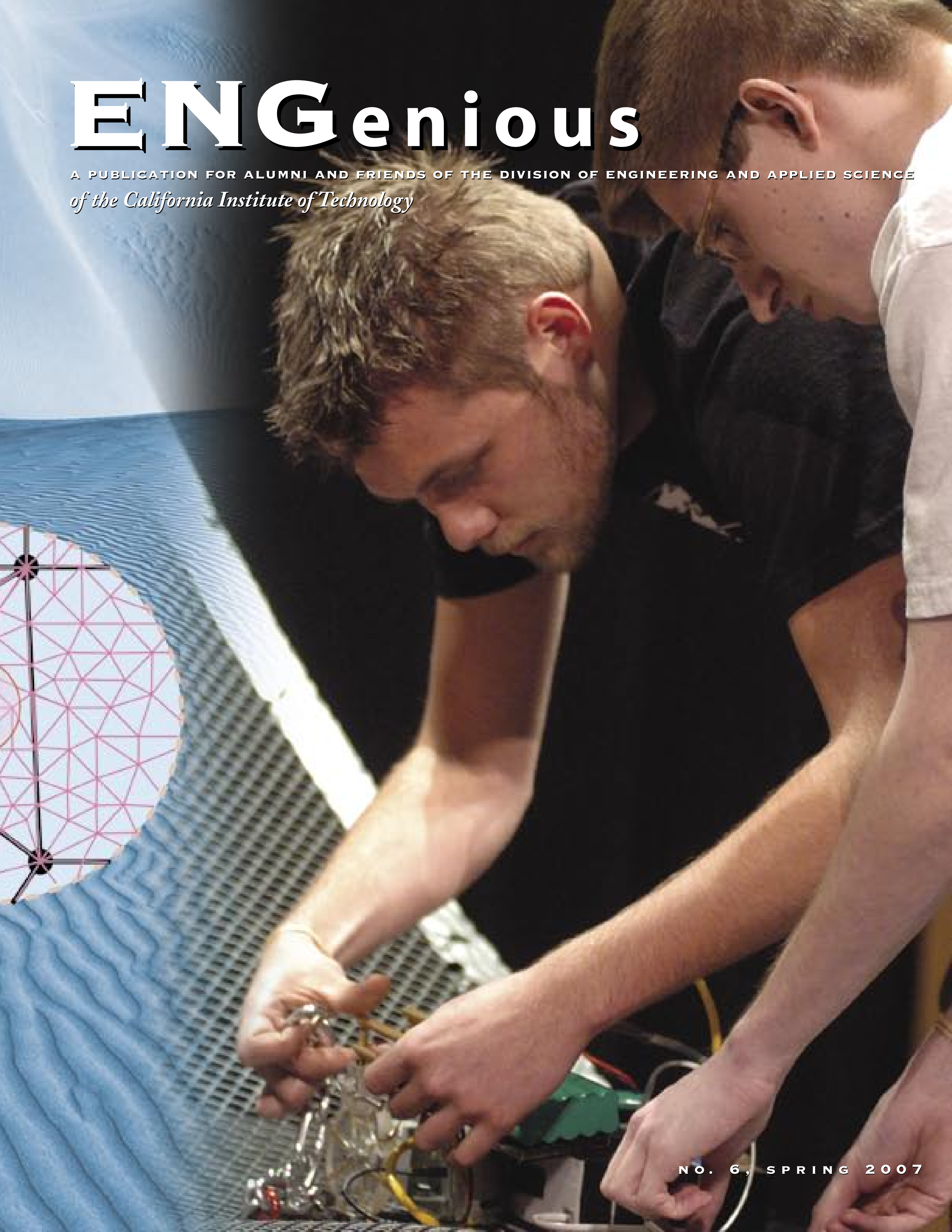
ENGenious

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



NO. 6, SPRING 2007

The Division of Engineering and Applied Science consists of thirteen Options working in five broad areas: Mechanics and Aerospace, Information and Communications, Materials and Devices, Environment and Civil, and Biology and Medicine. For more about E&AS visit http://www.eas.caltech.edu.

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ENGenious

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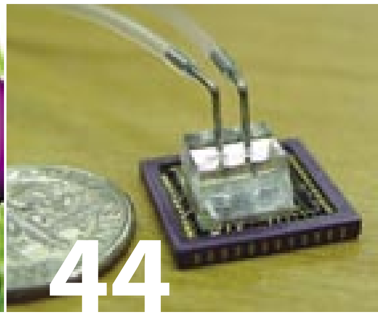
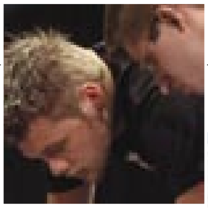
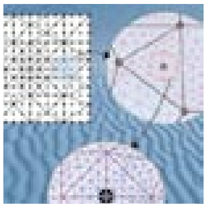
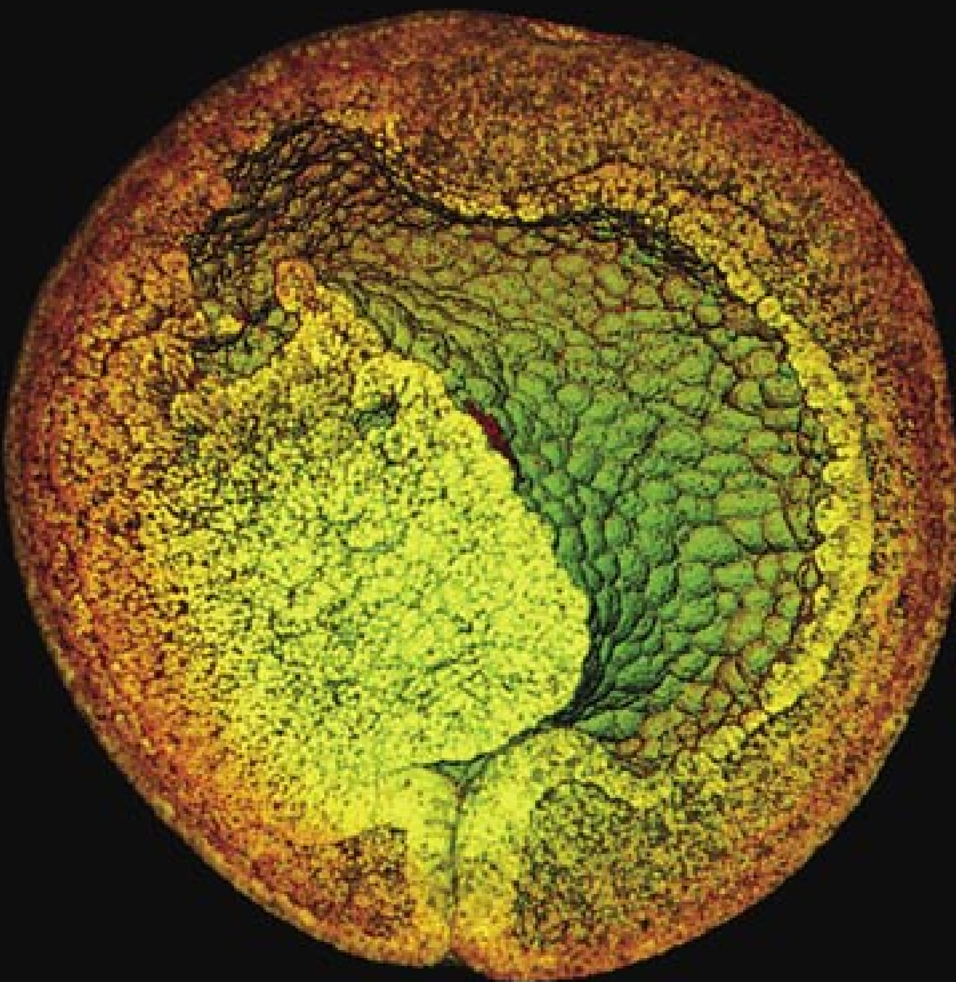






