjoy reading up on the history of the Department, the ground-breaking research that is currently engaging our faculty, and a profile of Carver Mead (BS '56, MS '57, PhD '60), Gordon and Betty Moore Professor of Engineering and Applied Science, Emeritus, a long-time and much beloved member of the Caltech family. We have rounded out this issue with articles that span the spectrum of activities in the Division, from nanotechnology to quantum algorithms, and I invite you to send us feedback as we endeavor to continue to share with our growing family of alumni and friends the magnificent work that goes on daily in the Division of Engineering and Applied Science at Caltech.



Ares Rosakis
Chair, Division of Engineering and Applied Science

Two GALCIT Alumni's Vision

Graduate Aerospace Laboratories of the California Institute of Technology (GALCIT) alumni Jain-Ming (James) Wu (MS '59, PhD '65) and Ying-Chu Lin (Susan) Wu (PhD '63) wanted to honor professors who have made a significant impact in their lives. Their vision and generous gift to Caltech has established a new lecture series in Aerospace. The first of these lectures was given in honor of Dr. Frank E. Marble, Richard L. and Dorothy M. Hayman Professor of Mechanical Engineering and Professor of Jet Propulsion, Emeritus, a faculty member of GALCIT since 1949. This lecture featured Sébastien Candel (MS '69, PhD '72) from École Centrale Paris, France, who discussed new perspectives in combustion dynamics and control. The second lecture in the series was given in honor of Dr. Anatol Roshko, Theodore von Kármán Professor of Aeronautics, Emeritus, a faculty member of GALCIT since 1952. This lecture featured Garry Brown from Princeton University who discussed structure and vorticity in turbulent shear flow. For more information visit: <http://www.galcit.caltech.edu>



Left to Right: Alumni Ying-Chu Lin (Susan) Wu and Jain-Ming (James) Wu

Sustainability: The Caltech Approach

The newly formed Resnick Institute is working on game-changing solutions to challenges in the generation, storage, transmission, conversion, and conservation of energy. The Resnick Institute recently partnered with Parsons Corporation



Harry Atwater, Director of the Resnick Institute

and organized a forum to identify needs and solutions associated with sustainable energy, sustainable infrastructure, and sustainability in national programs. This forum was an opportunity for researchers, academics, technology leaders, corporate developers, nongovernmental organizations, policy makers, and investors to meet and contribute to the development and deployment of sustainable energy and infrastructure technologies. The Resnick Institute and Caltech have also formed partnership with Swinerton Builders, Pasadena Water & Power, Perpetual Energy Systems, and SUNTECH to lead the way to a carbon-free, renewable energy future by building and activating new photovoltaic arrays. As of October 2010, Caltech's total solar generation capacity is 1.3 mega-watts, which will reduce greenhouse gas emissions by 1,500 metric tons annually. To learn more about the Resnick Institute efforts and to watch in inaugural lecture by Vinod Khosla, venture capitalist, green-tech enthusiast, and co-founder of Sun Microsystems visit:

<http://www.resnick.caltech.edu>

A Think and Do Tank

The Keck Institute for Space Studies (KISS) is a “think and do tank,” with the primary purpose of bringing together scientists and engineers for sustained technical interaction aimed at developing new space mission concepts and technology.



Sergio Pellegrino, a co-leader of the KISS Large Space Structures Study

Several of the KISS studies have been led by EAS faculty including: Large Space Structures; Mission Concepts for Accessing and Sampling High-Risk Terrain; and Future Missions to Titan: Scientific and Engineering Challenges. The EAS Division has also contributed to many other studies including: Coherent Instrumentation for Cosmic Microwave Background Polarization Observations; Quantifying the Sources and Sinks of Atmospheric CO₂; and Monitoring Earth Surface Changes from Space. To learn more about the studies and other programs of KISS visit:

<http://kiss.caltech.edu>

Improving Our Understanding of Climate and Earth Systems

The engineers and scientists who are a part of the Ronald and Maxine Linde Center for Global Environmental Science are working to strengthen scientific understanding and to answer fundamental questions about climate and Earth systems. These questions include: How has Earth’s climate varied in the past? What physics governs the retreat and advance of glaciers and sea ice? How do climate and the circulation of the atmosphere affect each other? How does aerosol pollution relate to climate change? Where does carbon dioxide come from and where does it go? Through field, laboratory, and theoretical studies and close collaboration with the Jet Propulsion Laboratory, the Linde Center scientists and engineers are improving our understanding of climate and Earth systems and informing public policy. They are also engaged in building a new sustainable home for the Ronald and Maxine Linde Center for Global Environmental Science. When completed in 2011, the Linde + Robinson Laboratory will be the first laboratory in a historic building to earn “LEED platinum”—the highest Leadership in Energy and Environmental Design ranking. Learn more by visiting: <http://linde.initiatives.caltech.edu>



Paul Wennberg, Director, Ronald and Maxine Linde Center for Global Environmental Science

Who's New

In the last three years eleven new faculty have joined the Division of EAS. They bring a host of novel research approaches and programs to the Division and the Institute as a whole. Below are short profiles of each, as well as a list of the most recent Moore Scholars who have enriched our research community by bringing new insights and building new connections.

New Faculty

José Andrade

Associate Professor of Civil and Mechanical Engineering



Professor Andrade's research objective is to develop a fundamental understanding of the multiscale and multiphysical behavior of porous media, with special application to geologic materials (e.g., soils, rocks) and engineered infrastructure materials (e.g., cements). With this objective in mind, the aim is to establish frameworks by which the microstructural features of porous materials affect macroscopic material properties. The main tools are mechanics, physics, computational mechanics, and advanced experimentation. Some current applications deal with reactive flow in deformable porous media for sustainable energy (e.g., CO₂ sequestration), mechanics and physics of granular materials for resilient infrastructure (e.g., liquefaction, landslides), and nanoscale modeling of calcium silicate hydrate (C-S-H) for sustainable construction materials (cements). This interdisciplinary research has various areas of synergy: environmental engineering, geotechnics, geosciences, physics, mechanics and computation, and structural engineering. José Andrade was born in Ecuador, South America, and immigrated to the United States at the age of 18 to obtain his BS in Civil Engineering at the Florida Institute of Technology. In 2001, Andrade received a fellowship to pursue his graduate studies at Stanford University. In 2006, he received his PhD in Civil Engineering with an emphasis on Geomechanics and then immediately joined the Theoretical and Applied Mechanics Group at Northwestern University as an Assistant Professor. Andrade is the recipient of several honors and awards including the 2006 Zienkiewicz Medal

in Computational Mechanics and a 2010 National Science Foundation (NSF) CAREER Award. He was a participant in the U.S. National Academy of Engineering Frontiers of Engineering meeting. Andrade's work is currently funded by NSF, US Department of Energy (DOE), and Air Force Office of Scientific Research (AFOSR).

Guillaume Blanquart

Assistant Professor of Mechanical Engineering



Professor Blanquart's research focuses on the modeling of multi-physics and multi-scale fluid mechanics problems resulting from the interaction between combustion processes and turbulent flows. At the center of the work are fundamental problems such as the formation of pollutants, the effects of turbulence on the dynamics of nano-particles and liquid droplets, and various hydrodynamic and flame instabilities. To build a better understanding of these complex flows, the research relies on high-fidelity numerical simulations and targets all scales, from the quantum level to the size of a vehicle, and all types of flows, from homogeneous mixtures to turbulent flows. For instance, the formation of soot particles is studied at the molecular level where the interactions between hydrocarbon species lead to the inception of the first soot particle, and throughout the cycle of an engine where the particles are transported in the turbulent field and slowly oxidized away by chemical reactions. The applications are diverse and include internal combustion engines, gas turbines, flow around reentry vehicles, inertial confinement fusion, fires, and the paint industry. Blanquart received his BS and his first MS in Applied Mathematics from École Polytechnique, France, in 2002. He received a second MS

in Aeronautics and Astronautics in 2004 and his PhD in Mechanical Engineering in 2008, both from Stanford University. He continued as a Postdoctoral Scholar under the supervision of Professor Heinz Pitsch at Stanford University before joining Caltech.

Simona Bordoni

Assistant Professor of Environmental Science and Engineering



Professor Bordoni is an atmospheric dynamicist interested in monsoons and tropical circulations. Using observations and models, her research investigates fundamental dynamical mechanisms that are implicated in the existence of monsoon systems, their location, and their different geographical features, and that might help understand how monsoons change in changing climates. In an ongoing project, she has, for instance, been able to simulate monsoons in a water-covered earth, showing that thermal contrasts between land and ocean, traditionally viewed as the fundamental cause of monsoon circulations, are not necessary for monsoon development. Bordoni received an Italian Laurea in Physics from the University of Rome Tor Vergata in 1996. She completed her PhD in Atmospheric Sciences at the University of California in Los Angeles in 2007, and later in the same year she was a Moore Postdoctoral Scholar at Caltech. She then worked at the National Center for Atmospheric Research as a Postdoctoral Fellow in the Advanced Study Program. Bordoni is the recipient of the American Geophysical Union James R. Holton Award 2009, the UCLA Bjercknes Memorial Award 2005, and a NASA Graduate Student Fellowship in Earth System Science 2003–2006.

Bordoni received an Italian Laurea in Physics from the University of Rome Tor Vergata in 1996. She completed her PhD in Atmospheric Sciences at the University of California in Los Angeles in 2007, and later in the same year she was a Moore Postdoctoral Scholar at Caltech. She then worked at the National Center for Atmospheric Research as a Postdoctoral Fellow in the Advanced Study Program. Bordoni is the recipient of the American Geophysical Union James R. Holton Award 2009, the UCLA Bjercknes Memorial Award 2005, and a NASA Graduate Student Fellowship in Earth System Science 2003–2006.

Azita Emami-Neyestanak

Assistant Professor of Electrical Engineering



Professor Emami's research interests are in high-performance integrated circuits and systems. She is interested in developing new analog, digital, and architecture-level solutions for building complex systems in highly scaled technologies. In particular, she focuses on mixed-signal design for efficient

and low-power data communication in advanced integrated systems, using both electrical and optical signaling techniques. The ultra-low-power and low-area circuits at the interfaces will have a great impact on the performance of multi-processors, biomedical devices, and sensor networks. She is currently working on efficient integrated biomedical implants for neural recording and stimulations. Novel integration techniques, which allow 3D structures, are also among her research interests. Emami received her BS in Electrical Engineering from Sharif University of Technology, Tehran, Iran, in 1997 with honors. She received both her MSc in 1999 and her PhD in Electrical Engineering in 2004 from Stanford University, where she received the Solid-State Fellowship. She was with the IBM T. J. Watson Research Center from 2004 to 2006 and with Columbia University (as an Assistant Professor) from 2006 to 2007. Emami received the NSF Faculty Early Career Development (CAREER) Award for her research on "Data Communication in Advanced Integrated Systems" in 2008 and the Okawa Foundation Research Grant award in 2010.

Julia Greer

Assistant Professor of Materials Science and Mechanics



The key focus in Professor Greer's research is the development of innovative experimental approaches to assess mechanical properties of materials with nano-scale dimensions. One such approach involves fabrication of nanopillars with different initial microstructures, ranging in diameter from below 100 nm to 1 micron by using Focused Ion Beam (FIB)-based and E-beam lithography/electroplating approaches. Their strengths are subsequently measured in a one-of-a-kind in-situ imaging and mechanical deformation instrument, SEMentor, comprised of Scanning Electron Microscope (SEM) and Nanoindenter. This allows for precise control of displacement and loading rates, as well as for simultaneous video capture of the deformation process. The powerful capability of simultaneous mechanical (and, if needed, electrical) data collection while performing real-time imaging of sample morphology evolution has enabled the discovery of a unique mechanical response observed in a variety of material classes. In a striking deviation from classical mechanics, she has ob-

served size-dependent strengths, discrete deformation signatures, and unusual deformation processes. She postulates that these intriguing phenomena arise from effects of free surfaces and serve as the fundamental reason for the observed differences in their plastic deformation from bulk.

Greer received her SB in Chemical Engineering with a minor in Advanced Music Performance from Massachusetts Institute of Technology (1997) and PhD in Materials Science and Engineering from Stanford University, working on nano-scale plasticity of gold (2005). She has also worked at Intel Corporation in a mask micro-fabrication facility (2000-03) and was a Postdoctoral Fellow at the Palo Alto Research Center, PARC (2005-07), where she studied organic flexible electronics. Greer is a recipient of the NASA Tech Briefs award (2010), DARPA Young Faculty Award (2009), Technology Review's Top Young Innovator Under 35 Award (TR-35, 2008), the NSF CAREER Award (2007), the Gold Materials Research Society's Graduate Student Award (2004), and American Association of University Women Fellowship (2003). She was one of 100 invited participants in the National Academy of Engineering's Frontiers of Engineering Symposium (2009) and was recently featured as a "Rising Star" in *Advanced Functional Materials* (2009). Julia joined Caltech in 2007. She is also a concert pianist. Her most recent performances include a violin-piano recital in the Lagerstrom Chamber Series (2009) and the Brahms Concerto No. 2 as a soloist with the Redwood Symphony (2006).

R. Andreas Krause

Assistant Professor of Computer Science



Professor Krause's research is in adaptive systems that actively acquire information, reason, and make decisions in large, distributed, and uncertain domains, such as sensor networks and the Web. The theoretical aspects of his work include statistical learning, Bayesian modeling, decision theory, and optimization. His group devises new algorithms with theoretical guarantees, builds models, analyzes large and complex data sets, and develops systems that can automatically acquire and reason about highly uncertain information. Example applications include monitoring earthquakes using community-held sensors, exploring biological ecosys-

tems using autonomous underwater vehicles, and studying how people make decisions under uncertainty. Krause received his Diplom in Computer Science and Mathematics from the Technical University of Munich, Germany (2004) and his PhD and MSc in Computer Science from Carnegie Mellon University (2008). At Caltech, he is a member of the Rigorous Systems Research Group, the Computation and Neural Systems faculty, and the Center for the Mathematics of Information. Krause is a recipient of an NSF CAREER award (2010) and the Okawa Foundation Research Grant (2009) recognizing top young researchers in telecommunications. His research on optimized information gathering received awards at several major conferences, as well as the best research paper award of the ASCE *Journal of Water Resources Planning and Management* (2009). He is also a passionate classical guitarist.

Katrina Ligett

Assistant Professor of Computer Science and Economics



The focus of much of Professor Ligett's work is on mathematical and computational approaches to fundamental problems in algorithmic game theory and in data privacy, with a particular emphasis on techniques from computational learning theory.

Nash equilibrium strategies are commonly used as a tool for studying selfish behavior in complex systems; the underlying assumption of this approach is that selfish players will find and settle at a Nash equilibrium despite working independently and competitively. In previous and ongoing work, Ligett explores alternative approaches to understanding selfishness, based on algorithms designed to learn. In many situations, understanding the outcomes of learning behaviors has provided new insight into the consequences of selfish play.

The goal of private data analysis is to allow the publication of broadly useful sanitized data while ensuring the privacy of the individuals represented in a database. Ligett's work in this area has provided novel algorithms that a database owner such as a hospital could use to release useful data to researchers, without compromising patient privacy.

Ligett received her ScB in Mathematics and Computer Science from Brown University (2004) and her PhD in Computer Science from Carnegie Mellon University

(2009). She is a recipient of the NSF Graduate Research Fellowship, the AT&T Labs Graduate Fellowship, the CIFellows Postdoctoral Fellowship, and the NSF Mathematical Sciences Postdoctoral Fellowship. She is currently a Postdoctoral Associate in the Computer Science Department at Cornell University and will join Caltech in Fall 2011 as an Assistant Professor of Computer Science and Economics.

Sergio Pellegrino

Joyce and Kent Kresa Professor of Aeronautics and Professor of Civil Engineering, and Jet Propulsion Laboratory Senior Research Scientist



Professor Pellegrino is interested in the mechanics of lightweight flexible structures and particularly in problems related to packaging and deployment. In recent years, one of his main interests has been deployable antennas made of ultra-thin composite materials that are constructed as a single piece, without any mechanical articulations. These structures are folded elastically and are able to self-deploy. Another area of his research has been concerned with the deployment and stability of stratospheric balloons.

Pellegrino received his Laurea in Civil Engineering from the University of Naples in 1982 and a PhD from the University of Cambridge in 1986. He joined the faculty at Cambridge in 1983, as an Assistant Lecturer, and then Lecturer, Reader, and Professor of Structural Engineering. He also served as the Deputy Head (Graduate Studies) of the Department of Engineering. He has held visiting research positions at the Institute for Space and Astronauti-

cal Science (Tokyo), the Nippon Telegraph and Telephone Corporation Spacecraft Structures Laboratory (Yokosuka, Japan), the European Space Technology Centre (Netherlands), the University of Colorado at Boulder, the University of Technology of Malaysia, and Stanford University.

Models of new deployable structures invented by Pellegrino were exhibited at “Contemporary Developments in Design Science: Buckminster Fuller Centennial,” New York 1995–96; “Building for the Future,” Istanbul 1996; “Les Ingenieurs du Siecle,” Centre Pompidou, Paris 1997; and the Farnborough Air Show in 2004. He is a Fellow of the Royal Academy of Engineering and a Chartered Structural Engineer.

Keith Schwab

Associate Professor of Applied Physics



Professor Schwab’s main research directions are to explore fundamental quantum behavior in mechanical structures, the quantum limits of measurements, and the boundary between the classical and quantum world. His research group utilizes and combines techniques from ultra-low temperature physics, ultra-sensitive electronic, microwave, and optical measurement, and nanoscale fabrication and material science. His current work is focused on producing and measuring the quantum ground state of a mechanical device and measuring motion that avoids the limitations of the Heisenberg Uncertainty Principle. His group collaborates widely with atomic and optical physics groups and has produced micro-fabricated single-atom traps and advanced opto-mechanical structures. Schwab received his BA in Physics from the University of Chicago (1990) and his PhD in Physics from the University of California, Berkeley (1996). He was a Sherman Fairchild Distinguished Scholar with Professor Michael Roukes at Caltech where he measured the quantum limit for heat transport. In 2000, he joined the National Security Agency and led a research group to probe the quantum limits of electrical and mechanical structures. He joined the Department of Physics at Cornell University in 2006, and arrived to Caltech in January of 2009. He has received a number of awards for his work, most notably, he was named a Young Global Leader by the World Economic Forum and has attended and contributed to the



annual meetings in Davos, Switzerland in 2005, 2007, and 2008. He is interested in broad issues of national and global security and has appeared on PBS as a panelist for a Fred Friendly Seminar in 2008.

Joel Tropp

Assistant Professor of Applied and Computational Mathematics



Professor Tropp's research focuses on algorithms for solving computationally difficult problems that arise in applied mathematics, statistics, electrical engineering, and computer science. In particular, he studies how constraints on data complexity can be used to develop new techniques for signal acquisition and processing. This area encompasses classical problems, such as variable selection in regression, as well as recent advances, such as compressive sampling. Other applications include inverse problems, machine learning, and data mining.

Tropp studied at the University of Texas at Austin. In

1999, he received his BS in Mathematics and his BA in Plan II Liberal Arts Honors. He completed his MS and PhD in Computational Applied Mathematics in 2001 and 2004 with funding from an NSF graduate fellowship. From 2004 to 2007, Tropp was appointed by the University of Michigan at Ann Arbor as T. H. Hildebrandt Research Assistant Professor. His postdoctoral work was supported by an NSF Mathematical Sciences Postdoctoral Research Fellowship.

Adam Wierman

Assistant Professor of Computer Science



Professor Wierman's research interests are in improving computer system design through the use of analytic modeling and performance analysis. His main focus is on scheduling and resource allocation decisions in computer systems. However, he has also been involved with the design of manufacturing, telecommunication protocols, and the electricity grid. In order to provide performance analysis of computer systems, his work draws on tools that are traditionally used in the operations research community, in particular stochastic modeling, queueing theory, and game theory. However, standard stochastic and queueing models are often not appropriate for computer science applications, and thus a key component of his research is the development of new stochastic models and analytic techniques. Wierman received his PhD (2007) and MS (2004) in Computer Science from Carnegie Mellon University under the supervision of Mor Harchol-Balter. He received his BS with University Honors in Computer Science and Mathematics with minors in Psychology and Statistics from Carnegie Mellon University (2001). He is a recipient of an NSF CAREER award, an Okawa Foundation Research Award, a Siebel Scholars Award, and multiple teaching awards, including the Caltech ASCIT Teaching Award, the Alan J. Perlis Student Teaching Award, and the Carnegie Mellon University Graduate Student Teaching Award. His doctoral dissertation also received multiple awards including the Carnegie Mellon Distinguished Dissertation Award. In addition, he recently served as a visiting researcher at the EURANDOM Institute in the Netherlands and a visiting fellow at the Isaac Newton Institute at Cambridge University.



Interior space of the Walter and Leonore Annenberg Center for Information Science and Technology

Moore Scholars

The Moore Distinguished Scholars program was established by Gordon and Betty Moore to invite researchers of exceptional quality who are distinguished at both the national and international levels to visit the California Institute of Technology for three to six months. There are no teaching or other obligations during the appointment, allowing Moore Scholars to focus on research.



Fazle Hussain

University of Houston Cullen Distinguished Professor; Director, Institute of Fluid Dynamics and Turbulence



Linda F. Nazar

University of Waterloo Professor of Chemistry, and Professor of Electrical Engineering



Lyle N. Long

Pennsylvania State University Distinguished Professor of Aerospace Engineering and Mathematics; Director, Computational Science Graduate Minor Program



Krishna V. Palem

Rice University Kenneth and Audrey Kennedy Professor of Computing



Eric Mjolsness

University of California, Irvine Professor of Information and Computer Science, and Professor of Mathematics

The First Half-Century

An Early History of the Caltech EE Department

by Donna Fox, Robert J. McEliece, and Babak Hassibi

Caltech's Electrical Engineering (EE) Department had its beginnings in the summer of 1910, when Throop Polytechnic Institute (TPI) moved from what is now known as Old Town Pasadena to a 22-acre quiet campus bordered by California Boulevard, Wilson Avenue, San Pasqual Street and Hill Avenue. In 1910, Throop Polytechnic, which became the California Institute of Technology a decade later, offered undergraduate degrees in mechanical, electrical, and civil engineering, but there was no administrative structure, so President James A. B. Scherer, at the behest of Caltech's founding father George Ellery Hale, invited Royal Sorensen to start up an Electrical Engineering Department. It is fair to say that this was one of the best appointments in Caltech's history: Sorensen remained the head of EE for more than 40 years and saw his fledgling Department become one of the powerhouses of electrical engineering in the United States.

Over the years since its inception, the EE Department has shifted its main research focus several times in line with the demands for new technology in a rapidly changing world—from early work on power engineering, to the war effort, to computing and communications. Pioneering research has led to major technological innovations, spawned other disciplines, and developed vitally important collaborations. EE's cutting-edge science has endured for a hundred years.

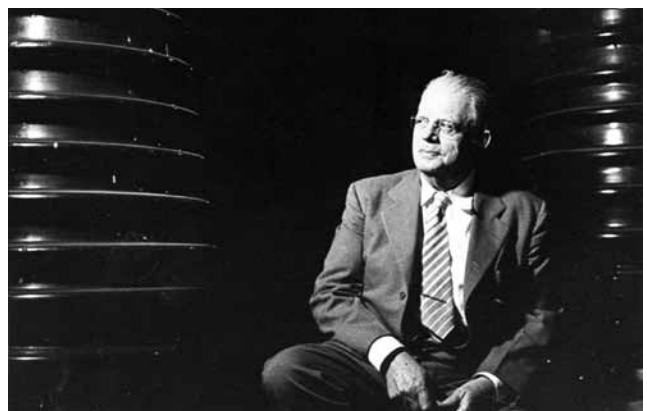
Engineering Based on the Fundamental Sciences

In 1910, when Sorensen, a 28-year-old graduate of the University of Colorado, left General Electric in Pittsfield, MA, to start the TPI EE Department, he worked with Scherer, Hale, and chemistry professor Arthur A. Noyes to produce a unique engineering department based on the fundamentals of physics and mathematics. At first, there were only three engineering students—two EE graduate students, and one mechanical engineering student. In 1913, TPI became Throop College of Technology, and Robert Millikan started a few years later (1917) as Director of Physical Research. In 1920, Millikan succeeded Scherer as Chief Executive, and

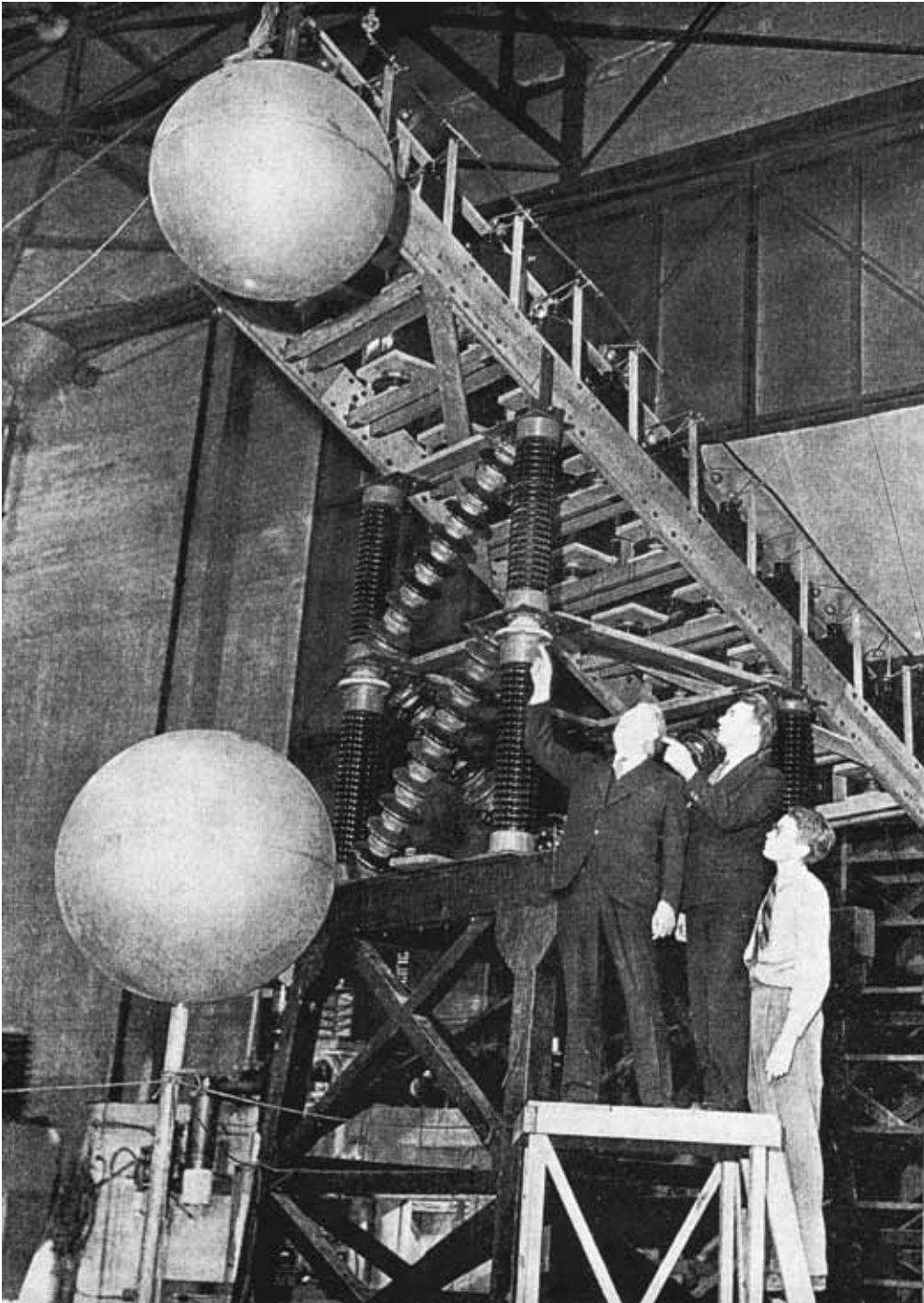
Throop became Caltech. The so-called “Big Three” (Hale, Noyes, and Millikan) drafted a new educational philosophy that emphasized pure science, and Sorensen conceived a plan for graduate study in EE, foreseeing a need for education beyond the traditional baccalaureate degree.

Power Engineering and the High-Voltage Lab

By the early 1920s, master's and doctoral programs in EE had begun, and the achievements of the large group of



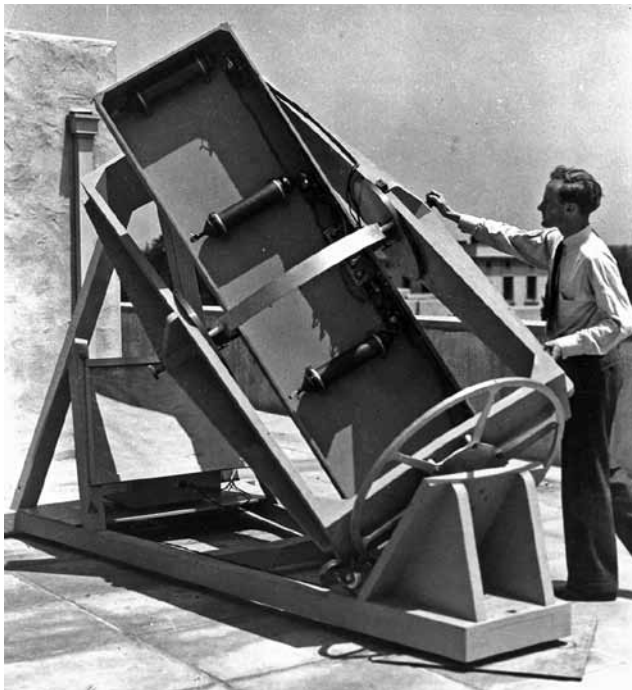
Royal Sorensen



2,000,000 volt surge generator of the High-Voltage Laboratory

alumni these produced proved the merits of his concept of emphasizing physics and mathematics. Sorenson was one of the first to realize the importance of a national grid system to distribute electrical power in large-scale and long-distance transmissions and participated in California's pioneering work on this. In a cooperative venture with the Southern California Edison Company (SCE) in 1923, a high-voltage laboratory was erected on campus (in the lo-

cation that is now Sloan Mathematics) to solve some of the emergent problems in power transmission. It was the first laboratory in the country to have a million-volt power source, provided by a cascade system of transformers designed by Sorensen himself. The High-Voltage Lab was available for both research and industrial testing and was used to aid SCE in the development of high-voltage transmission lines, to furnish lightning protection of oil storage



William Pickering, as grad student, with the experimental cosmic ray telescope he built, used to investigate the source and intensity of cosmic rays.

tanks for the oil industry, and for other research efforts to industrialize Southern California. Shortly after Caltech's lab was completed, a group of Stanford alumni built the Ryan high-voltage lab at Stanford in 1926, and for several years, Caltech and Stanford became the two outstanding schools in the country in the area of high-voltage work. For a time, Caltech was giving more PhD degrees in Electrical Engineering than MIT. Professor Charles Lauritsen built high-voltage vacuum tubes and EE Professor Francis Maxstadt was involved in the testing of insulators and towers, more so than even Sorensen himself. Professor Stuart Mackeown also spent a lot of time in the High-Voltage Lab.

Sorensen's experiments with high-power current interruption in vacuum, designed to address the serious problems of control and protection of high-voltage power systems, led to his invention of the vacuum switch in 1923, although it was not until 1960 that new technology would make this invention commercially feasible. His original model is on permanent display in the Smithsonian Institute in Washington, D.C.

In 1926, EE became part of the Physics and Mathematics Division, as the modern structure of Caltech's Divisions came into place.

Electronics

William Pickering, a New Zealander, came to Caltech as an

EE undergraduate student in the late 1920s, and stayed on to complete a PhD in Physics in 1936. At the time, radio communications and broadcasting were beginning to develop, but the use of electronics in control systems was not yet well known and, as the Department was still heavily oriented toward power engineering, radio communications and vacuum tubes were not considered very important. Mackeown, however, could see the growing importance of this field and urged Millikan to appoint a professor whose research specialty was electronics. Mackeown even offered to sacrifice his own salary for such an appointment. Pickering was the obvious choice and joined the EE faculty shortly after graduating.

During this period (1936), the Jet Propulsion Laboratory (JPL) began in Pasadena as the Guggenheim Aeronautical Laboratory, California Institute of Technology (GALCIT) rocket project, led by Professor Theodore von Kármán and financed by Harry Guggenheim. In 1940, the GALCIT group became a rocket research, development, and testing facility. A few years later, a substantial contract from the U.S. Army Air Corps transformed it into the large, permanent laboratory it is now, and its name was changed to JPL. Its purpose was to research, develop, and test missile technology. There was a need for electronics to support missile guidance and tracking systems, and Pickering's specialization in electronics drew him there. In 1954, he became the director of JPL and remained in that position until 1976. Under his leadership, electronics grew in prominence at the lab, which became a NASA facility in 1958, and work began on a worldwide, civilian satellite communications network, known today as the Deep Space Network (DSN).

The War Years

During the World War II years, Caltech's EE program was put on hold. Several faculty members left to take various war jobs, and from 1943 until 1946, Pickering organized a three-year, year-round Navy "V-12" curriculum to meet the military's need for radar training. Upon completion of the program, students went to MIT's Radiation Laboratory (Rad Lab) to study the more specific techniques. Pickering visited the Rad Lab periodically to learn more about the electrical characteristics of waveguides. He also organized and managed the Engineering and Science Management War Training (ESMWT) program, a series of evening courses that were given all around Los Angeles, and personally taught some of the approximately 20 different courses.

It was mostly done at the junior college level and was presented at several high schools in the area.

The war effort also caused other Caltech faculty to redirect their focus. Gilbert McCann (PhD EE '39) joined Westinghouse in Pittsburgh to study natural lightning phenomena. But when his research was diverted to support the military, he was set to work devising a way of doing complex engineering calculations using electrical circuits to simulate mechanical forces. This was to become the basis of the analog computer that he invented to do calculations that would previously have taken years. McCann used this computer to design a system for improving the tracking accuracy of anti-aircraft guns, which enabled the British to shoot down almost all the German V-1 bombers crossing England's eastern coastline.

After the war, Frederick Lindvall (PhD EE '28), who was the first to receive a PhD from the Caltech EE Department, became Professor of Electrical and Mechanical Engineering and Chairman of the Engineering and Applied Science Division, a position he held for 24 years. Lindvall pioneered and taught advanced engineering courses, and encouraged students to take as many courses as possible in other departments and divisions at Caltech. He introduced the concepts of "interdisciplinary research," "systems engineering," and "management of technology."

The Computing Era

In 1946, McCann left Westinghouse to join Caltech's EE faculty and began setting up an analysis lab to build an improved version of his analog computer. He negotiated a deal with Westinghouse to make two of everything, so that the duplicate parts were sent to his Caltech lab at a reduced cost. The 33,000-pound computer was assembled with the help of EE professors Charles Wilts (who eventually became inter-



Left to Right: Frederick Lindvall, Lee DuBridg, Gilbert McCann, and Kendrick Hebert in the Willis H. Booth Computing Center

ested in control systems) and Bart Locanthi. Their computer became known as Caltech's "Direct Analogy Electrical Analog Computer," and it provided service for JPL, the military, and the entire Southern California aerospace industry. The computer was mainly used to solve design analysis problems in the fields of solid mechanics, fluid mechanics, and heat transfer. In particular, methods of structural stress analysis, vibration analysis, and aero-elastic analysis of airframes were developed, the latter carried out primarily by McCann, Wilts, and Richard MacNeal (MS EE '47, PhD EE '49).