Cover Image: Montage created from photos and research images highlighting the strengths of Mechanical Engineering at Caltech. Two 2007 ME72 contestants are shown, Jeff Kranski and Tony Kelman, making last-millisecond adjustments to their machines. The lattice figure is from research by current PhD student Vikram Gavini (MS '04). It depicts the hierarchy of triangulations that form the basis of a new method (called QC-OFDFT) for conducting electronic structure calculations at continuum length scales. This method probes the quantum-mechanical nature of defects in solids where necessary, while seamlessly capturing long-ranged continuum fields. The backdrop of sand dunes is in reference to a long-standing inquiry by Caltech researchers into the "booming sand dune" phenomenon. Melany Hunt, Executive Officer and Professor of Mechanical Engineering, and her colleagues have recently made great progress on understanding the origins of this "music of the dunes."



An early frog embryo, imaged at high-resolution using surface imaging microscopy, a novel technique first applied to developmental biology in the Biological Imaging Center at Caltech. In this neurula-stage embryo, the archenteron (large cavity) has formed and the blastopore has closed, thus completing the major goals of gastrulation. Quantitative analytical techniques demonstrate that the cellular events of gastrulation are dissociable, providing a possible explanation for the observed diversity of gastrulation mechanisms among amphibians. The Director of the Biological Imaging Center is Scott Fraser, Anna L. Rosen Professor of Biology and Professor of Bioengineering.

This and related research is being carried out by members of the new BioDevices and BioImaging (BDBI) sub-option in Bioengineering at Caltech. The BDBI group develops technologies for manipulating and probing biological systems. Research areas include BioMEMS, laboratories-on-a-chip, microfluidic devices, molecular devices, medical devices (such as neural interfaces and micropumps), non-invasive biological and biomedical imaging, optical trapping and manipulation of molecules, and novel instrumentation and measurement principles. Visit http://www.be.caltech.edu for details.

In this issue of **ENGenious**, *we offer a profile of the Mechanical Engineering Option as we celebrate the Centennial of Mechanical Engineering at Caltech this year. The Centennial is being marked by a Symposium on March 30–31, 2007. Caltech alumnus Tom Tyson (BS '54, PhD '67) and Professor Chris Brennen are serving as co-chairs of the event, and speakers include the president of Caltech, Jean-Lou Chameau, and the former president of the University of Michigan, James Duderstadt (MS '65, PhD '68). Talks by our alumni on electric cars, oil and gas exploration, nanomechanics for biological structures, and space exploration round out the program, with presentations by faculty and students as well. See* http://www.me100.caltech.edu *for details of this special event.*

We are also very much looking forward to September, when we will hold an international conference celebrating 50 years of space technology hosted by the Graduate Aeronautical Laboratories (GALCIT), Northrop Grumman Space Technology, and NASA's Jet Propulsion Laboratory. Speakers include the president of Northrop Grumman Space Technology, Alexis Livanos (BS '70, MS '73, PhD '75), who we have interviewed in these pages; Charles Elachi, Director of JPL; Michael Griffin, Administrator of NASA; astronaut and Caltech Trustee Sally Ride; former U.S. Senator and astronaut Harrison Schmitt (BS '57); and John Mather, 2006 Nobel Laureate. Visit http://www.galcit.caltech.edu/space50 *for more information.*

The continuing generosity of the Gordon and Betty Moore Foundation is evident by the recent establishment of the Caltech Center for Sustainable Energy Research (CCSER). This Center has the goal of replacing fossil fuel as an energy source. In an interview, the principal faculty members, led by Professor Harry Atwater, describe the scientific goals and the challenges.

This issue of **ENGenious** *also reports on lensless microscopes, floating DNA circuits, the evolution of the Sherman Fairchild Library in the era of digital publishing, and the expanding possibilities for collaborations between the Division and the Jet Propulsion Laboratory.*

In many ways, we are who we hire. I am happy to introduce eight new faculty members to you in these pages—as well as announce that there are currently nine active faculty search committees operating on behalf of the Division.

As always, we welcome your feedback, and we hope you will visit us when you are in the area.