By 1950, the McCann's lab had become too busy for Caltech. The director of GALCIT, Clark Millikan, suggested spinning off a commercial company, and Computer Engineering Associates (CEA) was formed on Halstead Street in Pasadena. McCann, the largest shareholder, could not run the company since he would have to resign his faculty position to do so, but MacNeal and William Dixon (BS EE '48, MS EE '49, PhD EE '52) became senior managers, and Locanthi was in charge of constructing the computers. They were built pri-

marily for the burgeoning American aircraft industry.

Shortly before the spin-off, McCann recruited Stanley Frankel to head a small, innovative digital computing unit. A computer scientist with a PhD in Physics from Berkeley, Frankel had become interested in digital computing during his time at the Manhattan Project in Los Alamos. At Caltech, he worked with graduate student Bernard Alder (PhD EE '52) on his thesis project—the simulation of the interaction of atoms using statistical mechanics and liquid theory—for which they developed what is now called the Monte Carlo method of statistical analysis. This pioneering work has become essential to a wide range of scientific and technical work, from nuclear weapons development to VLSI chip design.

In the 1950s, Frankel designed the logic for a general-purpose “poor man’s computer,” called MINAC. Librascope, a Southern California company located in Glendale, licensed the design from Caltech and hired Frankel and physics graduate student James Cass (MS EE '53) to turn the design into a production-ready product. Marketed as the LGP-30, it may well be considered to be the first personal computer and is now on display at the Smithsonian Institute and the Computer History Museum in San Jose, CA.

Growth in the 50s

Robert Langmuir (PhD Physics '43) left the General Electric Research Laboratories in New York in 1948 to join the EE faculty and remained there until his retirement in 1980. He had invented and patented a mass spectrometer in 1940 and discovered the radioactive isotope K37. While at General Electric, Langmuir had worked on the development of CW (continuous wave) magnetrons, which were later used by the Navy to jam enemy radar. In 1960, Langmuir participated in the building of the 1.5 BeV synchrotron at Caltech, the first to operate in the United States. He also taught courses in electricity and magnetism, and electronics, while conducting research in various topics in applied physics and engineering.

Five years later, in 1953, Lester Field arrived from Stanford, where he had been one of the originators of their electron-tube laboratory. He continued traveling-wave tube work at Caltech, setting up his lab in the basement of Spalding. Field developed several forms of beam plasma and established a tube-research activity that expanded

into a group studying plasma physics and microwave interaction with matter. After the microwave-tube era came to an end in the late fifties, his research focused mostly on plasma physics. Charles Papas, who joined the EE faculty a year after Fields (1954), focused his work on electricity and magnetism. In 1965, he wrote a book, *Theory of Electromagnetic Wave Propagation*, based on his Caltech lectures, in which he presented a number of newly important topics in the theory of electromagnetic wave propagation and antennas in a coherent and simple way, providing evidence that these ideas developed from the Maxwell field equations.

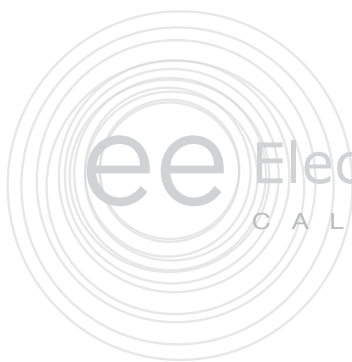
David Middlebrook, who joined the EE faculty immediately after gaining a Stanford PhD in 1955, became known as a power electronics icon. In 1970, he founded the Power Electronics Group at Caltech, which developed into an academic discipline. His teaching was widely lauded by both students and colleagues, and in 1997 he was awarded Caltech’s highest teaching award, the Richard P. Feynman Prize for Excellence in Teaching. He had a deep understanding of both power electronics and electronic circuit design and taught analog and power electronics courses both publicly and at Caltech. His seminal book, *An Introduction to Junction Transistor Theory*, helped engineers understand how to apply transistors in circuit design. His extra-element theorem, which yields simple formulas for the effect of adding a single element to an electronic circuit, is still widely used in circuit design and measurement.

This glimpse into the early evolution of Caltech’s EE Department highlights its heritage. Space limitations prevent us from casting a wider net and crediting all those whose work has been a part of this impressive history. Since its beginnings in 1910, the EE Department has laid a strong foundation to support the scientific research and discovery that continues today. Since the 1960s, it has expanded into new areas, such as solid-state circuits and devices, electromagnetics and optics, control, communications and information systems, and networks. It also played a critical role in spawning the Applied Physics, Computer Science, Control and Dynamical Systems, and Computational and Neural Systems Departments at Caltech and retains close ties to these through several joint faculty appointments. Our complementary article highlighting current faculty research interests provides further details. **E N G**

Visit: <http://ee2.caltech.edu/centennial/memories>



A research fellow in Electrical Engineering tests a microwave antenna.



Electrical Engineering

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Electrical Engineering

Celebrating the Past Century and Pondering the Next

In celebration of the centennial of Electrical Engineering (EE) at Caltech, ENGenious sat down with the EE professorial faculty to learn more about them and their vision for the future. Three themes ran through all of our conversations: the opportunities that lie on the boundaries of disciplines; the key role played by mathematics and physics; and the impact made by students.

Our journey into Caltech EE started with the Executive Officer of the Electrical Engineering Department, Professor Babak Hassibi. When asked what makes Caltech EE unique, he replied that compared with other top schools, the Department is much smaller. “We can’t cover every area in EE,” he said, “so the emphasis has been to hire in strategic areas where we think the impact can be higher. We take a lot of care to ensure that the groups we have in these areas are world class and highly visible,” he added. “The small size of the Department gives us more freedom to explore different things. At a bigger school, if I want to go outside my comfort zone and do something else, I’ll likely be treading on someone else’s toes. Here that doesn’t happen, so the faculty can be a lot more flexible. And because the Department is small, there isn’t much of a boundary between EE and other areas such as Computer Science (CS), Applied Physics, Applied Math, or Control and Dynamical Systems. In fact, in many cases, these Departments grew out of EE.”

These permeable boundaries are the key to Hassibi’s vision for the future of EE. “The next century will be a lot more interdisciplinary, in the sense that much of the exciting stuff will happen at the boundary of the current disciplines,” he said. Engineering schools are still structured on the basis of 19th century technology, where there was a clear division between mechanical engineering, electrical engineering, civil engineering, and such, Hassibi pointed out. “If we were to start universities and create disciplines from scratch today, I doubt we would do it in the same way.” He sees the

next century as one in which disciplines that have become highly specialized begin to talk with one another. “Caltech’s students are already open to this mode of thinking,” he said. “Every year, we have several undergraduates who double major in things that one would not have thought of in the past—like EE and biology, or EE and economics. I think in the 21st century there will be a lot of opportunities for people with this kind of interdisciplinary background.”

Expanding on the key role played by students, he explained that the experience they get at a place like Caltech is different. “We pay attention to the student experience—and I don’t think it is just lip service.

The next century will be a lot more interdisciplinary, in the sense that much of the exciting stuff will happen at the boundary of the current disciplines.

Each EE faculty, on average, gets 7 or 8 undergraduate advisees, and this year one-fifth of all graduate applicants to Caltech applied to the EE program. So it’s a very visible Department and the faculty interact with a large body of the Caltech students. The EE students here get a very solid and broad education.” Hassibi went to Stanford for graduate school, where the EE graduate student body alone numbers between 600 and 700. When he was taking classes, the only students he met were other EE students. At Caltech, because it is smaller, there is a much greater mix of students who take the different courses. For example, Hassibi said, if there is a course on optimization for EE students to take, it is often taught by someone who is a non-EE faculty, and there will be students from EE, CS, Applied Math, and even Economics in the class. “So just the fact that students sit next to students with different backgrounds and



different interests makes the student experience unique.”

Asked how he came to the field of electrical engineering, Hassibi replied, “When I was in high school in Iran I wanted to do physics. If I had been able to leave the country immediately after high school and come to the States, that’s probably what I would have studied. However, as I could not leave Iran, it seemed more prudent to pursue something I could make a living off, and electrical engineering seemed the right compromise. When I look at it now, I realize I didn’t really know what EE was when I came out of high school. I had exposure to parts of physics such as electricity, and magnetism, but I didn’t really know how they were used in electronic circuits or signal processing. Over the years, I have had the good fortune of having many outstanding professors who have helped shape my career, and have been able to cut out a niche in control, communication, and signal processing that I find very satisfying, both in terms of educating students and research-wise.”

When asked to speak about his research, the conversation quickly turned to his love of mathematics.

Babak Hassibi

Professor of Electrical Engineering and Executive Officer for Electrical Engineering, and Associate Director of Information Science and Technology

“*My original interest in physics was because it was mathematical, beautiful math that you could use to explain certain phenomena. I’ve now discovered that there is also beautiful math you can use to design systems and figure out how they work.*”



Yaser Abu-Mostafa

*Professor of Electrical Engineering
and Computer Science*

“*EE has become a very versatile discipline and the research culture makes it easy for us to investigate novel issues that are mathematically rich without worrying too much about how they relate to electricity.*”

“We’re an engineering department, so we care about solving problems, putting systems together, designing things, optimizing performance, and all that. Different people use different tools for that. The tools that my group uses are very mathematical—but they are tools, nonetheless—and actually do help in solving problems that otherwise cannot be solved. My original interest in physics was because it was mathematical, beautiful math that you could use to explain certain phenomena. I’ve now discovered that there is also beautiful math you can use to design systems and figure out how they work. One of the areas we research is communication over wireless networks without any infrastructure (ad hoc networks). It turns out that these networks are useful not just for communications; they can also sense, or even influence, the environment. As an example, think of a network of cars and stop lights with sensing and wireless capabilities. As your car approaches the intersection it sends a signal to the traffic light, “I am here, turn green,” then, the traffic light responds, “Please wait, another car is in the intersection.” There are infinite possibilities of how these sensing networks can change and improve our world.”

Yaser S. Abu-Mostafa, Professor of Electrical Engineering and Computer Science, gave us more insight into the important role of mathematics in EE: “Electrical engineers have always been comfortable with advanced mathematics, and whenever a new engineering discipline arose that required mathematical sophistication, it found its home in electrical engineering even if it had little to do with electricity. As a result, EE has become a very versatile discipline and the research culture makes it easy for us to investigate novel issues that are mathematically rich without worrying too much about how they relate to electricity. The result over the decades is a vast body of knowledge that has a profound impact on society in a wider range of applications than most engineering disciplines.”

The journey of Assistant Professor of Electrical Engineering and Computer Science Tracey Ho to EE also started with mathematics, but first she took a detour.

“I studied EE in college because I liked mathematics and the subject had interesting applications of fun math. After college I worked for a year-and-a-half in the Ministry of Transport in Singapore, but then decided I liked engineering more than writing policy papers and speeches, so I went back to graduate school. I was very happy to find a place as dynamic and exciting, and at the same time as welcoming and supportive, as Caltech.”

Currently Ho’s group is investigating reliable communication in diverse network scenarios, using analytical tools from information theory and networking to characterize fundamental communication limits, and using coding to approach those limits. She is interested in exploring applications in space missions communications and has had discussions on coding for wireless communications in spacecraft with colleagues at JPL. “I suppose there would be a certain vicarious thrill to have my work make it to outer space,” she said.

Ho’s interaction with JPL follows a strong tradition of cooperation. According to Charles Elachi, Professor of Electrical Engineering and Planetary Science, Caltech Vice President, and Director of the Jet Propulsion Laboratory, “The EE Department can take particular pride in providing some of the key leadership at JPL, such as Bill Pickering, who is considered to be ‘the mother of JPL.’ Although Von Kármán was the original founder, JPL’s missions to explore the solar system began during Pickering’s tenure. In the last fifty years, we have gone from not knowing how to launch something into space to having twenty spacecraft exploring the solar system and monitoring almost every parameter of our planet to understand the changes that are happening to it. The things that Caltech and JPL have been able to accomplish in such a short time are amazing,

Tracey Ho

*Assistant Professor of Electrical Engineering
and Computer Science*

“*I suppose there would be a certain vicarious thrill to have my work make it to outer space.*”





Charles Elachi

Caltech Vice President; Director of the Jet Propulsion Laboratory; Professor of Electrical Engineering and Planetary Science

“*Tesla is becoming a cool person...a key electrical engineer is becoming a cool person. That's not very common. Young people are becoming more interested and they find electrical engineering to be a cool business to work in.*”

and that is something that we can all take pride in.

Elachi then turned his thoughts to the next generation. “I think for young people, EE is a field that will have some very exciting developments in the future, because there will be a lot of innovation in very practical things that will improve our life and strengthen the economy, such as the use of remote sensing to monitor what’s happening to our planet.”

He added, “Tesla is becoming a cool person. Tesla did a lot of fundamental work in electrical engineering a hundred and some years ago but then he was not as highlighted in his innovation as Edison. But now it seems for the young people, Tesla is becoming cool—the electric cars are called the Tesla car. What is interesting about it is that it’s now in the public media; a key electrical engineer is becoming a cool person. That’s not very common. Young people are becoming more interested and they find electrical engineering to be a cool business to work in.”

Continuing with the theme of inspiring the next generation, when we asked Gordon and Betty Moore Professor of Computation and Neural Systems and Electrical Engineering Jehoshua Bruck about magical moments in his career, the conversation quickly turned to students. “There are many magical moments related to watching students grow,” he said. “Training, motivating, and inspiring the next generation is in some sense more important than the actual work we do right now, because they in turn will inspire the next generation and so on. I think the Caltech logo shows the most important thing we do: the two hands aren’t holding the torch together—one hand is passing it to the other. It shows the passing down of the light of knowledge.” Teaching and learning is not just about the mechanics of how to solve a problem,” he added. “You want to deepen understanding.”

Bruck’s other passion is his research, which combines the design of distributed information systems and the theoretical study of biological circuits and systems. After graduating from Technion-Israel Institute of Technology, he worked for IBM for a few years in Israel before going to graduate school at Stanford. “During my time at IBM, I had my first research results,” he recalled. “My wife came

to pick me up and I told her that today I had found such a beautiful thing in my research that it's very likely I will never find something of that magnitude again in my whole career." Obviously, it has happened many times since then, he added, "But every day, I feel I've won the lottery because of the work we do here. We're having a lot of fun and yet for some strange reason they keep paying us."

We also spoke about good fortune with P.P. Vaidyanathan, Professor of Electrical Engineering. "The breakthrough that got me into the field of signal processing happened when, back home in India, there was a professor in my master's program who announced a lottery for a project in the application of microprocessors in biological signal processing, and I was lucky enough to get it. I thought this was great because he was the best professor and I wanted to work with him. That professor was a great man, but he didn't have any background in signal processing so I had to more or less learn it myself. In those days, there was only one book on signal processing in my building and I had to take an hour-long bus ride to the Indian Statistical Institute to get hold of other books on the subject, so life was hard in those days."

Before diving into his research Professor Vaidyanathan gave us an overview of the EE Department. "There are the physical layer faculty, people who build things and make them work, and there are people like me who do a lot of theoretical work bordering on information science." These days, he said, the Department has become very information science-oriented, and information sciences itself is very mathematical. This trend will continue; information processing and mathematics are required in digital communications, radar signal processing, image and speech processing, and even in molecular biology. "As

Jehoshua (Shuki) Bruck

Gordon and Betty Moore Professor of Computation and Neural Systems and Electrical Engineering

“*There are many magical moments related to watching students grow. Training, motivating, and inspiring the next generation is in some sense more important than the actual work we do.*”





P.P. Vaidyanathan

Professor of Electrical Engineering

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a theoretician doing work on computer signal processing, I could find a lot of interesting problems in DNA,” he said. “For example, how do you computationally predict the location of a gene? Or a non-coding gene? These questions are very interesting from a signal processor’s viewpoint.”

Another EE faculty member who is exploring the boundaries of EE and biology is Ali Hajimiri, Thomas G. Myers Professor of Electrical Engineering. “There are tremendous opportunities on the boundary between EE and bioengineering,” he said. “We can make sophisticated systems such as integrated circuits that can have a significant, tangible impact on people’s lives. It’s very important for me to see that.”

One of Hajimiri’s research areas is self-healing systems and circuits. Biological systems, he explained, have a lot of resilience built into them. For example, if we cut our hand, we don’t die, we heal. His group is trying to engineer systems that also heal if there

is a failure. “The self-healing is done in multiple layers: at the circuit, at the device level, and at the system level, and all of these things have to work together,” he explained.

Hajimiri described the EE Department as “a collection of centers of excellence that allow faculty to work closely with each other, as evidenced by the kind of creative things and tangible results that have come out.” He then sent a message to the alumni. “Caltech can only remain as influential as it is by maintaining a very high level of quality. We would like alumni to be involved in our activities, contribute to them, talk to us, give us feedback, and provide an environment where we can exchange ideas and thoughts and receive the benefit of their experience.”

This invitation to alumni to get involved was shared by many of the EE faculty, including Amnon Yariv, Martin and Eileen Summerfield Professor of Applied Physics and Professor of Electrical Engineering. “The message I would like to transmit to our alumni is that in spite of our great

achievements in EE we are a very vulnerable organism, chiefly because of our small size. Our success depends critically on attracting the best possible faculty and graduate students. As a matter of fact, without top students the best faculty will not come here, and vice versa. If I had to limit myself to one area where our alumni and friends can be of assistance, it would be to help us attract, by personal involvement and financial help, the best graduate students in the world.”

Its open, welcoming, and interdisciplinary nature is one of the unique features of the EE Department, Yariv said. “The ability to have students in my group from other departments, especially Physics, enabled me to follow research directions that were not traditionally EE.” He finds it exciting to see graduate students pushing at and even crossing the boundaries of various fields. “Maybe the single most exciting moment in my career occurred back around 1970, when after two years of trying, one of my first graduate students, David Hall, succeeded in demonstrating the possibility of guiding and modulating light in a semiconductor p-n junction. This helped launch the field of optoelectronics and much of our own subsequent work.” Currently, the Amnon group’s research aims at developing “the new technologies that will be mandated by the seemingly endless appetite for optical bandwidth.” Specifically, they are working at extending, to the field of laser optics, some key ideas that form the foundation of the microwaves and the radio frequencies fields.

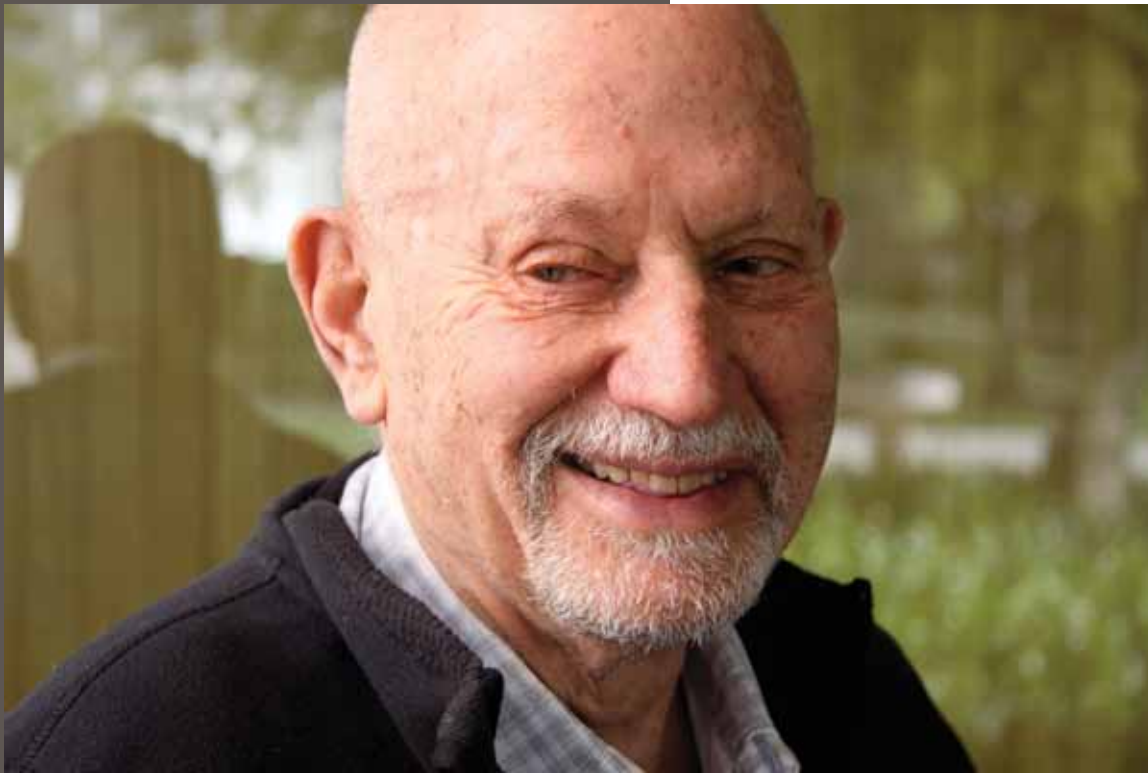
Axel Scherer, Bernard A. Neches Professor of Electrical Engineering, Applied Physics, and Physics, also emphasized the key role played by students. “The

Ali Hajimiri

Thomas G. Myers Professor of Electrical Engineering

“*We can make sophisticated systems such as integrated circuits that can have a significant, tangible impact on people’s lives. It’s very important for me to see that.*”





Amnon Yariv

Martin and Eileen Summerfield Professor of Applied Physics and Professor of Electrical Engineering

“If I had to limit myself to one area where our alumni and friends can be of assistance, it would be to help us attract, by personal involvement and financial help, the best graduate students in the world.”

students are what makes EE unique. They are the people who drive the research in my group and the energy that makes things work. This generation of students will learn the vocabulary, not only of electrical engineering, but of biology and other sciences that apply to the work. For the past 18 years I have taught a freshman class co-listed in Applied Physics and EE that encourages people to make real devices early on in their undergraduate career. When I started teaching it, there were mainly electrical engineering and applied physics students. But now geologists, biologists, and astronomers take this class because they're interested in how small things get made. I tell my students that chemistry, physics, biology, and engineering all come together at the smallest scale, and we're headed into a world where the traditional boundaries are shrinking. The tools of electrical engineering are being adopted by many other disciplines and it's a good sign."

Asked about his own group's research, Scherer said, "My students and I are building systems that can be used to increase the capabilities of medical care without increasing the cost." They recently developed an inexpensive method

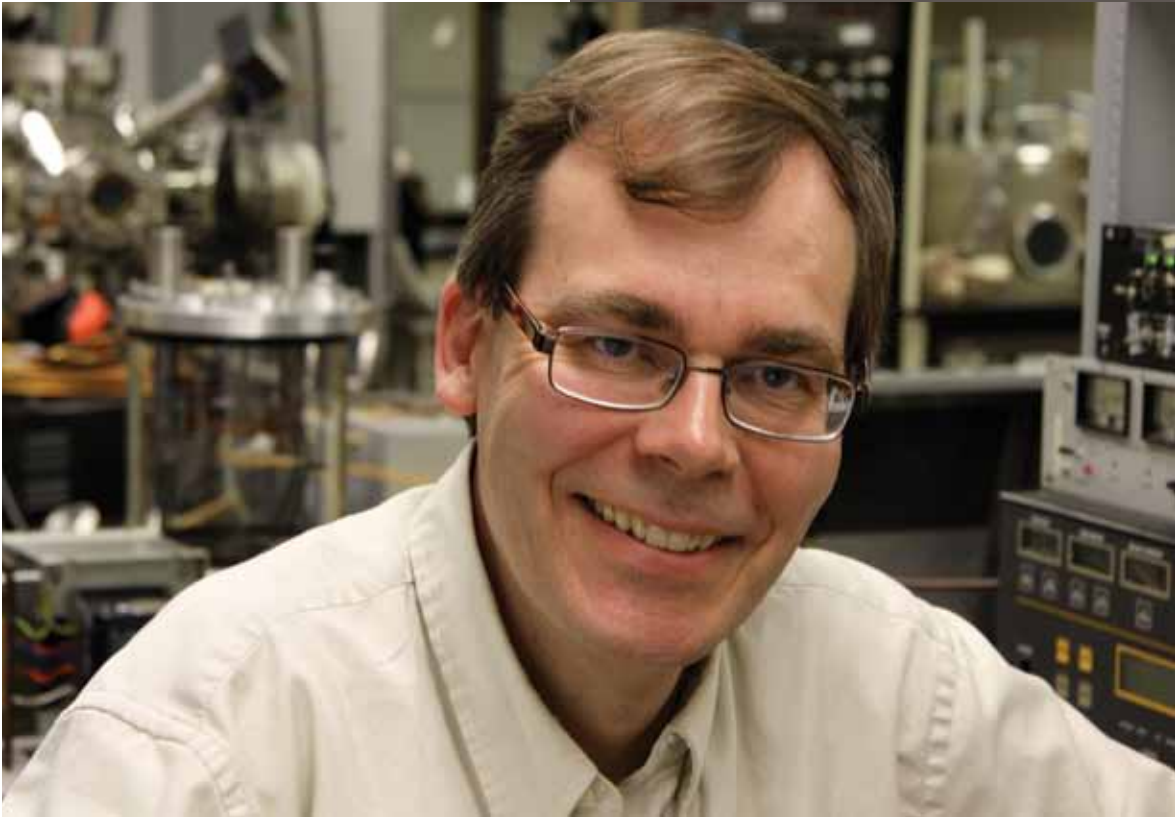
of identifying whether pathogens are viruses or bacteria, so that the correct treatment—antibiotics or not—can be administered promptly, at a cost of about \$100 instead of the \$50,000 it costs now. An interesting byproduct is that the process is also more efficient; the results of the analysis are available within minutes rather than hours. “That’s a big difference,” Scherer said, “because you can tell the patient the answer within a couple of minutes, and they don’t have to come back later.”

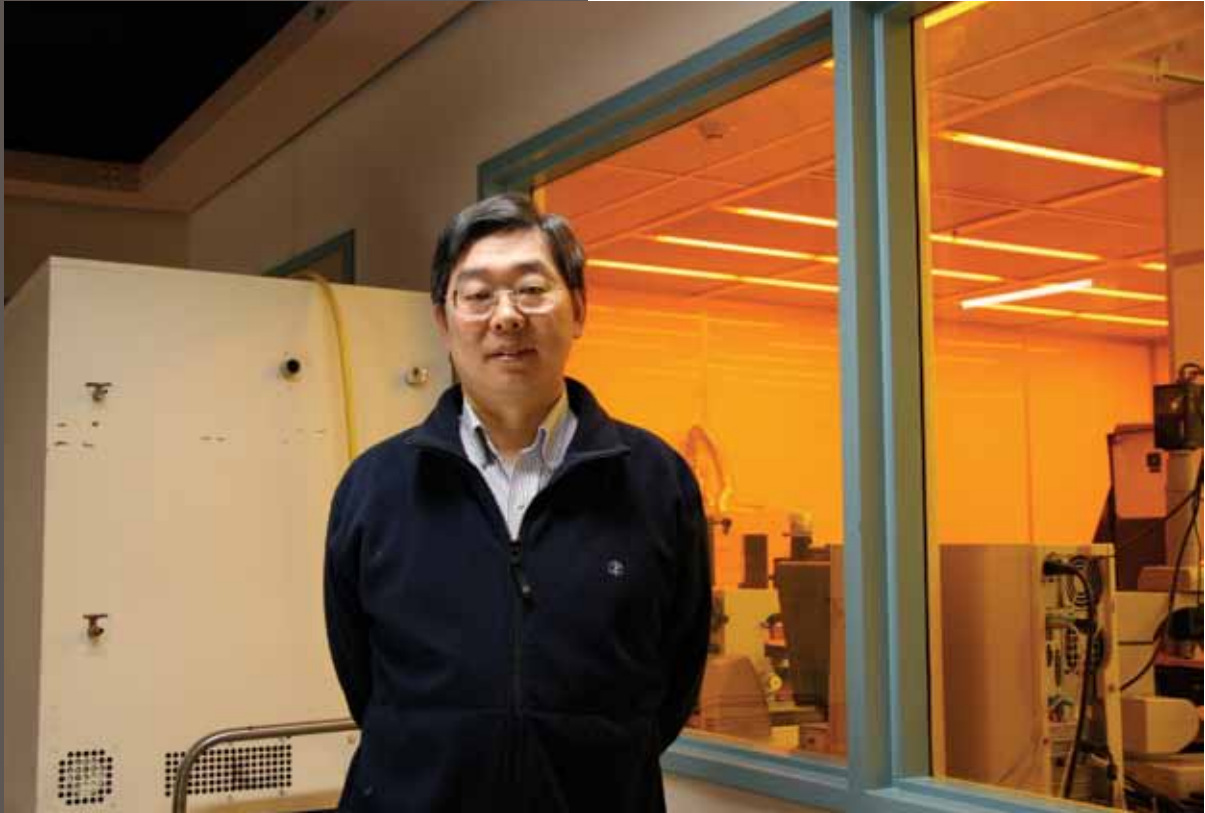
To further investigate how the use of technology is unifying efforts across disciplines we spoke with Yu-Chong Tai, Professor of Electrical Engineering and Mechanical Engineering. “About 10 years ago, it struck me that bio implants were really in the stone age. I decided that this offered me a wonderful opportunity to keep busy for the rest of my career. Think about shrinking a cell phone down to the size of a rice grain, then adding sensors, wireless communications, and other functions, and putting it in the

Axel Scherer

*Bernard A. Neches Professor of Electrical Engineering, Applied Physics, and Physics;
Co-Director, Kavli Nanoscience Institute*

“*The students are what makes EE unique. They are the people who drive the research in my group and the energy that makes things work.*”





Yu-Chong Tai

*Professor of Electrical Engineering
and Mechanical Engineering*

“*Think about shrinking a cell phone down to the size of a rice grain, then adding sensors, wireless communications, and other functions, and putting it in the human body.*”

human body. If I can live 50 years longer, I think I will see this realized. Biology has done a great job of providing clues of where we need to go, but now we need technological breakthroughs.”

Tai and colleagues, including Azita Emami-Neyestanak, Assistant Professor of Electrical Engineering, are working on retinal implants. Emami-Neyestanak's group, which works on microelectronics, is currently building very low power micro-chips to implant inside the eye of people who have lost their retina, but still have functioning neurons. They will then wirelessly send the information about the image to the implant, which will in turn stimulate the neurons in the eye to transmit the image to the brain's visual cortex.”

In addition to microelectronics, Emami-Neyestanak is passionate about bringing more women into engineering and conveying to them that engineering is a field that has a lot of human components to it. Some female students

think that electrical engineering is about sitting behind a computer and being isolated from the world, but actually, she said, engineering in general and electrical engineering specifically is a very interactive area of research that is very rewarding. “Caltech is a very good environment for female students,” she added, “and the question of whether you are a man or a woman never comes up. Everyone just does what they are passionate about.”

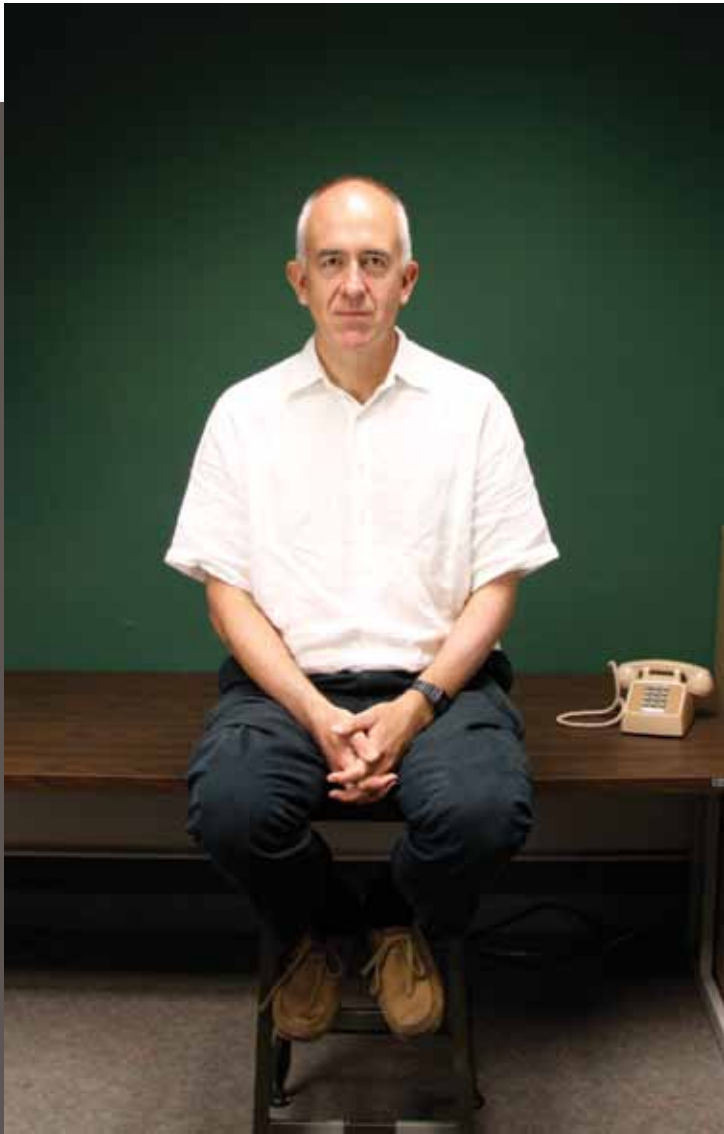
Emami-Neyestanak’s path to EE started in Iran. “I went to a girls only high school, which was for exceptionally talented students. We were the only school that had the freedom to do things differently. I got very interested in hardware design, and that’s how I ended up coming to the field of EE. For me it was the best choice, because I like physics and math, but at the same time I liked to build things that can eventually be used to change the world.”

Azita Emami-Neyestanak

Assistant Professor of Electrical Engineering

“*Caltech is a very good environment for female students, and the question of whether you are a man or a woman never comes up. Everyone just does what they are passionate about.*”





Pietro Perona

Allen E. Puckett Professor of Electrical Engineering

“*We seem to be very lucky in that we have a harmonious group that gets along really well, with respect for each other. And we are exceptionally good at what we do.*”

Several of the EE faculty commented on how the impact of the Department is out of proportion relative to its size. Pietro Perona, Allen E. Puckett Professor of Electrical Engineering, explained that “the quality of both faculty and students is incredible, which means that our work is, on average, the most innovative and useful. The quality of interpersonal relationships is also exceptional. We seem to be very lucky in that we have a harmonious group that gets along really well, with respect for each other. And we are exceptionally good at what we do.”

Perona has also joined those with a growing interest in biology, and is researching the application of machine vision to measuring the behavior of laboratory animals. “This is very exciting because it allows me to explore what ‘behavior’ is,” he said, “and it is enabling unprecedented experiments in genetics and in ethology.” He is also studying how humans allocate their visual resources to optimize their performance in a given task. “It appears that humans are surprisingly optimal.”