DAVID B. RUTLEDGE
Chair, Division of Engineering and Applied Science

'Round About the Institute

Astronomers and Astrophysicists

Under One Roof

In December 2008, astronomers and astrophysicists at Caltech will have a new home. Last January, the campus community gathered to break ground for the Cahill Center for Astronomy and Astrophysics. For the first time, Caltech's astronomers and astrophysicists will be housed in one building. "Pulling together the Division's many activities in astronomy and astrophysics to achieve optimal synergy has been our goal for some time," says Tom Tombrello, Division Chair for Physics, Mathematics, and Astronomy. "The Cahill Center is an essential step in this progression." The $50 million center will be located on the south side of California Boulevard, between the Institute's athletic facilities on the south and the rest of the campus on the north. Internationally recognized architect Thom Mayne and his firm, Morphosis, designed the visually impressive, yet functional structure.

Keep track of the construction at: http://cahill.caltech.edu

Pictured top right (left to right): Richard Baptie of the general contractor Hathaway Dinwiddie; building architect Thom Mayne; Physics, Mathematics, and Astronomy Division Chair Tom Tombrello; building benefactor Charles H. Cahill; President of Caltech Jean-Lou Chameau; Pasadena Mayor Bill Bogaard; and Caltech faculty planning chair Tom Phillips.

Undergraduates Dvin Adalian and Ricky Jones on the Olive Walk.

Olive Walk Vintage

Hard Pressed Students in Production

Upon enouragement from Caltech's new president (and an invitation to Chez Chameau upon success), students Dvin Adalian and Ricky Jones went into olive oil production last fall. Gallons of olives from the Olive Walk's *Olea europaea* specimens, many blenders, five screens and some processes better left undescribed all went into the first pressing of Caltech's very own. Although not ready for a Caltech spin-off, the students were successful enough to dine with President Chamaeu and his wife, Carol Carmichael, several weeks later.

A Fond Farewell

Carolyn Ash Retires

After 30 Years at Caltech, Carolyn Ash, Director of Student-Faculty Programs, is hanging up her SURF board and heading off to retirement. Carolyn's contributions to the Institute and undergraduate research are enormous and immeasurable—hard to quantify even for a place like Caltech. Over 400 students now participate each year in the Summer Undergraduate Research Program (SURF) that she nurtured and expanded over many years. Many of the students increasingly find SURF opportunities at JPL—so many that Dr. Charles Elachi, Director of JPL and Professor of Electrical Engineering and Planetary Science, remarked at her retirement bash that by extrapolating current numbers, he calculates that the entire work force of JPL will be made up of SURF students by about 2020.

Pictured at right: Carolyn with her son, Steve, and granddaughter's Madelyn, Skylar, and Hayley.

Science is for Kids

"Floor-breaking" at The Children's Center

The Children's Center at Caltech (CCC) is building "The Science Lab at the CCC." Early this year, President Chameau, with president of the CCC board of trustees, Marionne Epalle, and CCC executive director, Susan Wood, led the "floor-breaking" (as one of the kids described it) with help from the youngsters. This indoor-outdoor laboratory, a delightful and creative structure (see image of maquette below), will grow out from two existing CCC buildings. Our budding scientists will be able to perform experiments and make science-based inquiries year round. What a wonderful start!

Get to know the Children's Center at:
http://www.ccc.caltech.edu

Pictured at left, along with many eager helpers (left to right): president of the CCC board of trustees, Marionne Epalle, Caltech President Jean-Lou Chameau, and the CCC executive director, Susan Wood. Near left: architect's maquette.

Who's New

Our newest colleagues bring a host of novel research approaches and programs to campus. Find here short profiles of no less that eight new professors, three joint appointments, and our most recent Moore Scholar. President Jean-Lou Chameau has also joined the EAS faculty as Professor of Civil Engineering and Environmental Science and Engineering—while we haven't caught him in the lab yet, he has been spotted recently with a shovel and a hard hat breaking ground!

New Faculty

John O. Dabiri: Assistant Professor of Aeronautics and Bioengineering

John O. Dabiri's interests are in the mechanics and dynamics of biological flows in general and biological propulsion in particular. Experimental methods and physical models are implemented in applications including aquatic locomotion, fluid dynamic energy conversion, and cardiac flow diagnostics. A current paradigm for his research is the study of jellyfish as a model system for fluid dynamic and behavioral (e.g., sensing and control) aspects of biological propulsion. In addition, the concept of optimal vortex formation is being generalized with the aim of discovering underlying design principles in biological and bio-inspired propulsion systems.

Dabiri received BSE degree in Mechanical and Aerospace Engineering from Princeton University (2001) and an MS degree in Aeronautics from Caltech in 2003 as a National Defense Science and Engineering Graduate Fellow. He received a PhD in Bioengineering from Caltech in 2005 as a Betty and Gordon Moore Fellow.

Chiara Daraio: Assistant Professor of Aeronautics and Applied Physics

Chiara Daraio's interests reside at the interface of materials science, condensed matter physics, and solid mechanics, particularly in the design, development, and testing of multi-scale metamaterials; phononic crystals; responsive soft matter; tunable acoustics; highly nonlinear solitary waves; mechanical and electronic properties of nano and biomaterials; advanced characterization of materials (high resolution TEM, in-situ analysis, FIB, AFM); synthesis, fabrication and assembly of nanomaterials and composite nanostructures.

Daraio received her Laurea degree (equivalent to a master's degree) in Mechanical Engineering from the Università di Ancona, Università Politecnica delle Marche, Ancona, Italy (2001). She received MS (2003) and PhD degrees (2006) in Materials Science and Engineering from the University of California, San Diego. She has been a guest researcher at the Lawrence Berkeley National Laboratory, National Center for Electron Microscopy since 2003 and is a recipient of the gold Materials Research Society Graduate Student Award (2005).