Another faculty member who works on the boundary of disciplines is Changhuei Yang, Associate Professor of Electrical Engineering and Bioengineering. On the subject of crossing boundaries he explained, “Caltech faculty can freely expand to different areas and that may not be as easy to do in bigger schools in which you can’t really expand too far before knocking into somebody else’s research area. Another good thing about Caltech EE and Caltech in general is that it’s relatively easy for a new professor to come in and try to explore different research areas.”

Yang tries to focus his group on developing practical technologies that can significantly impact medicine. One area is doing biochemical assessment on tissues without any invasive chemical or physical process. Human tissue is opaque and scatters light very strongly. What we have found is that this scattering process, even though it looks random, is actually deterministic in nature. This means that if you take all those scattered lights and time reverse them you can actually force them to retrace their path through the tissue and recover back what was originally sent into the tissue. You don’t get the complete set of information

back, but you get a pretty good subset of it.” This work can potentially lead to deep tissue optical imaging that will give biochemical information, something that ultrasound or X-rays cannot do. For example, he said, cancer cells might express biochemicals before they become a tumor, and if we could image that, it would be very useful.

Whether it is cancer, devices, theory, or systems, EE faculty take delight in the fact that they can work on whatever they are passionate about. When asked what he would like to work on, David Rutledge, Kiyo and Eiko Tomiyasu Professor of Electrical Engineering, replied, “I have always worked on what I wanted to work on. I have only one project now, assessing future fossil-fuel supplies and the possible climate impacts. It has everything: geology, engineering, atmospheric science, politics, and scandal.”

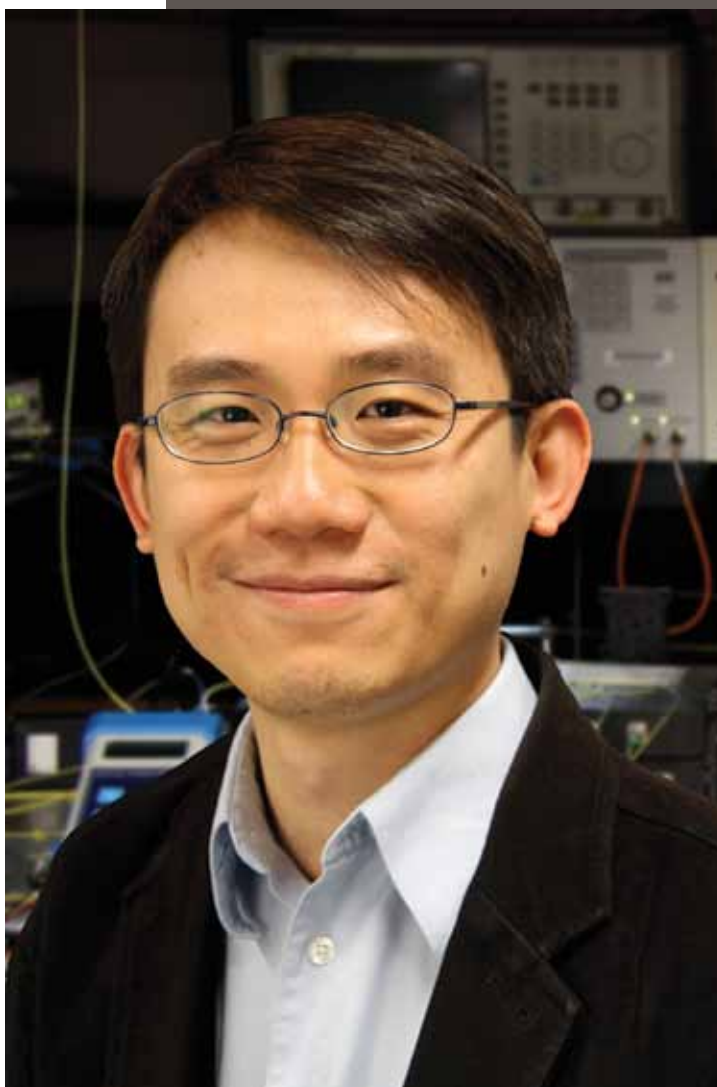
The path Professor Rutledge took to EE also involved mathematics, but in a slightly different way. “I was an undergraduate major in mathematics at a liberal arts college, and I had a summer job at Rensselaer Polytechnic Institute (RPI). The main thing the job taught me was that I was not going to make a living at mathematics. However, my roommate was in EE, and I became interested in his circuits textbooks.”

Professor of Electrical Engineering Michelle Effros’s path to electrical engineering was anything but direct. “If asked, as a high school senior or even a college freshman, to list my top 20 or 30 potential majors, engineering would not have appeared on the list,” she said. “I didn’t know what engineers did. I didn’t have any friends or relatives in engineering, and I recall quite distinctly that engineering didn’t ‘sound good,’ though I knew almost nothing about it. My first engineering class at Stanford was called ‘visual thinking’, and it was taught in the Mechanical Engineering Department. It was one of those classes where you do all kinds of crazy projects—building devices out of a short list of allowed supplies to solve very particular problems, like popping a 3-foot-diameter balloon in the middle of a pond without the use of projectiles.

Changhuei Yang

Associate Professor of Electrical Engineering and Bioengineering

“*Caltech faculty can freely expand to different areas and that may not be as easy to do in bigger schools in which you can’t really expand too far before knocking into somebody else’s research area.*”





David Rutledge

*Kiyo and Eiko Tomiyasu
Professor of Electrical Engineering*

“*I have only one project now, assessing future fossil-fuel supplies and the possible climate impacts. It has everything: geology, engineering, atmospheric science, politics, and scandal.*”

I enjoyed it, so that got me thinking about engineering.”

Now that she is on the path of EE, Effros finds that “Information theory is full of magic, with results that seem almost impossible yet are true and can be proven using only a few simple tools. Some of my favorite moments at work are when I am giving a talk or teaching a class and I can feel the concentration and intensity in the room. I also love the moments when you understand something for the first time. In an instant, something difficult that you have fought with and struggled against becomes clear, almost like a part snapping into place. Somehow, it’s surprising every time.”

Effros and her group study the theoretical limits of communication networks. “Communication networks play such a central role in our society. These days everything from entertainment to health services, government operations, and the economy relies, in critical ways, on our cell phone networks and the Internet,” Effros noted. “It’s surprising that almost nothing is known about how much information these networks can carry.” She is building mathematical and computational tools for bounding network capacities. And

she explained, “These tools are important because they will allow us to compare competing network designs and build better networks in the future.”

Steven H. Low, Professor of Computer Science and Electrical Engineering, also puts mathematical tools to work in the study of network systems. As he explained, “There seems to be a very strong and coherent underlying set of mathematical tools and mathematical perspectives that apply to a whole set of applications whether it is social networks, the Internet, or power networks. These associated sets of tools cut across Applied Math, Computer Science, and EE, so we’re trying to pull together the underlying core that will support all the different applications that are emerging.”

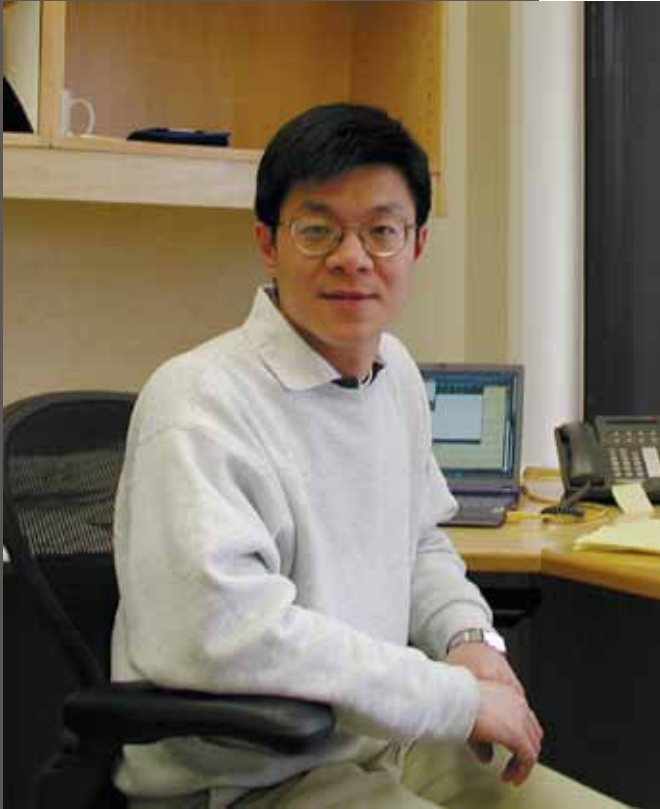
Low has pioneered development of mathematical theory of Internet congestion control that brings rigor and elegance to the Internet research and impacts the practice

Michelle Effros

Professor of Electrical Engineering

“*Information theory is full of magic, with results that seem almost impossible yet are true and can be proven using only a few simple tools.*”





Steven Low

*Professor of Computer Science
and Electrical Engineering*

“*In the next couple decades the electricity network will go through the same kind of architectural transformation that the telephone network has gone through in the last fifteen years. I’m trying to understand the theories and algorithms that Caltech can design to facilitate and guide this transformation.*”

of congestion control. His team has helped break world records of data transfers and the technology based on his research is powering the world’s second largest content distribution network. Low predicts that “in the next couple decades the electricity network will go through the same kind of architectural transformation that the telephone network has gone through in the last fifteen years. I’m trying to develop theories and algorithms that can help us understand and guide this transformation. This transformation is going to dramatically change how power is generated, transmitted, and consumed, and we want to understand not only the engineering of power networks and how they will evolve in the future but also the economic and even regulatory structures that go with it. A new thinking will be needed to really exploit emerging trends, and also to best capture the opportunities and manage the risks. I think this is really exciting.”

Another EE faculty member who is working on developing a new way of thinking is John C. Doyle, John G. Braun Professor of Control and Dynamical Systems, Electrical Engineering, and Bioengineering. “I’m not interested in how we build functional systems. That’s easy. How do we build systems that are robust, sustainable, and don’t do unexpected things.”

Asked to reflect on the EE centennial celebration, Doyle commented that the boundaries that are being celebrated are a hundred years old and a little out of date. “But we don’t know how to redraw those boundaries yet,” he said. “I’m working on the Internet, smart grid, microbes, intensive care units, wildfire, earthquakes, which have theoretical foundations in physics, but are so complex that physicists have a hard time with them. On the one hand I’m eager to try to describe it but at the same time what I end up saying doesn’t hold together very well. It’s just a bunch of seemingly disconnected things. Not as disconnected as it sounds, but the connections are hard to explain. I’d love to continue to try.”

When we asked Doyle to predict the theme for the next century of EE, he said it would probably be massive extinction. “If we avoid massive extinction, it will be

because of less technology. We're already committed to such heavy use of technology that I don't see how we can retreat from it, but it needs to be much lighter on the environment. The twentieth century gave us the capacity to build anything we can imagine, but it didn't give us the capacity to make it sustainable and robust. Can the twenty-first century be the century of sustainability and robustness or will it be the century of extinction?" **ENR**

Visit: <http://ee.caltech.edu/people>

John Doyle

John G. Braun Professor of Control and Dynamical Systems, Electrical Engineering, and Bioengineering

“I'm not interested in how we build functional systems. That's easy. How do we build systems that are robust, sustainable, and don't do unexpected things.”



Cool Earth Solar

GALCIT Alumni Are Diving into Muddy Problems and Coming out with Clear Solutions

Cool Earth Solar is a company founded and managed by Graduate Aerospace Laboratories of the California Institute of Technology (GALCIT) alumni Eric Cummings PhD '95 (Founder), Jacques Belanger PhD '93 (Vice President of Technology), and Aurelius Prochazka PhD '93 (Principal Scientist). The company has developed breakthrough concentrated photovoltaic solar technology that will dramatically reduce the cost and time needed to build large-scale power plants that can generate clean energy at prices competitive with fossil fuels. This new technology uses 8-foot-diameter inflated plastic balloons with a reflective lower surface that focuses sunlight onto a built-in photovoltaic cell.

We at ENGenious had the pleasure of sitting down with Eric, Jacques, and Aurelius to discuss their company, the global energy crisis, and the impact that Caltech and GALCIT had on their lives and careers.

ENGenious: What is the idea behind Cool Earth Solar?



Eric: We want to compete against coal without subsidies and without altruism. We want to be a great investment, the best and cheapest way to make electricity. We get to keep the coal in the ground. We get to use our oil for things that are better than putting smoke up a chimney. Renewable energies do not present a threat, and our view is that there is nothing but upside. We want to be responsible to future generations, and we really don't want to be hated by all of our descendants for having wasted and squandered resources. Also, I'm just not a big fan of going to war for energy, and I don't want to see a future where we have to defend our energy interests with violence.

ENGenious: What inspired you to become an engineer?

Eric: It really must have been my dad. When I was a kid growing up, he would spend the evenings on the recliner in our family room solving some design problem on a quadropad. He was a microwave engineer and a workaholic and I looked up to that. When I was in kindergarten, I used to do the same kind of thing, only I was designing airplanes made out of lawn mowers.



Jacques: When I was a kid I was always fascinated with new construction. It could be a bridge or a building and that interest slowly migrated into an interest for different modes of transportation. Creating something in your head and being able to go through the process of creating a product, like a plane or a bridge, was totally fascinating for me.

ENGenious: How has Caltech influenced you?

Jacques: Caltech had a very rigorous approach to problem

solving, which taught me to always go back to the principle and build the base for my solution. Caltech taught me how to solve problems; it is not the answer that is important, it is the process. This will always stay with me.

Eric: We all had Hans Hornung, the C. L. “Kelly” Johnson Professor of Aeronautics, as an advisor in some capacity. He is a remarkable person and a truly passionate problem solver. He was the director of GALCIT at the time and was trying to commission a new facility called the T-5 Hypervelocity Shock Tunnel. This was a very complicated and multidisciplinary process for which he formed a great team of grad students to solve the problems. I really enjoyed it because one day I might be machining threads in a piece of metal, and the next day designing a laser, and the day after that trying to figure out how to press grooves into a piece of stainless steel.

Jacques: The key thing that worked in T-5 was teamwork. We had a very tough facility to build and ran into a lot of trouble, but it was amazing. When you assemble a very good team, the amount of work that can be accomplished is unbelievable.

Eric: Some of my fondest memories of that time are sitting at the blackboard on a Friday afternoon and somebody posing a question to Hans. Hans would stand there and scribble away, doing calculations much faster than we could do on a calculator, and end up with an answer that was practically dead on and correct. That was a very important skill that he taught and it helped us when we were trying to start Cool Earth and had to figure out how we could possibly solve a problem as big as the global energy crisis.

The other person that I keep with me is Paul Dimotakis, the Northrop Professor of Aeronautics and Professor of Applied Physics, and JPL Chief Technologist, who is a really amazing researcher. One day in class, he posed a very difficult question and everybody gave a partial explanation that wasn't satisfactory. Finally, he said, “I detect a lot of muddying thinking here” and then he stood back, erased the board, and calmly gave a crystal clear explanation. It didn't seem that way at first, but while there was a lot of ambiguity and uncertainty, there was also a very clear and concise right answer to the question. That was just astonishing and kind of liberating.

I've been looking for those kinds of crisp, right answers since then. Whenever I spot myself in some muddying think-

ing, I try to get to the bottom of it until I have an absolute solid answer for something. When devising solutions to problems that are fairly out there, having that kind of mastery of the topic, embodied by this lack of muddying thinking, is pretty important.

ENGenious: What advice do you have for Caltech students?

Eric: You're much more likely to get wealthy doing something you're excited, ambitious, and motivated to do than something you're doing just from nine to five.



Aurelius: I want to expand on that a little bit. When you come into GALCIT, you should realize that you're entering a very interdisciplinary school and you have access to many different types of people. Eric's thesis work was a combination of chemistry, aerodynamics and fluids. I did computer science, applied math, and even minored in economics. Jacques did a minor in planetary science. This interdisciplinary world had a great impact on the companies that we have started, which have involved people from astrophysics, mechanical engineering, and computer science. So follow your heart and do not be stuck in any particular school or any type of work.

Eric: You know, we could be more practical: actually, what you need is to get some smart undergrads in your classes. They're smart enough to know to ask lots of questions that slow the professors down so you can actually write down what they've scrawled on the board. The undergraduates have it all figured out. Follow their lead.

Aurelius: Make every effort to meet and work with the undergraduates.

Eric: Undergraduates are really amazing at Caltech.

ENGenious: What are your thoughts on the global energy crisis?

Eric: I take it very seriously. It was 2005; I had three young children and a job that I loved at a national lab. I was pretty happy and comfortable in life. Then I went to a meeting in Washington, D.C., where Professor Nate Lewis, George L. Argyros Professor and Professor of Chemistry, gave an incredible 45-minute talk about “The Problem”—the energy

problem, the urgency of it, the size and how our concepts of possible solutions are really off by orders of magnitudes. It was an incredibly moving experience for me. When I left that meeting, I had resolved that I was going to dedicate my life to solving this problem. I didn't know exactly how that was going to play out, but there was no question about it after that.

I began to consider practical present-day solutions to the problem, with the right scaling characteristics and economics. I decided to quit my job to devote myself full time to finding a solution, and it took about a year to come up with something that actually penciled out in principle. You can imagine that starting a company with a product as unlikely as inflatable solar concentrators was a fairly high-risk, low-odds proposition. That was how Cool Earth started.

As a scientific community, we need more focus on basic practicalities such as scalability. There are some solutions that people are spending a lot of time on that use rare materials like indium, platinum, and palladium. But any solution that uses a significant amount of these rare materials to produce electricity doesn't end up penciling out; economically such approaches can't be viable. What will we do when we run out of indium or tellurium? Mine another planet?