Chin-Lin Guo: Assistant Professor of Bioengineering and Applied Physics

Chin-Lin Guo investigates cellular mechanisms of self-organization in biological systems, particularly the biomechanics that enhance and stabilize spatio-temporal control, where collective locomotion usually leads to integrated global behaviors. A current project investigates how a single cell polarizes along a unique axis, with a focus on cytoskeleton-mediated processes. He is also interested in the transport mechanism for multi-cell group motion, which appears in embryogenesis, tissue development, and wound healing. His lab plans to combine techniques of advanced optics, clean-room fabrication, and molecular biology to identify these mechanisms. Theoretical models using statistical mechanics and nonlinear dynamics combined with experimental results are also in progress.

Chin-Lin Guo received his MD in 1994 from the Medical School of the National Taiwan University in Taipei and an MS degree in Electrical Engineering in 1996 from the National Taiwan University. After earning a PhD in Physics (2001) from the University of California, San Diego as a Burroughs Wellcome graduate fellow, he visited the

Molecular and Cell Biology Department at Harvard University from 2002 to 2006 as a Helen Hay Whitney postdoctoral fellow.

Tracey C. Ho: Assistant Professor of Electrical Engineering and Computer Science

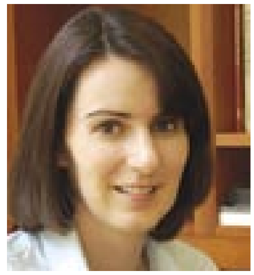
Tracey Ho's research interests are at the intersection of information theory, networking, and machine learning. She is particularly interested in the theoretical and practical implications of generalizing network behavior from routing/forwarding to network coding. Her previous and ongoing work considers routing, compression, reliability, coordination, and security in distributed network operation.

Ho received SB and MEng degrees in electrical engineering (1999) and a PhD in electrical engineering and computer science (2004) from the Massachusetts Institute of Technology. She has done postdoctoral work at the University of Illinois at Urbana-Champaign and Lucent's Bell Labs.

Swaminathan Krishnan: Assistant Professor of Civil Engineering

Swaminathan Krishnan's areas of interest are structural engineering, computational mechanics, earthquake engineering, and computational seismology. He received his BS (1992) from the Indian Institute of Technology, Madras, his MS (1994) from Rice University, Houston, and his PhD (2004) from Caltech. Between his MS and PhD degrees he worked in the structural engineering industry designing tall buildings in Indonesia, South Korea, and Taiwan. Following his PhD he pursued post-doctoral research at the Seismological Laboratory at Caltech, collaborating with seismologists on the end-to-end simulation of a large San Andreas fault earthquake and the resulting damage to tall buildings in southern California. His future research will focus on developing nonlinear analysis techniques for the accurate simulation of damage in various types of structural systems, plugging the current deficiencies in end-to-end simulations by incorporating uncertainty, soil-structure interaction, and economic analysis, as well as simulating broadband ground motion which requires a probabilistic approach. One of his core missions is to enable nonlinear analysis of structures to be adopted in design by practicing structural engineers through the development of user-friendly software accessible over the internet.

Beverley J. McKeon: Assistant Professor of Aeronautics



Beverley McKeon's research interests lie in the manipulation of steady and unsteady wall-bounded flows, both as a means for performance enhancement (for example in terms of drag or noise reduction or the replacement of traditional control surfaces) and as a diagnostic tool to investigate fundamental flow physics. Techniques include the application of modern materials and microfabrication techniques to the development of "smart" surfaces that can influence flow through local morphing on a range of scales, and the application of control-theoretic tools to describe canonical and practical flows. Thus the research is situated at the intersection of fluid dynamics, solid mechanics, and control in order to address questions of fundamental interest and with application to the aerospace industry.

McKeon received BA and MEng degrees from the University of Cambridge in 1996, before traveling to Princeton University on Fulbright and Guggenheim Scholarships. There she received an MA (1999) and a PhD (2003) in Mechanical and Aerospace Engineering. She returned to the U.K. as a postdoctoral research associate working in flow control in the Department of Aeronautics at Imperial College London, and subsequently as a Royal Society Dorothy Hodgkin Fellow, before joining Caltech.

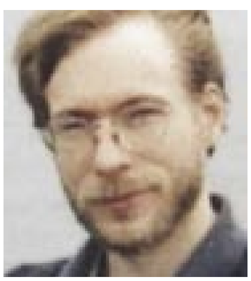
Sandra M. Troian: Professor of Applied Physics, Aeronautics, and Mechanical Engineering

Sandra Troian's research interests are in high-resolution lithography by microscale contact printing; microfluidic delivery systems using micropatterned thermocapillary flow; boundary conditions for liquid on solid flows; rivulet instabilities in driven spreading films; onset and evolution of digitated structures in spreading surfactant films; and slip behavior and foam stabilization in polymer-surfactant films.

Prior to joining Caltech, Troian was a Professor of Chemical Engineering at Princeton University, and an affiliated faculty member in the Departments of Physics, Mechanical and Aerospace Engineering, and Applied and Computational Mathematics.

Troian received her BA in Physics from Harvard University in 1980, a MS in Physics at Cornell University in 1984, and her PhD in Physics from Cornell University in 1987.

Axel van de Walle: Assistant Professor of Materials Science

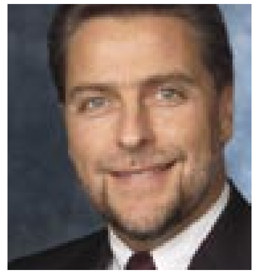


Axel van de Walle's interests center on designing and employing software tools constituting a so-called "virtual laboratory," where materials can be discovered, optimized, and characterized through automated high-throughput computational techniques. He has used these tools in a number of technological applications, including precipitation-hardened super alloys, multicomponent semiconductors, lead-free solders, and ion conductors for fuel cells. These tools also enable the calculations of phase diagrams as well as material properties such as diffusion coefficients, interfacial and surface energies, and electronic and phonon excitation spectra.

Before his arrival at Caltech, van de Walle was a Senior Research Associate at Northwestern University. He received his BEng from the École Polytechnique de Montréal (1995) and his PhD in Materials Science and Engineering from the Massachusetts Institute of Technology (2000).

Joint Appointments

John F. Brady: Chevron Professor of Chemical Engineering and Professor of Mechanical Engineering

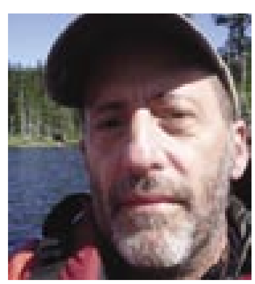


John F. Brady received his BS in chemical engineering from the University of Pennsylvania in 1975 and spent the next year at Cambridge University as a Churchill Scholar. He received both an MS and a PhD in chemical engineering from Stanford University, the latter in 1981. Following a postdoctoral year at the Ecole Supériéure de Physique et de Chimie Industrielles, he joined the Chemical Engineering department at MIT. Brady moved to Caltech in 1985.

Brady's research interests are in the mechanical and transport properties of two-phase materials, especially complex fluids such as biological liquids, colloid dispersions, suspensions, and porous media. His research takes a multilevel approach and combines elements of statistical and continuum mechanics to understand how macroscopic behavior emerges from microscale physics. He is particularly noted for the invention of the Stokesian Dynamics technique for simulating the behavior of particles dispersed in a viscous fluid under a wide range of conditions.

Brady has been recognized for his work by many awards, including a Presidential Young Investigator Award, a Camille and Henry Dreyfus Teacher-Scholar Award, the ASEE Curtis W. McGraw Research Award, and the Corrsin and Batchelor lectureships in fluid mechanics. He is a fellow of the American Physical Society and a member of the National Academy of Engineering.

James P. Eisenstein: Frank J. Roshek Professor of Physics and Applied Physics



James P. Eisenstein's research in experimental condensed matter physics focuses on the emergent behavior of large numbers of interacting electrons confined to move in two dimensions. In recent years, he and his students and postdocs have discovered a variety of new phases of electronic matter, including the long-sought Bose-Einstein condensate of excitons.

Eisenstein received an AB degree from Oberlin College in Physics and Mathematics in 1974, a PhD from the University of California, Berkeley in Physics in 1980, and was a member of the Technical Staff of AT&T Bell Laboratories from 1983 to 1996. He joined Caltech in 1996.

Scott E. Fraser: Anna L. Rosen Professor of Biology and Professor of Bioengineering

Scott E. Fraser has a long-standing interest in the imaging and molecular analysis of intact biological systems, and has been active in developing new technologies for novel assays. He has been the Anna L. Rosen Professor of Biology and Director of the Biological Imaging Center at the Beckman Institute since 1991, and the Director of the Caltech Brain Imaging Center since 2002. Before coming to Caltech, he served on the faculty and as the Chair of the Department of Physiology and Biophysics at the University of California, Irvine.

Fraser has been active in the advanced training of interdisciplinary students and post-doctoral fellows, serving as the co-director of the Marine Biological Lab's Embryology Course (with Professor Marianne Bronner-Fraser) and the co-director of Caltech's Initiative in Computational Molecular Biology (with Professor Michael Roukes). Fraser is involved in many professional societies including the American Association for the Advancement of Science; the Society for Developmental Biology; the Society for Neuroscience; the Biophysical Society; the Society of Photo-Optical Instrumentation Engineers; and the American Society for Cell Biology.

He is editor of *Developmental Biology*, and serves on the editorial boards for *NeuroImage*, *Molecular Imaging*, and *Development*. He has earned several awards for teaching and mentoring, as well as the McKnight Scholar Award and the Marcus Singer Medal. He is a fellow of the American Association for the Advancement of Science and of the European Academy of Science. Recent awards include the R&D100 Prize and the NASA Space Act Prize for the invention of new microscope techniques. Fraser earned his BS with honors in Physics from Harvey Mudd College and his PhD (1979) in Biophysics with Distinction from Johns Hopkins University.

Moore Distinguished Scholar

Krishna V. Palem: Georgia Institute of Technology

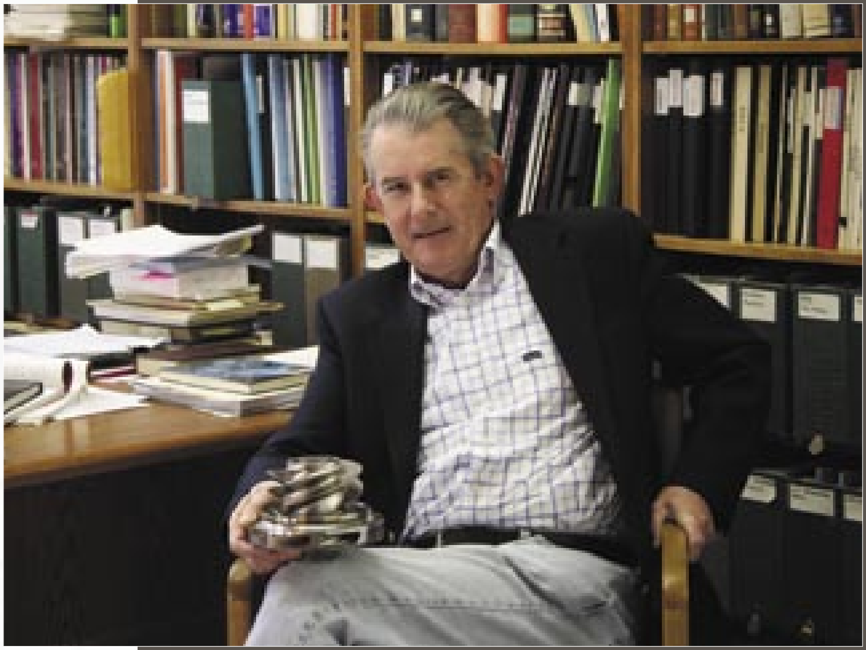
Krishna V. Palem is Professor of Electrical and Computer Engineering and Professor of Computer Science at the Georgia Institute of Technology. He is a leader in embedded systems research, and founding director of CREST, the Center for Research in Embedded Systems and Technology. The research mission of CREST is to develop compiler-centric software and hardware/software co-design to aid the programmer to rapidly prototype embedded applications.