ENGenious: **What do you mean by scalability?**

Eric: Caltech has been instrumental in getting the message of scalability out. A coal plant puts out about 500,000 watts and by 2050 humans will be consuming about 30 (10^{12} watts) terawatts. We need to have a viable alternative solution to fossil fuels by then. When Cool Earth Solar was funded, we were planning on producing 50 megawatts (10^6 watts) per year. At this rate, it would take us ten years to replace one coal plant. Let's say we scale up by an order of magnitude. Then we're replacing a coal plant a year, where China, at least up until recently, was putting up a coal plant every two weeks.

So we take our business, scale it up by a factor of ten. Scale that up by a factor of ten. Scale that up by a factor of ten, and another factor of ten. What we need then is to roll out 500 gigawatts (10^9 watts) of renewable power

plants every year and sustain that for 20, 40 years. What is astonishing about Cool Earth Solar is that, at least in principle, we can do that 10,000 times scaling without any implausible use of resources and without hitting any limits.

The problem is daunting, but what's amazing is that with our technology today we have already produced enough plastic film (to make the balloons) to solve 100% of the problem. We don't need any kind of crazy scale-up of that resource. Cool Earth Solar is dedicated to finding the materials and the components that we can manufacture in



Jacques Belanger (Vice President of Technology) and Eric Cummings (Founder)

sufficient quantity to scale and engineer our plants such that every time we need to do an order of magnitude scale up, there are no essential roadblocks.

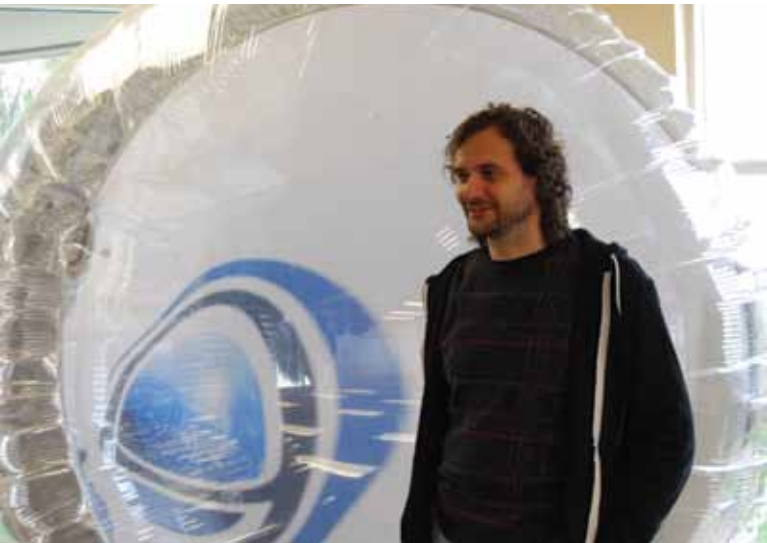
ENGenious: **How has your work influenced your children?**

Eric: As I mentioned before, I have inherited the workaholic gene from my dad. Consequently, I work at home all the time. So my kids really know what I'm doing. They understand it. They are excited about it. They can tell when we've made an advance and when we're struggling with a problem. I think it's very important for kids to see and experience that adults work hard and that they have problems that they struggle with—this is good for kids' education and their intellectual development.

Jacques: My two girls are starting to really be interested in science. They always ask me what's going on at work and when are we going to produce electricity. They are quite interested in what we're doing.

ENGenious: What is a typical day like for you?

Eric: The interesting thing about Cool Earth Solar is that we have so many different types of problems and challenges that every day is different. While this gets me going, it is also difficult to be interrupted several times a day with a wide variety of challenges, like a software or low-level firmware problem versus a fluid mechanics problem versus a materials problem. When I really want to dive into a particular problem, I try to carve out a few days. If I'm lucky, I



Aurelius Prochazka (Principal Scientist) stands in front of one of Cool Earth Solar's balloon-shaped solar concentrators.

can carve out a whole week and isolate myself to just work on that single problem. That's actually my favorite thing to do—take a deep dive and not come up until there's a real solution.

Jacques: I complement Eric because I like to be at the company early and move things along, work with the engineers and try to help them out. I like the interaction with people on a daily basis.

Aurelius: There's not really a typical day in terms of what we're doing. I hope every day is different and better, and that the problems that we're solving lead to more interesting questions for the next day.

ENGenious: What do you find most satisfying?

Eric: Diving into muddy problems and coming out with a clear solution. What usually happens when you really tackle a tough problem and go at it remorselessly is that, at some

point, something crystallizes in your brain and you realize there's actually a deeper principle; you learn a new rule and, suddenly, you see your problem now not as a single problem, but as an entire class of problems and that the rule applies broadly to this much larger class. It's like breaking a log jam with a large technical advance in a short amount of time because you've got this new clarity, this new understanding of something. This is definitely the most sustaining thing. It's way too rare, but it's incredibly sustaining.

Jacques: For me it goes back to what inspired me to become an engineer—building things and solving problems along the way. When you have a problem you find a solution, design the remedy, and have it made. Once it is built and it does what you want, you are done. That is what it's all about. Solving problems and moving forward.

Aurelius: Progress is very important, not only progress in solving the problem, but boiling it down to a type of solution that you can use. I am pretty good at finding the principle.

ENGenious: Anything else you want to add?

Eric: We are looking for the brightest minds in the universe to solve the biggest problem facing mankind. Seriously, we really are looking for people who have the ability to reason their way through problems that don't have a precedent or that don't have tremendously relevant precedents. We want the kind of people who can take a particularly challenging problem, distill it, crystallize an understanding around it, and come up with a solution for all time. That's really the kind of engineer and scientist we're looking for, and there are many among your readership.

If you are looking for a mission, there is no better mission than solving the energy problem. So whether you join Cool Earth Solar or not, I really hope alumni try to follow the path that we have taken in some way. We all had very comfortable and successful lives and we've made abrupt changes in them to address this problem. I hope many more alumni make that shift. Caltech, with its intellectual leadership, can also become the technical leader in this transformation, because it is a transformation in need of technical leadership. **ENIG**

Visit: <http://www.coolearthsolar.com>



Carver Mead

ENGenious met with Caltech alumnus Carver Mead (BS '56, MS '57, PhD '60) to learn more about his passions and how his Caltech education shaped him. For the past 50 years, Carver Mead has focused his research and teaching on the physics and technology of electron devices. He is a prolific inventor and is extremely creative. He also loves to teach, encouraging his students to create clean designs and contribute more than their share.

ENGenious: You seem to reinvent yourself every few years. How do you do it?

Mead: Well, you have to! That's the only way to keep going, at least for me. In my case, it's about a 13-year cycle. I get to where I feel like I'm not doing anything new anymore. I'm grinding away at the same stuff. I start getting depressed and end up mucking around for a year or two. Usually I plod from one thing to another until something grabs me. When I get into a new endeavor, I get lots of new ideas and a lot of them are wrong, of course. I explore a lot of avenues, many of which other people have done. But some, they haven't, and I don't know the difference in the beginning so I muck around and I try to get my own idea about how things are. It turns out it's extremely rare that I get all the same ideas as everybody else. I don't start by reading what everybody did—I go to seminars. I find that the fields have gotten so fragmented today that you can get a little bit here and a little bit there. I go to the astronomy seminars, the physics seminars, the biology seminars, the geology seminars, and the planetary science ones because different people have different takes on things. They think about things in different ways. Also every once in a while, somebody will say something that clicks. Caltech seminars are very unique because the speakers are instructed to make them accessible to a broader audience. For that rea-

Caltech seminars are unique because the speakers are instructed to make them accessible to a broader audience. For that reason, they will often say very revealing things because they're not just among specialists.

son, they will often say very revealing things because they're not just among specialists. So you hear people say things that you won't find in any of the papers because papers are written for a very narrow audience of people that think exactly alike. You don't ever see the out-of-the-box stuff there. That's why our seminars at Caltech are particularly good. You get insights that you just wouldn't get from a standard technical paper.

ENGenious: What types of things grab you?

Mead: Oh, there have been lots of them. In the beginning, it was the tunneling stuff. When I was a graduate student, I got fascinated by Leo Osaki, the guy who did the tunnel diode in the '50s. I just fell in love with that whole thing and, even though I was doing my thesis on something else, when I finished I just had to work on it. When I got on the faculty in the late '50s, I had this little lab and started doing experiments. In the beginning, it was just what everybody else was doing. Gradually I figured out some different ways of looking at it, and I ended up doing a bunch of stuff that people hadn't done. That was just a wonderful period—it was my first real independent research, and it was really neat. So there have been a bunch of things like that.

I tend to hang out in my mind with the people who have done really clear thinking in the area that I'm trying to push ahead. With my present work, the person I hang out with a fair bit is Einstein...

ENGenious: What are you working on right now?

Mead: Right now I'm working on reconceptualization of electrodynamics and gravitation. A lot of that's been done, but the way people are doing it is very murky and complicated. I believe there's a simpler way of doing it, and I'm gradually getting results. They seem to be holding together and that's very exciting.

ENGenious: What keeps you up at night?

Mead: Well, what usually happens is that I'll be working on something and I get really tired. I'll have dinner, relax, and go to sleep. Then in the middle of the night, usually between one and three in the morning, I'll have this period when I'm awake and very creative. I'm told there's something that happens in your brain at those hours. I don't purport to know anything about that, but that's when I get the new ways of thinking. Then I get up in the morning and start working on the problem.

ENGenious: Who inspires you?

Mead: I tend to hang out in my mind with the people who have done really clear thinking in the area that I'm trying to push ahead. With my present work, the person I hang out with a fair bit is Einstein because he started on this path and

then he went off on another path. I read his work before he went off on the path that everybody else uses now, and I can see what he was thinking. So those tend to be the people who inspire me.

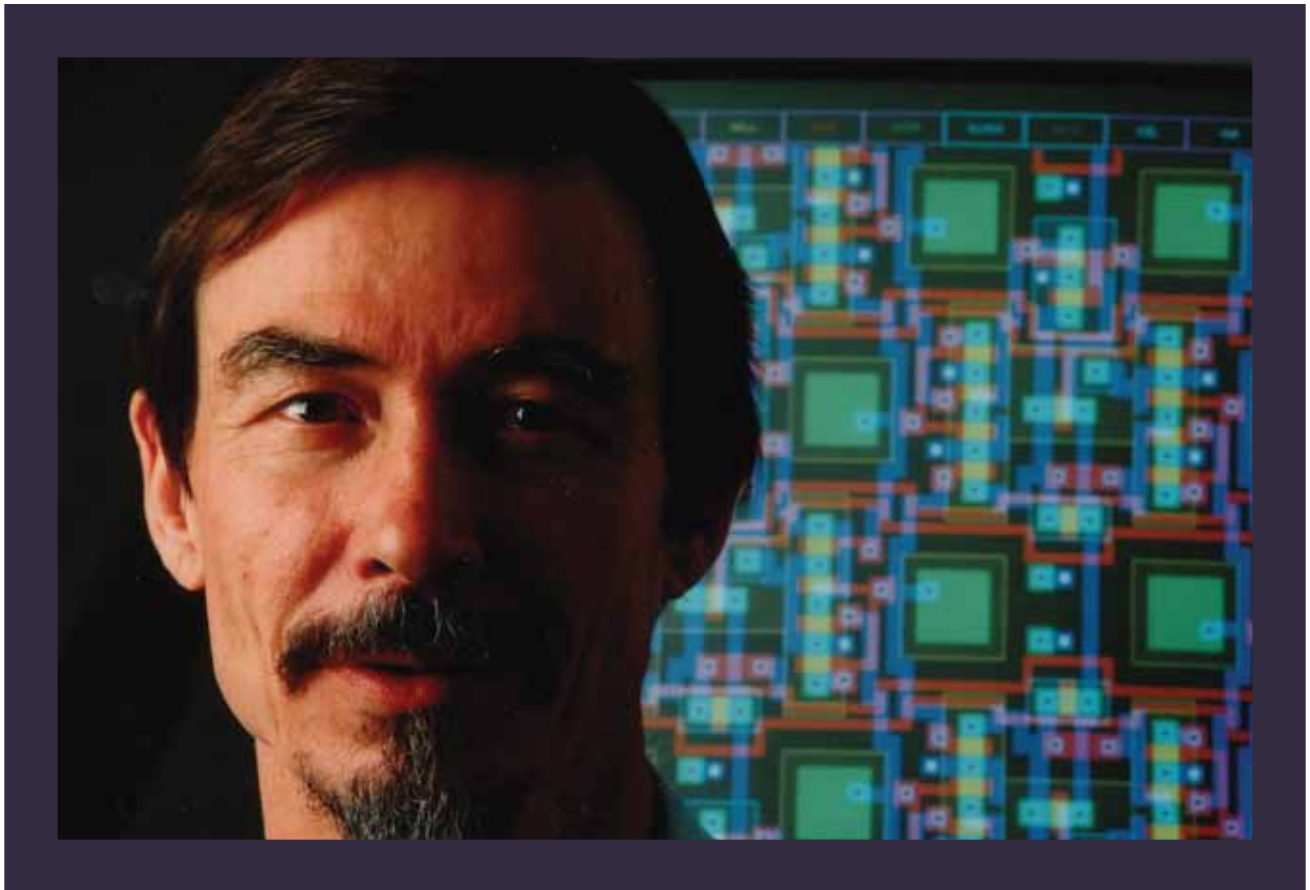
ENGenious: You have a passion for teaching. What were some of your first teaching experiences?

Mead: It was the mid-fifties and Caltech had just hired Dave Middlebrook from Stanford. Dave had this wonderful British way about him, and he taught the graduate course in transistor electronics, which of course I loved, so I took it in my first year of grad school. In my second-year, Dave decided he'd take a leave of absence to write his new book, so, as a second year grad student, I got to teach the course. Talk about being thrown into the deep end of the pool! I had been a



Carver Mead with group of students

teaching assistant as an undergrad, and I was pretty good at it, but teaching an entire course was quite an interesting experience. I started the first week trying to teach it the way Middlebrook did. A lot of the students were from Europe and had had an additional year of education beyond what we had in our bachelor's degree, so they were already better at a lot of the things than I was. The first weekend I went for a walk in the mountains and thought, "I'm never going to make it." I walked and walked and thought, "I can't pretend to be a little miniature Dave Middlebrook. If I'm going to succeed at teaching this course, I have to teach it the way



Carver Mead in front of a computer chip from the '80s

I understand it, not the way he understands it.” So the next Monday, I went in and I taught things the way I understood them, and the students gradually stopped harassing me and started listening. A few weeks later, we had a good relationship, and they felt they were learning something. By the end of the course, they were actually saying good things as they picked up their exams. That was an important learning experience for me. I’m never going to succeed trying to be somebody else, I just have to do it my own way. When you think about it, we’ve come light years from then. The transistors in those days were used in hearing aids and that’s about it. It was a really, really long way from there to here.

ENGenious: *This year we are celebrating the centennial of Electrical Engineering at Caltech. Where do you think we are headed?*

Mead: Everybody asks me that—if we knew that, it wouldn’t be the future! There are some things about the future you can predict because the question is well formed. Like Gordon Moore’s question to me of “How small can transistors

get?” I was working on electron tunneling, which is something that happens when things get very small, and Gordon asked me, “Does tunneling affect how small you can make a transistor?” I said, “It certainly will,” and he said, “Well, how small is that?” Then I thought, “Oops, now I’ve got to put my money where my mouth is,” so I went away and worked on it with a student. There had been enough other work done in the field that we knew the physics. We could work out approximately where you’d start to have problems, and it turned out to be a much smaller transistor than anybody thought. We were able to predict something that has actually held up for 30 years. That’s because the question was well formed: This is a transistor. How small can I make it? Therefore, if I can make it that small, I can put a zillion of them on a piece of silicon this size, etc., etc. It was an important observation that led to the industry going on this path of making things smaller. Everybody points to that as a prediction of the future—but it really was an observation about physical limits. But from it you could infer that, if people got their act together, it wouldn’t be physics that limited them.

ENGenious: What limits us?

Mead: Politics does for sure—but that isn’t something I know anything about. The exciting ones are where we are limited because we haven’t thought the thought yet. Just take a homespun example with the telephone. It used to be that when you called a phone, you called a place. Now, when you call a phone, you call a person. People don’t even think about it now. But, in fact, it’s a completely different thought and a very recent one. It’s much more effective because, typically, most of us don’t want to call a place—we want to call a person. This is an example of where the availability of the technology makes you think differently about the world and your life. Another example is the Web. It has completely transformed the world economically, intellectually, and in terms of international relations. It will, as time goes on, have a far larger effect than any political moves anybody makes. I know many of the people that did the early experiments on the Web. The integrated circuit work enabled some of it also. But none of us predicted the impact it would have on the entire fabric of human culture. It’s been marvelous! It is, by far, the biggest contribution to international peace and prosperity that has ever been, and it’s really our only hope for peace among nations and for a constructive world. It causes you to have a whole different global viewpoint.

ENGenious: Will technology continue to transform the world?

Mead: Yes. Will it transform it in a positive way? Absolutely. It’s the one force we have that is more powerful than human greed and control mania. Will it continue to evolve and will the next 100 years be even more positive than the last? Yes. How exactly? Part of it will be an obvious evolution of what we have now. But the most exciting part will come out of left field, and we will say, Wow!

ENGenious: What role is Caltech playing in this transformation?

Mead: Caltech exposes students to the way of thinking and designing that is essential for this transformation. Dick Feynman said, “The real glory of science is that we can find a way of thinking such that the law is evident.” So instead of grinding away through piles of garbage, it’s clear because you found the right way of thinking about it. With engineering, we call it a clean design. The Apple iPhone is an example of a clean design. It works the way you want it to. Tektronics

used to make oscilloscopes where it was as if the instruction manual was on the front panel. If people design good instruments, it is obvious how to use them. That’s the equivalent in engineering of the thing Feynman said about science. Caltech has enough of this, which the students get exposed to. The good ones will realize that that’s

the way they want to work, and they will go off and do remarkable things. One of our former students, Dave Gillespie (BS ’86, MS ’88), did the human interface work on the touch pads that are used in a lot of mobile devices. He’s the best human interface person I ever knew, even when he was a student here. He made enormous contributions to the work we were doing, and he’s still at it. He’s the guru of Synaptics and just continues to come up with these wonderful things.

We at Caltech have contributed more than our share to the world. As we’re looking to the future, which should be our aspiration, we want to give more than our share of those natural, beautiful, clear, clean, glorious contributions. **EN G**

There are some things about the future you can predict because the question is well formed. Like Gordon Moore’s question to me of “How small can transistors get?”

Carver Mead is Gordon and Betty Moore Professor of Engineering and Applied Science, Emeritus

Visit <http://www.cns.caltech.edu/people/faculty/mead.html>

Size Matters

Mechanical Properties of Materials at the Nano-scale

by Julia Greer

While “super-sizing” seems to be the driving force of our food industry, the direction of materials research has been quite the opposite: the dimensions of most technological devices are getting ever smaller. These advances in nanotechnology have a tremendous impact on parts of the economy as diverse as information, energy, health, agriculture, security, and transportation. Some of the examples include data storage at densities greater than one terabit per square inch, high-efficiency solid-state engines, single-cell diagnostics of complex diseases (e.g., cancer), and the development of ultra-light yet super-strong materials for vehicles, with the sizes of the components of these technological devices reduced to the sub-micron scale. How well these devices function directly depends on their structural integrity and mechanical stability, driving the necessity to understand and predict the mechanical properties of materials at reduced dimensions.

At the nano-scale, yield and fracture strengths, for example, have been found to deviate from classical mechanics laws and, therefore, can no longer be inferred from the

bulk (large-scale) response or from the literature. Unfortunately, the few existing conventional experimental techniques for assessing mechanical properties at this scale are insufficient, not easily accessible, and generally limited to thin films. In order to design reliable devices, a fundamental understanding of mechanical properties as a function of feature size is desperately needed. The key remaining question is whether materials really are stronger at the sub-micron scale, and, if so, then why and how.

A major component of my research is the development of innovative experimental approaches to assess the mechanical properties of materials whose dimensions have been reduced to the nano-scale not only vertically, as is the case for thin films, but also laterally.

To enable the development of innovative experimental approaches, when I first arrived at Caltech in 2007, my colleague Dr. Warren Oliver built a unique in-situ mechanical deformation instrument called SEMentor (Figure 1) based on concepts that I had devel-



Julia Greer next to the SEMentor instrument

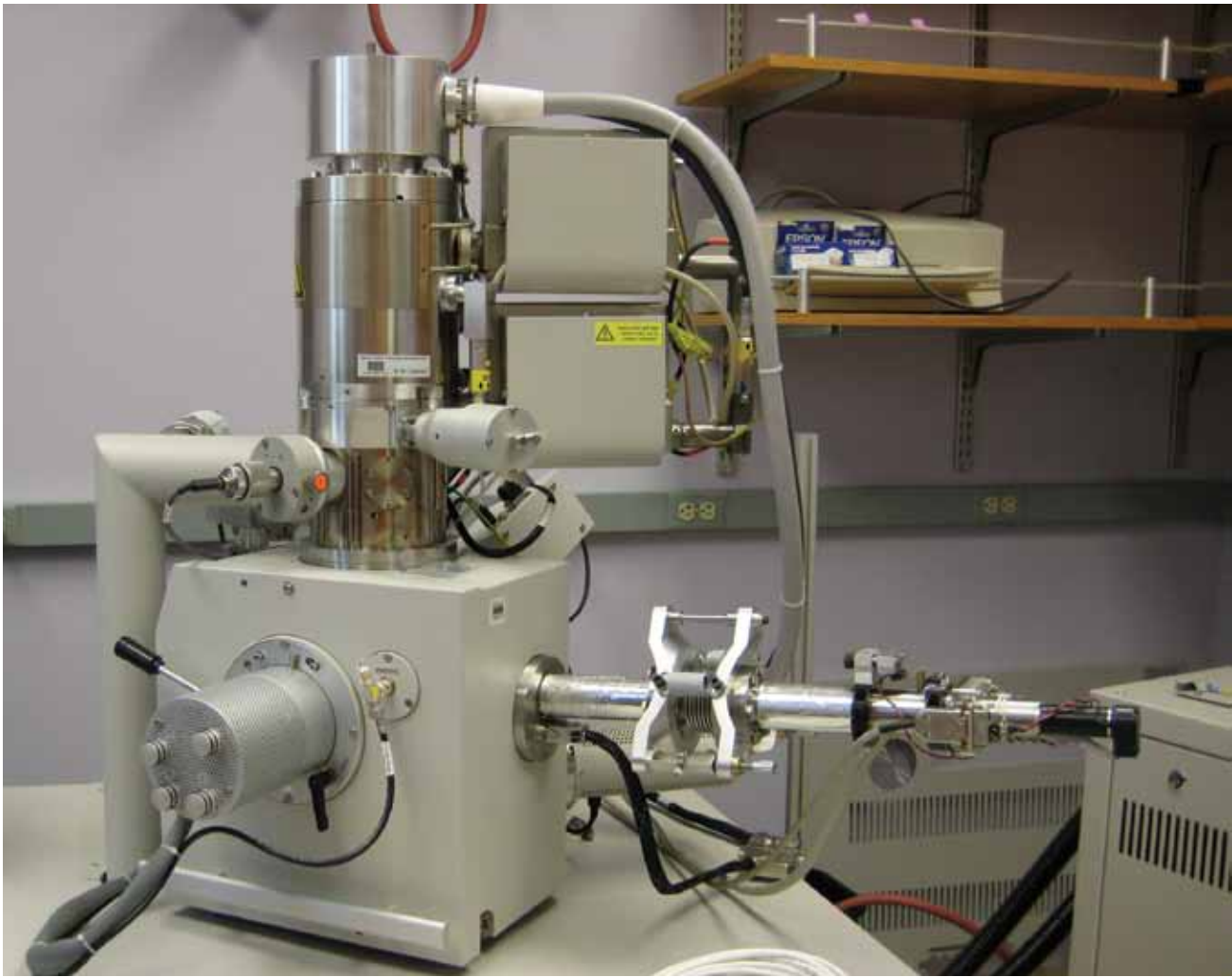


Figure 1: SEMentor is comprised of a Scanning Electron Microscope (SEM) and a nanoindenter, which allows for the precise control of deformation with simultaneous video capture.

oped. SEMentor is composed of a nanomechanical module, similar to a commercial Agilent nanoindenter, inside a Scanning Electron Microscope (SEM). The former offers a precise control and high resolution of load and displacement (and their rates) as well as contact stiffness during the experiment, while the latter allows the researcher to visualize the process. Most importantly, the SEMentor enables two powerful, and previously unattainable, capabilities: (1) tensile testing, which cannot be accomplished in a regular nanoindenter, and (2) simultaneous video capturing and mechanical data collection, which allows for a direct correlation between sample morphology evolution and specific attributes of the load-displacement curve.

Specifically, we have been investigating the differences in mechanical behavior in five different microstructure classes: (1) face-centered cubic (fcc) single

crystals, (2) body-centered cubic (bcc) single crystals, (3) nano-crystalline metals, (4) nano-twinned metals, and (5) amorphous metallic glasses (Figure 2).

In a striking deviation from classical mechanics, we observe a **SMALLER IS STRONGER** phenomenon in both fcc and bcc single crystals, manifested by the significant (~50x) increase in strength as material size is reduced to 100 nm (Figure 3).

To the contrary, nano-crystalline metals tend to exhibit the opposite trend: **SMALLER IS WEAKER**. Recently we found that metallic glasses, whose Achilles' heel has always been the occurrence of catastrophic failure at very small tensile strains, exhibit non-trivial ductility when reduced to the nano-scale. We discovered a transition to very different room-temperature failure and deformation modes of metallic glasses, or amorphous metallic al-


loys, when reduced to the nano-scale—from highly localized, catastrophic shear band formation to homogeneous deformation, exhibiting non-trivial plasticity and necking before failure [Transition from a strong-yet-brittle to a stronger-and-ductile state by size reduction of metallic glasses. *Nature Materials*, 2010, 9:215–9.]. Furthermore, unlike in the large scale or bulk, where plasticity commences in a smooth fashion, all of these materials exhibit numerous discrete strain bursts during plastic deformation.

These remarkable differences in the mechanical response of nano-scale solids subjected to uniaxial compression and tension challenge the applicability of conventional plasticity models at this scale. We postulate that the differences in mechanical response arise from the effects of free surfaces, as nanopillars have a much higher surface-area-to-volume ratio compared with bulk. Therefore, surfaces are expected to pose a significant effect on their properties, as manifested by the notable differences in defect activity when deformed. As the deformation mechanisms generally determine the materials' mechanical properties, the specific effects of surfaces on strength are different for each microstructure class. In fcc and bcc crystals, for example, the mechanical properties depend on dislocation behavior, in nano-crystalline solids they depend on grain-boundary activity, and in amorphous metallic glasses they depend on shear transformation zones. The interactions between these elements with free surfaces serve as the fundamental reason for the observed size-dependent strengths in nano-scale structures.

As for future research, by taking advantage of the powerful new capabilities offered by the SEMentor, as well as the newly developed nano-scale fabrication techniques such as e-beam lithography and electroplating (hence no longer relying on the Focused Ion Beam), we can now address much more complex problems. These problems involve the deformation of a variety of material classes with different initial microstructures rather than single crystalline metals, whose deformation is now relatively well understood.

We are starting to investigate the behavior of materials that contain boundaries as opposed to single crystals only. For example, we are looking at the effects of combining both extrinsic dimensions and intrinsic characteristic microstructural length scales on the mechanical behavior in surface-dominated structures (such as boundary-containing samples, multi-layered structures, and nanocrystalline metals). The competition between these two scales and the material deformation behavior in the presence of boundaries, inter-

faces, and free surfaces is far from being quantified or understood, yet is critical for understanding and exploiting the structural integrity of material constituents composing bulk structural materials and small-scale components and devices.

By using this knowledge, researchers will be able to define material design space in multiple dimensions and to learn how to create structural materials with vastly superior properties than can currently be achieved. 

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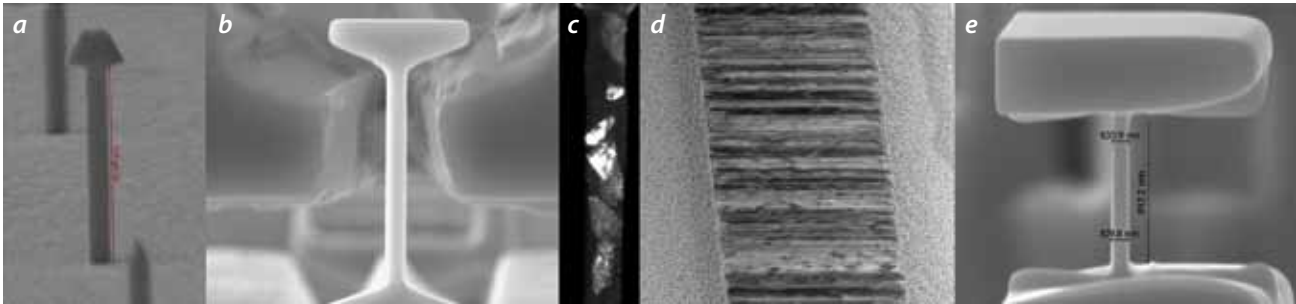


Figure 2: (a) SEM image of a face-centered cubic (fcc) single crystalline Cu tensile nano-pillar with 100nm diameter; (b) SEM image of body-centered cubic (bcc) single crystalline tensile Nb nano-pillar with 400nm diameter; (c) TEM (transmission electron microscope) image of a nano-crystalline Ni nano-pillar with 100nm diameter; (d) TEM image of a nano-twinned Cu nano-pillar with periodic twin boundaries spaced at ~3–4 nm; (e) SEM image of 100nm diameter tensile metallic glass ($Zr_{35}Ti_{30}Co_6Be_{29}$) nano-pillar.

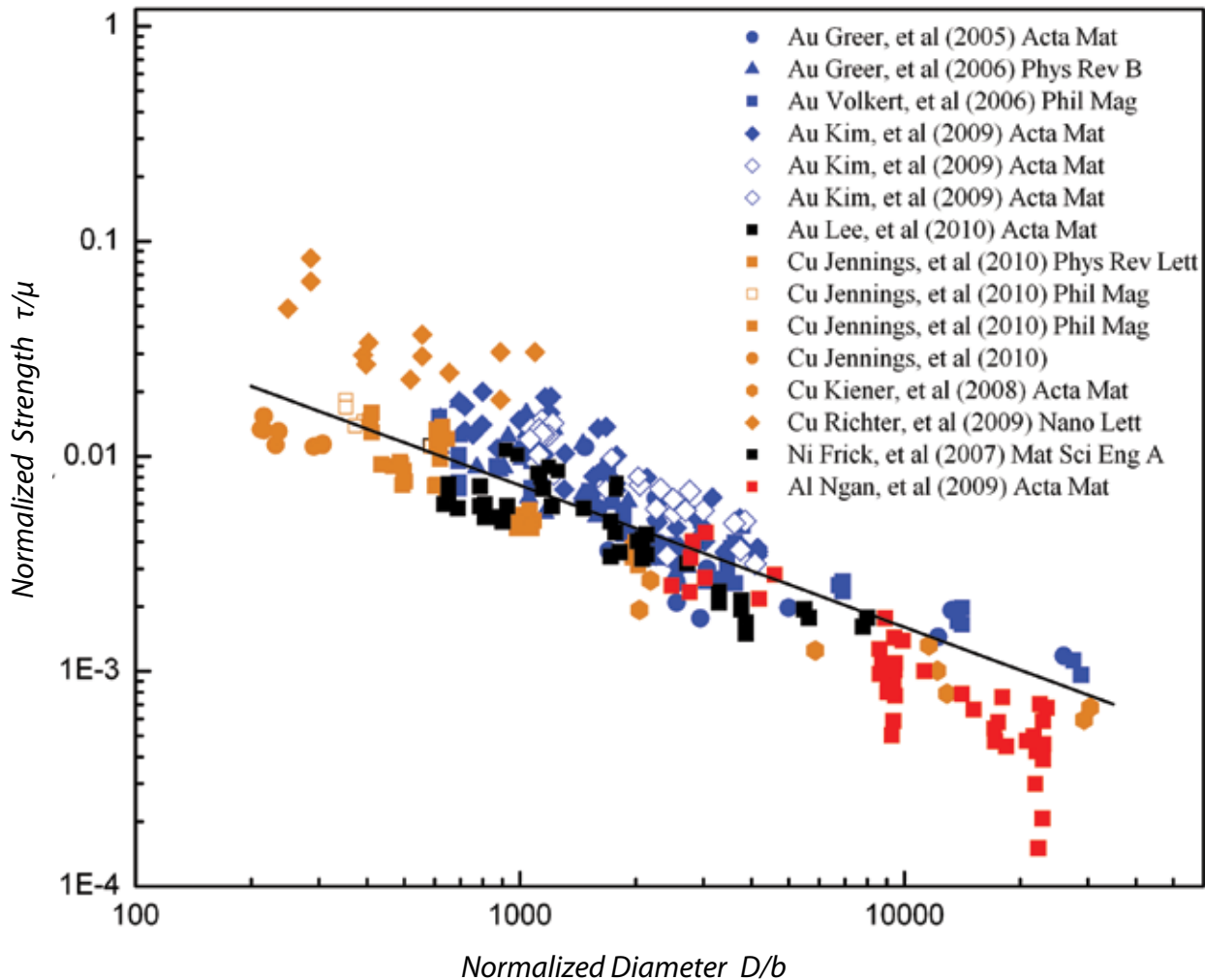


Figure 3: “Smaller is stronger”—the normalized strength is shown as a function of normalized pillar diameter for several different fcc metals.

Making a Dramatic Change by Starting with the Fundamentals

by Sandy Irani

Sandy Irani is a Professor of Computer Science at the University of California, Irvine, and a Visiting Associate in the Caltech Department of Computing and Mathematical Sciences. After making a major change in her research focus, Professor Irani spent a sabbatical year at Caltech's Institute for Quantum Information (IQI). The abstract nature of math fascinates her, and she spends her days as a computer scientist applying mathematical techniques to fundamental problems in physics.

I have had a very dramatic change in my research focus in the last five years. I used to work on online algorithms, and now I'm working more in the area of quantum information and computation. The change came about simply because I got restless and wanted to work on something new. We're very lucky in academia that we can decide to do something completely different and don't need to ask anyone's permission. We just have to learn the new area. It was a big change and a fairly steep learning curve to get into a new area, but it was very interesting. I had a good time learning a new topic.

My previous research area was in traditional algorithm design, and I specialized in applications to computer systems. I worked on things like memory management, web caching, and different ways of computing with low power, like algorithms for powering down laptops and, therefore, all kinds of optimization problems as they applied to computer systems.

I don't really know what made me change fields; I just wanted to learn something new, and I was really poking around in the dark. What I did know was that I wanted to start with the fundamentals and really learn about the basic science before I jumped in.

I started by taking a quantum mechanics class and actually doing the homework. I was always curious about quantum mechanics. I had never taken it in college and I knew that within computer science, there was a growing com-

munity of researchers working on quantum computation.

The idea behind the general area of quantum computation is that we can use matter at the quantum level to store and process information, like storing a bit of information in the spin of an electron. The laws of physics are quite different at this level than they are at the macroscopic level. In theory, at least, if this could be accomplished, we could

build computing devices that are much more powerful than conventional classical machines. We can't actually build these machines yet, but in the meantime, we are trying to answer questions like, if these machines could be built, what exactly

Our business in theoretical computer science is to understand mathematically the computational difficulty of problems and to classify them in terms of their complexity.

can we do with them? What is their power computationally? What kinds of problems can they intrinsically solve?