Palem has played an active role in enabling a community of research in embedded and hybrid systems internationally through invited and keynote lectures, conference organization and participation as well as editorial contributions to journals. He serves on the editorial board of the *ACM Transactions on Embedded Computing Systems*. With Guang Gao, he started the Compilers, Architectures and Synthesis for Embedded Systems (CASES) workshop series in 1998. Since then, this workshop has blossomed into a thriving international conference sponsored by ACM SIGs.

From 1986 to 1994, Palem was a member of the IBM T. J. Watson Research Center. He was a Schonbrunn visiting professor at the Hebrew University of Jerusalem, Israel, where he was recognized for excellence in teaching, and has held visiting positions at the National University and Nanyang Technological University of Singapore. He is a fellow of the ACM and the IEEE.

Mechanical Engi

Celebrating 100 Years of Forward Motion in a Constantly Changing Landscape



"We stretch the limits of what is called mechanical engineering," Tim Colonius, Professor of Mechanical Engineering, remarks simply. To see what he means, just consider a sampling of eight research projects by current mechanical engineering faculty: artificial hearts for infants; creating and simulating laboratory earthquakes; active ferroelectric materials; algorithms to process neural information; nanofabrication of high-performance electrodes; modeling of big debris flows; the response of structures to accidental explosions; the creation of genetic algorithms for solving design problems.

This breadth is anchored by the deep understanding and teaching of the fundamentals: thermal sciences, fluid and solid mechanics, mechanical systems, robotics, control, and engineering design. The professors who are capable of this stretch are a special breed, as you will see below in this profile of the current faculty members of the Mechanical Engineering Option at Caltech. We tried to capture the whole gestalt of the group, mostly in their own words. Being engineers, most can tell you the exact day they started at Caltech. For **Joel Burdick** (Professor of Mechanical Engineering and Bioengineering), it was May 3, 1988.

"I was fresh out of grad school. I finished my PhD, took six weeks off to tour the east coast, and then flew out here and started work. I've been on the third floor of Thomas the whole time. My wife says I'm a fossil in training." Burdick's work stretches between several fields. "I think Caltech is a great research environment if you like to do interdisciplinary research, and that's where I like to work: on the robotics side between mechanical engineering,

Chris Brennen

Richard L. and Dorothy M. Hayman Professor of Mechanical Engineering

My grandfather on my mother's side was a mechanical engineer. In fact he was the head of the Belfast College of Technology. But he died five years before I was born. I was always interested in mechanical things. In the small Irish village where I grew up there was a real paucity of mechanical things to play with, especially in the aftermath of the Second World War. But still, I took apart my father's power lawn mower, the only one in the village, but couldn't put it back together. I loved doing things with my hands, and I loved practical physics. I was fortunate that I had teachers at the little Irish high school both in math and in physics that encouraged me and inspired me. And I was very fortunate—because of these excellent teachers, I managed to win a scholarship to go to Oxford University. That was a culture shock of the first magnitude. Somehow I survived and indeed I enjoyed it. I did all my degrees at Oxford. Then I went to work for the British government; I did a postdoc in a lab near London. While I was there, Caltech Professor Ted Wu came to visit; we got into conversation and had a great talk. He seemed very interested in what I was doing. A few weeks later he wrote to me and asked me to come here on a one-year postdoc, and that's what happened. I came here on a one-year postdoc—and that was 38 years ago. Chance has a lot to do with life sometimes.

neering

electrical engineering, and computer science; and in more recent years on the bioengineering side between mechanical engineering, computation and neural systems, and biology. I got started by trying to bring mechanical tools and intellectual tools from robotics to apply to neuroscience, particularly clinical neuroscience." His work in this area, in collaboration with people like Richard Anderson (James G. Boswell Professor of Neuroscience) and Yu-Chong Tai (Professor of Electrical Engineering and Mechanical Engineering), aims to restore capability lost through neural deficits by connecting devices that directly interface with neural signals from the brain to devices to enable function such as arm movement. "We work primarily on animal models, but some of the work is moving towards humans. I am really a tool builder—robotic electrodes, algorithms to process neural data—and while I don't plan to be a neuroscientist, I find myself going deeper into this area and bringing tools to help the biologists understand the underlying neural-biological questions." One of Burdick's strengths is on the mathematical, algorithmic side. "The robotics work has moved from mechanical design and analysis to algorithms and software, because that is where the interesting work is. Everything is run by computers now, and networks are everywhere—and so incorporating how computing and information and networking fits into mechanical systems in increasingly a greater part of what we do."

Kaushik Bhattacharya

Professor of Mechanics and Materials Science

I interviewed here when I was a student. The interview was spread out over three days; you meet great people and you have great conversations. What really struck me was that it was a place where people were very comfortable with themselves. There is not an artificial intensity. That struck me then, and that's what strikes me even now. It's a beautiful campus, great people, and people are very comfortable with who they are. It's not a pressure-cooker—people know you are doing some interesting things and people ask: can we help you? I think that's what's special about this place. Small enough to be personal, informal. You often think of elite places being very intense, high-pressure. Caltech combines very high standards with a very friendly atmosphere; that's what strikes me even today about Caltech.

Richard Murray (BS '85), Thomas E. and Doris Everhart Professor of Control and Dynamical Systems, is an ME professor deeply interested in the ways information and networking are integrated into mechanical—and biological—systems. A sabbatical in the late '90s at United Technologies Research Center initially encouraged his interest in 'smart products.' The idea was to embed information in mechanical systems. "When I came back to Caltech, I got more interested in information systems, and so the next six years or so were spent looking at cooperative control of multi-vehicle systems, for instance, but looking less at the *vehicle*, and more at the *cooperation*, which is more of an information problem. How do they talk to each other? That then led to more interaction with people in computer science, Mani Chandy, Jason Hickey, as examples, and I started to think about the role of formal methods in computer science, improving cooperative behavior, and so on."

Murray became Division Chair in 2000, so new research was effectively put on hold. "I decided not to get involved in biology, which was obviously extremely exciting; I didn't have time. John Doyle and Rob Phillips both used to say, 'You got to get interested in this stuff—communication, feedback, it's all here.' And I said no, no, no, no, no; but then on more or less the first day of September 2005, which was Day One of not being Division Chair, I said: Yes!" This "yes" has led to Murray to agree to teach a "Physical Biology Boot Camp" with Rob Phillips, Professor of Applied Physics and Mechanical Engineering, in June, 2007. "The whole reason to teach it is because I don't yet know enough to know what the right research problems are. And as Rob is fond of saying, one way to really understand something is to dive in and start teaching it." Murray is exploring biological systems at the level of the ecosystem, the organism, and the cell. Where is the mechanical engineering in all this organic stuff? "The organism and the cell are fundamentally machines. They take in energy in some form or another; they convert that energy into motion; they process information that controls what the machine does; and that information process is part of the machine. There are very few machines anymore that are purely what we might think of as mechanical. They are all combinations of mechanical, electrical, informational, and even biological. So that's the direction I want to go."

Murray is also still very involved in autonomy work as leader of Team Caltech. The Team is fielding a vehicle in the DARPA 2007 Urban Challenge, an autonomous vehicle competition that will take place on November 3, 2007. The latest milestone occurred on March 18: the vehicle demonstrated the ability to drive through intersections, detect an obstacle blocking a lane, and plan and execute a U-turn.

Tim Colonius, Professor of Mechanical Engineering, works in computational fluid dynamics—simulating and predicting complex fluid flow on large computer clusters. He and his group develop algorithms and use them to

Ares Rosakis

Theodore von Kármán Professor of Aeronautics and Mechanical Engineering
Director, Graduate Aeronautical Laboratories (GALCIT)

Interactions with people like Erik Antonsson have always been very rewarding—we have been active in things that have to do with space science due to our respective roles—mine as Director of GALCIT, and his as (former) Chief Technologist of JPL. Of course I also work closely with the other solids professors especially with Ravi with whom I share laboratory facilities. One of the most exciting parts of my current research is doing laboratory seismology, and in this I work very closely with Nadia Lapusta. Since her arrival in 2004, we have already shared one student and we are in the process of getting another to work with us on these earthquake problems. The students are of very high caliber; our new student will actually be carrying out both experiments, from my side, and theory and numerics from Nadia's side.

study the physics of unsteady flows, including turbulence, aeroacoustics, instabilities, and multiphase flows. One area he is particularly excited about is flow control—adding a brain to a fluid flow. “If you want to control the dynamics of a fluid, the turbulent or unsteady motion, you can use sensors, actuators, and a controller to reach flow states that you could not realize in the natural flow.” This work has many applications, particularly in aerodynamics—examples including reattaching separated flows on aircraft wings, reducing jet noise, and eliminating the ‘whistle’ that occurs when flow passes over cavities in an aerodynamic surface.

Colonius derives much enjoyment from working with students. “The quality of the students we get is phenomenal. We have access to the very best students and it makes it so fun to work here. A lot of them take the research to places where you couldn’t have taken it, or you didn’t think to take it and so it pushes the boundaries of what you know and what you think about.” However, for Colonius the real draw is simply the work itself. “As much as I love working with students, I love the luxury of just working on a problem, writing some code and getting results. The nuts and bolts of research. If I can carve out time in the day to do that, it’s a happy day.”

Nadia Lapusta

Assistant Professor of Mechanical Engineering and Geophysics

In Mechanical Engineering, as in the rest of Caltech, you have this amazing concentration of talented people, both in terms of faculty and also students and postdoctoral researchers. And when you talk to people here, everyone is so excited about their research—and not only are they doing things differently, they are doing something interesting. No matter whom you talk to, you come away with the feeling that if you were not going to continue in your own field, it would be so great to do what they are doing. That’s what makes it so successful.

Professor of Mechanical Engineering **Melany Hunt**, currently serving as the Executive Officer for Mechanical Engineering, is one of the professors who also recalls the exact day she started at Caltech: February 1, 1988. “I do a lot of experimental work developing ways to compute large-scale flows—modeling big debris flows or landslide flows. We are looking at liquid flows with lots of particles. These are very complex flows and so we do a lot of experiments trying to understand how you can simplify the particle interactions in a way that would be useful for modeling.” Hunt delivered a Watson Lecture last January on the sounds that emanate from sand dunes: low-pitched droning that accompanies the avalanching of sand down the leeward face of a large dune. “People at Caltech have thought about this for years and years. Ron Scott [Dotty and Dick Hayman Professor of Engineering, Emeritus], who passed away in 2005, was the one that got us first interested in it. We’ve made almost 30 trips out to the dunes and we’ve gotten better every time in terms of what we are doing and what we are measuring.” The internal structures of booming dunes tend to sustain and amplify certain notes, acting like the body of a well-crafted musical instrument. These structures have been computer simulated, and the model's behavior is consistent with years of field observations using seismic refraction, frequency measurements, and subsurface soil sampling. You can compare the music of these booming dunes with the sound of a cello. "In a cello, the musician bows the strings, and the sound is amplified through vibrations of the cello and the enclosed air. In the dune, we excite the system by avalanching the sand on the upper surface, and sound is amplified in a dry, loose upper layer of sand."

Another researcher in complex flows is **John Brady**, Chevron Professor of Chemical Engineering and Professor of Mechanical Engineering. "The research that I do is really in the area of fluid mechanics and transport processes, which has a lot of connections with people in EAS." His work in complex flows extends to electro-rheological 'smart fluids,' that is, fluids which, by an application of an external field, electrical or magnetic, change from a fluid to a solid in milliseconds, reversibly. "The electric field interacts with the particles that are in solution and causes the particles to form chains and solidify, but you can remove the field and the particles all wander off again." He has also been exploring lately 'shear thickening fluids.' "The faster you try and flow them, the stiffer and more resistant to flow they become. Most fluids do not behave this way. Take water: no matter how fast you go, it has the same proportional resistance to the speed. Cornstarch and water makes a nice shear thickening fluid. You can walk on cornstarch. People have made bulletproof vests out of shear thickening fluids. Basically you can take a Kevlar vest with many, many less layers of Kevlar and dip it into a mixture of cornstarch and water (it's a little more complicated than that) and get the same stopping power. The result of that is that the bullet proof vest is now flexible. It's more like a shirt."