What I am interested in is asking these kinds of questions in relation to problems in physics. Physicists have been using computers for decades to understand quantum systems: to simulate them over time or to compute their fundamental properties. Some of the techniques have been very successful, some not so successful. They just seem to work well in certain situations. What I wanted to do was to really understand these questions from the point of view of computational complexity. Our business in theoretical computer science is to understand mathematically the computational difficulty of problems and to classify them in terms of their complexity.



One of my first pivotal moments in quantum information came about three years ago when we discovered a surprising result about the inherent computational difficulty of a problem that physicists have been using computers to solve in special cases. A fundamental problem in computational physics is to find the lowest energy state of a system, given the parameters. Physicists believe that this problem is computationally difficult for two-dimensional systems, but easier for one-dimensional systems. This belief is based on experience, since algorithms have been developed that work quite well on special one-dimensional cases. However, we still didn't know if there were a general algorithm that, given any one-dimensional quantum system, could compute its ground state. We showed that one-dimensional systems can, in principle, also be computationally difficult [D. Aharonov, D. Gottesman, S. Irani, J. Kempe. The Power of Quantum Systems on a Line. *Communications on Mathematical Physics*, vol. 287, no. 1, pp. 41-65, 2009.] and hence brought some bad news into the picture. We don't

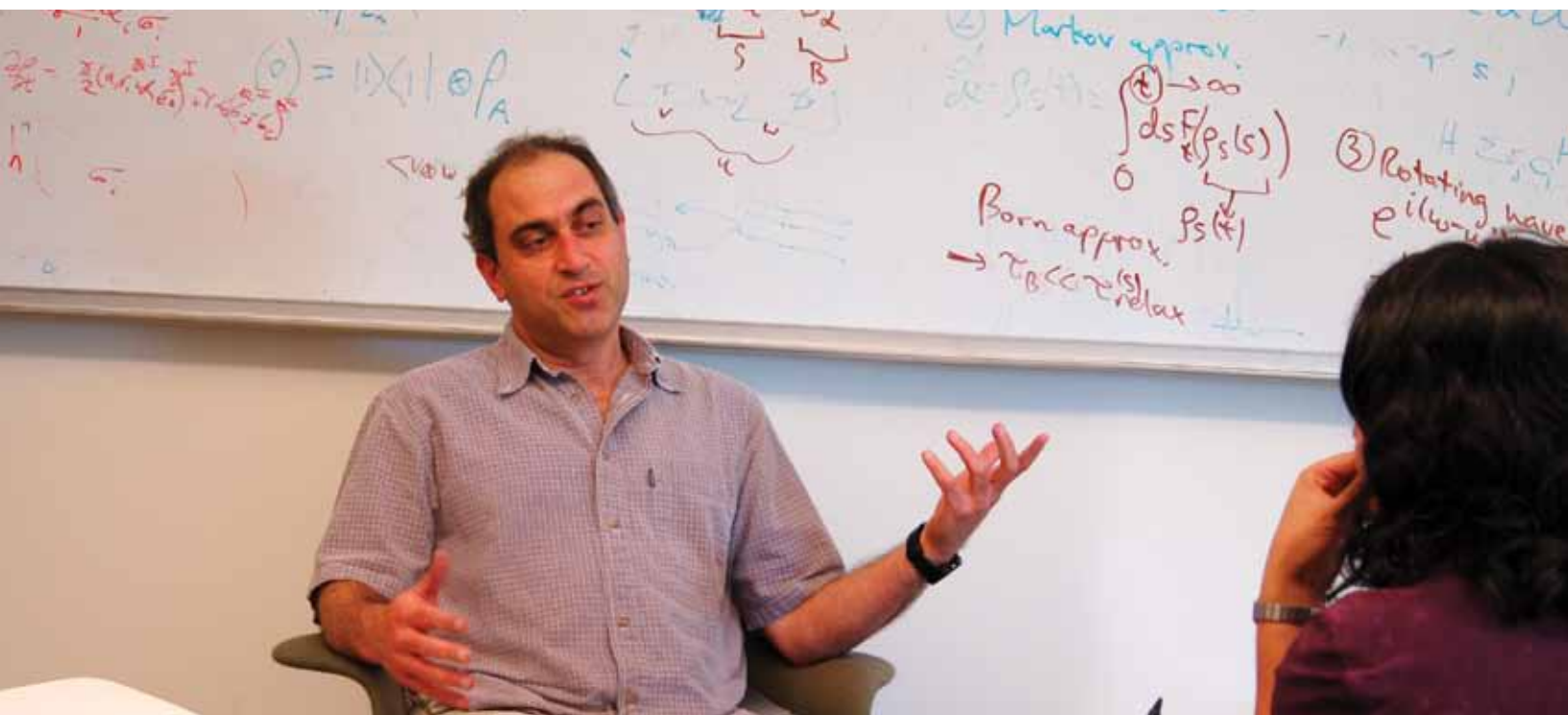
expect, either with classical computers or even quantum computers, to be able to solve this problem. But there's a positive side to this result in that the proof involves showing that the lowest energy state of a one-dimensional quantum system can encode the answers to hard problems. So this presents the possibility of a new model for a one-dimensional quantum computer instead of a two-dimensional one.

What I find very compelling about this new field is that by putting computer scientists and physicists together, researchers are actually coming up with new ways to solve physics problems on garden-variety classical computers. These new solutions would not have been uncovered if we had not been looking at these problems through the lens of computation and information. It may be a while before we have large-scale quantum computers, or maybe never, but many interesting things are coming out of the cross fertilization between physicists and computer scientists at national powerhouses such as IQI.

IQI is one of the main reasons I chose to do my sabbatical at Caltech. While there is a lot of exciting research happening at the University of California, Irvine, there is no one else working in quantum information science, so I felt a bit like I was in a silo. Also, I am not free to get up and move across the country for a year because of my family. I was, therefore, lucky to have IQI within driving distance. It's a hotbed of activity that has been instrumental in bringing people together and creating a center of activity. If you look at the list of postdocs that have come through IQI, it basically reads like a who's who in the field. There's a whole community of people working on questions that I'm interested in, and all kinds of related questions in the general field of quantum information. Two other aspects that make IQI so successful are its physical location in the new Annenberg Building for Information Science and Technology and its steady stream of visitors. IQI is a common destination for top researchers and scientists from around the country and the world to come and spend a few days or a few weeks at.

Even though I am no longer on sabbatical, I have been coming back to Caltech on a regular basis to attend talks and work with colleagues. I am sure that IQI will be an important resource for me as I continue to work in this exciting and growing field. **ENIG**

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Quantum Algorithms

A Test for the Laws of Physics

by Leonard J. Schulman

The relationship between science and engineering is unequal. Science has custody of the noble truths; engineering is in charge of getting things done. One engineering proposal, however, defies this asymmetry. A successful quantum computer would verify as-yet untested predictions of quantum mechanics. Such verification is not a foregone conclusion.

Forty-five years ago, when computers began to enter the academic and commercial world, researchers asked what types of problems could foreseeably be solved on them. As computers improved from year to year, it was clear that this question must be couched in a suitably abstract framework. Soon, the mathematician Jack Edmonds and others had focused on what we still consider a fundamental distinction: between the problems that can be solved in time bounded by a *polynomial* in the input size, and those that cannot. For computer scientists, the divide between problems solvable in polynomial time and all others is a useful, if rough, demarcation between the problems that are tractable (can be solved with reasonable effort) and those that are intractable.

Early computer scientists studied a wide variety of physical implementations of computing devices, but when they modeled these mathematically, they discovered that the class of problems solvable in polynomial time never changed, and they called this class P. (Some prefer a variant, BPP, but we digress.) The class P could be perceived, then, as a property of physical reality—a limit on the computational power of physical devices. Although the concept of polynomial time was originally formulated to answer an *engineering* question, the class of problems P was quickly absorbed into a *scientific* assertion about what is physically possible in our universe.

One problem that seemed to be intractable, or outside of polynomial time, is this: given a whole number, find its

factorization into primes. This task has intrigued mathematicians at least since the early nineteenth century. Confidence in its intractability was so strong that in the 1970s, in work for which, in 2002, they were given the Turing award (the highest award in computer science), Ron Rivest, Adi Shamir, and Leonard Adleman invented a cryptosystem (RSA) whose security depended on this assertion [A method for obtaining digital signatures and public-key cryptosystems. *C. ACM*, 21:120-126, 1978]. Today their cryptosystem is widely used for commercial and other transactions.

Early in the 1980s the physicist Richard Feynman observed that computers were having difficulty with another kind of computation: simulating quantum mechanical dynamics [Simulating physics with computers. *International Journal of Theoretical Physics*, 21 (6/7):467-488, 1982]. This may at first seem unremarkable: all manner of physical processes, such as the weather, are hard to simulate. But Feynman's difficulty was altogether greater. In the mathematical theory of quantum mechanics, the number of parameters needed to describe a many-particle system grows *exponentially* in the number of particles. This is because each particle of the system is, to varying degrees, in each of its possible states at once—what is called a “superposition”—and because to write down the state of the whole system we need to keep track of each way of *combining* the states of all the particles. As far as we know, the system cannot be simulated without doing so. The problem of simulating quantum dynamics seems to lie far outside of P.

Now, something about this picture is suspicious. Many problems are hard to compute, but the problem of simulating quantum dynamics should not be on that list. After all, the universe performs these computations all the time—in real time. What gives? Feynman suggested two possible resolutions. The first is:

(1) There is some clever, mysterious way of computing quantum mechanical simulations that doesn't require writ-

ing down and updating all those exponentially-many parameters.

Feynman couldn't think of one, nor has any other physicist, computer scientist, or mathematician. Indeed, the possibility seems to run counter to how quantum mechanics works. For the remainder of this essay, we'll dismiss the possibility.

Feynman's second suggestion was:

(2) Devices operating on the principles of quantum mechanics have inherently greater computational power than those operating on the principles of classical mechanics.

*What quantum
computation has done
is to take Schrödinger's
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of the realm of theory and
into the arena of testable
experimental predictions.*

Feynman did not have the mathematical framework (known as complexity theory) to take possibility (2) further, but a decade later, the computer scientists Ethan Bernstein and Umesh Vazirani did [Quantum complexity theory. *SIAM J. Comput.*, 26(5):1411-1473, 1997. (STOC 1993)]. They were able to show (under certain abstract assumptions) that the class of tractable (polynomial-time solvable)

problems is indeed greater in a quantum-mechanical world than it would be in a classical world. This is a deep *scientific* statement about what is or is not physically possible in our universe. Within a year, the computer scientist Peter Shor had derived from it a great *engineering* accomplishment: a polynomial time algorithm for factoring numbers on a quantum computer [Polynomial-time algorithms for prime factorization and discrete logarithms on a quantum computer. *SIAM J. Computing*, 26:1484-1509, 1997. (FOCS 1994)]. So it turns out that polynomial time, in a quantum mechanical universe, is adequate to solve problems that seem to require far *more* than polynomial time if you rely only on *classical* physics processes.

To date, however, the prototype quantum computers that have been built are very limited. Shor's algorithm, to be useful, must be run on a quantum computer large

enough to produce, and maintain and manipulate over an extended time, particular kinds of quantum superpositions involving (at least) hundreds of particles. Superpositions like this have never been observed. (Which is why we still get away with using RSA.) Indeed, the prediction that they exist has troubled physicists since the inception of quantum theory. Erwin Schrödinger, a founder of the theory, memorably told of a (hypothetical) cat in a simultaneous superposition of two states: alive and dead. The whole point of this image is that it is ridiculous—nothing as complex as a cat has ever straddled reality so delicately. Yet subatomic particles are always in superpositions, and quantum theory knows no size limit: what it prescribes for particles, it predicts for cats...and for computers.

What quantum computation has done is to take Schrödinger's improbable feline spectre out of the realm of theory and into the arena of testable experimental predictions. Since the computational implications of these predictions are remarkable, it behooves us to consider an alternative remarkable possibility—that a quantum computer of a useful size is a physical impossibility, that large numbers cannot be quickly factored, that Schrödinger's cat was never in danger—in short, a third possible way of resolving Feynman's conundrum:

(3) Quantum theory is incorrect for large, complex systems.

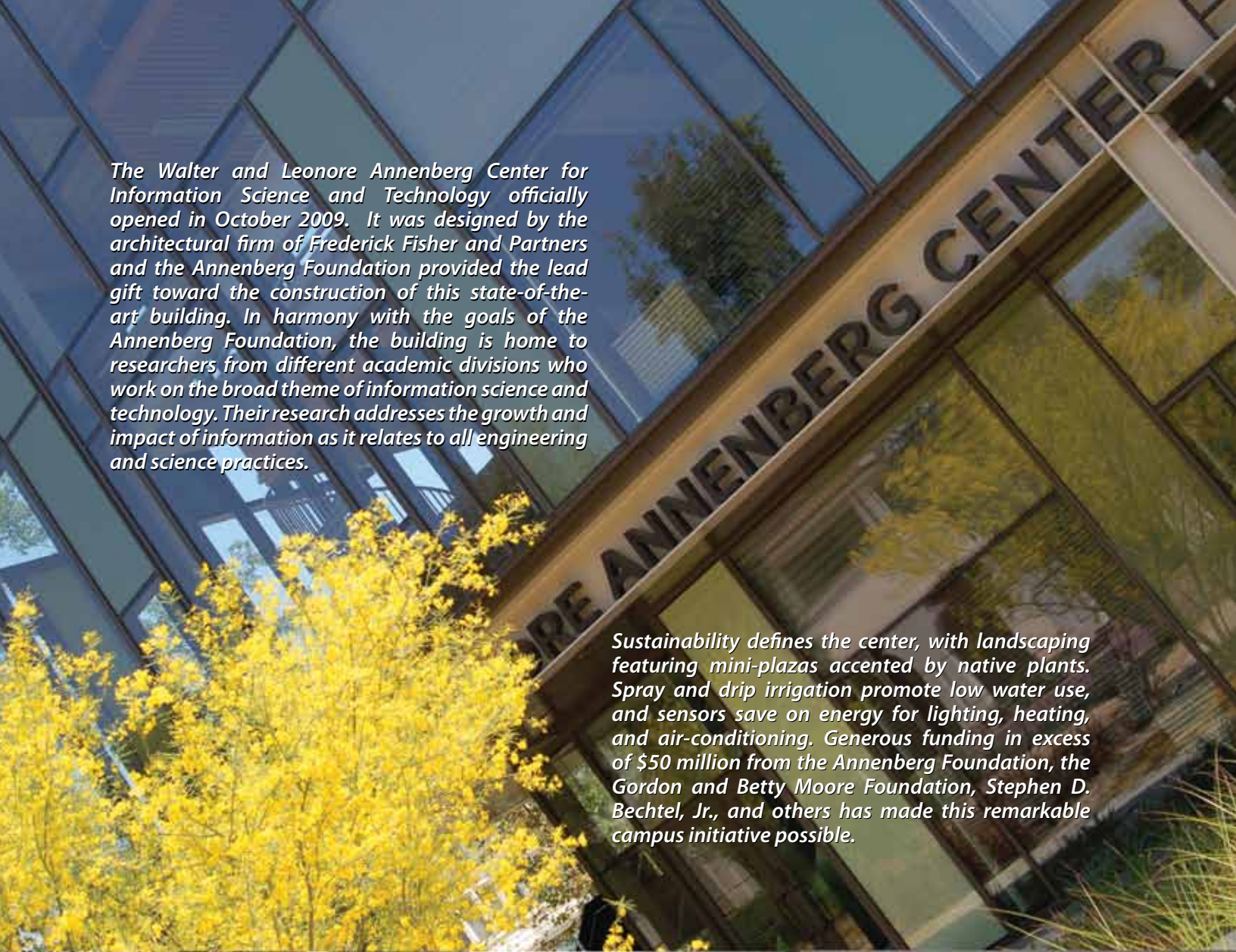
Large quantum systems are so hard to control in the laboratory that our theory for them is only an extrapolation of what we know for small systems. Like earlier extrapolations—Newtonian mechanics, which Albert Einstein revised at high velocities, or the flatness of the earth, which the ancient Greeks revised at large distances—it might be wrong. Quantum computers, as computers, will probably not be useful until they contain hundreds of “quantum bits” (basically, particles involved in the computation). As experimental tests of quantum mechanics, however, they are already charting new terrain: recent experiments have reached a dozen quantum bits.

Where do we stand? Quantum algorithms—nothing but engineering designs—are so powerful that they pose a test to the laws of physics. In a manner of speaking, these algorithms have given teeth to Schrödinger's troublesome cat, who is forcing us to discover something startling about the reality we live in. What will it be? Scenario (2),

in which our previous understanding of computation is revealed to have been fundamentally flawed? Or scenario (3), in which our understanding of physics turns out to have been no better? The only test is in the laboratory. **E N G**

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The Walter and Leonore Annenberg Center for Information Science and Technology officially opened in October 2009. It was designed by the architectural firm of Frederick Fisher and Partners and the Annenberg Foundation provided the lead gift toward the construction of this state-of-the-art building. In harmony with the goals of the Annenberg Foundation, the building is home to researchers from different academic divisions who work on the broad theme of information science and technology. Their research addresses the growth and impact of information as it relates to all engineering and science practices.

Sustainability defines the center, with landscaping featuring mini-plazas accented by native plants. Spray and drip irrigation promote low water use, and sensors save on energy for lighting, heating, and air-conditioning. Generous funding in excess of \$50 million from the Annenberg Foundation, the Gordon and Betty Moore Foundation, Stephen D. Bechtel, Jr., and others has made this remarkable campus initiative possible.





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