The newest assistant professor in Mechanical Engineering is **Nadia Lapusta**. She arrived in late 2002. "It's a wonderful place. It's a very unique place in the sense that it is much smaller than what you would expect based on

Tim Colonius

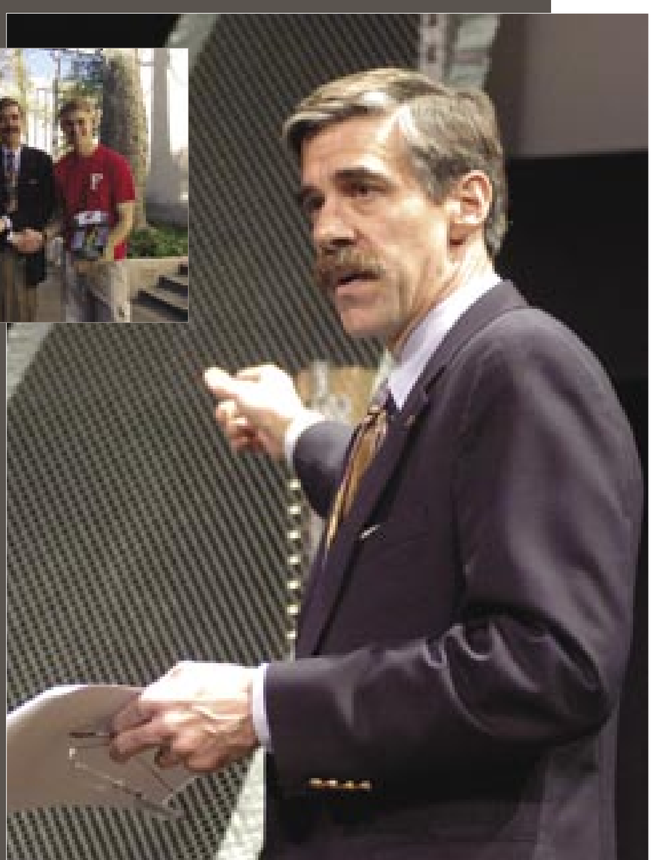
Professor of Mechanical Engineering

At the end of the day, engineering is about making tools to solve real-world problems. So research in Mechanical Engineering is either research into the tools that are going to be used to create things in the future or research into the things you are going to build. We mechanical engineers are very much in demand: we have a skill set that is very much in demand. Collaborators from across campus find us, and we in turn have intentionally been very broad in our focus. For these reasons we have been very successful with lots of different activities at Caltech.

Erik Antonsson
Professor of Mechanical Engineering

After this year's contest, I was walking back to my office from the auditorium and I ran into Mike Ikeda and Ghyrn Loveness. Their feet were not yet on the ground, they were just still aglow. And we had a wonderful conversation. They made comments much along the lines of "this is why we came to Caltech" and they were just so excited. I think they came in second place.

After all the nice words had been said and I was still enjoying their high level of excitement, they wanted to get a picture. So we posed on the walkway near Spalding in a nice spot, and a young lady took the picture of the three of us. I am shaking each of their hands like this [demonstrating]. And they sent the picture to me. And it's just wonderful. The glow on their faces is just priceless.



the impact it makes. In ME, as in the rest of Caltech, you have this amazing concentration of talented people, both in terms of faculty and also students and postdoctoral researchers. And the research is very multidisciplinary. My primary interest is the mechanics of solids but I am applying that mostly to earthquake processes, their physics and modeling. So I have a joint appointment with GPS [the Division of Geological and Planetary Sciences] and my students come from ME, Aeronautics, and Geophysics."

Lapusta is interested broadly in friction laws, fracture, and earthquake mechanics. "Earthquakes and earth movements are very interesting phenomena. A whole variety of behaviors is possible. For example, if two plates slide slowly, the frictional heat produced has time to dissipate. But imagine what happens when they slide really fast: you deposit heat where you slide. The solid materials then heat up, and at certain depths, there is melting—and that of course changes the behavior. When the earthquake stops, the material hardens producing something like a glass. Some people think that those melts should be preserved—they have found some, but not enough to account for all the heat that should have been generated. So there are other theories being proposed, many ideas. We try to formulate laws based on theories, and then test them in our models. For example, Yi Liu, a PhD student in ME, works with me on developing computational methods that would allow accurate simulations of earthquake cycles with different laws applied on the sliding interface or fault. The results of simulations can be compared to seismic and geodetic observations. I also collaborate with Professor Ares Rosakis on modeling high-speed frictional and fracture experiments done by our joint student, Xiao Lu. We use modeling to devise new experiments."

Lapusta observes that "a lot of people here have some practical applications for their work, but really the emphasis is on fundamental research. But that means the importance of the work is only felt much later. So supporting research in ME is really supporting the future. The impact of Caltech ME is disproportionate to its size. ME at MIT has roughly 90 faculty—but we have 18, less if you consider that some of us have primary appointments in other options or divisions."

The newest full professor is **Sandra Troian**, Professor of Applied Physics, Aeronautics, and Mechanical Engineering, who first came to Caltech in 2004. "The most wonderful year of my life had to be the one I spent here as a Moore Scholar. It was by far a most intellectually invigorating time. I interacted with many people and when it came time to leave I was sad to go; I felt that the environment here fit me like a glove. I was very happy when I heard after returning to Princeton that I would have the opportunity to come back for good."

Troian joined Caltech as a member of the faculty in the fall of 2006, and in particular joined the ME faculty because of their expertise in fluid and thermal sciences and the burgeoning emphasis on MEMS and microfluidics. "The confluence of MEMS devices and micro/nanofluidic flows is a rather new area in mechanical engineering. Some fundamental scientific questions as well as new technologies become possible in the study of liquid flow with interesting material properties inside or around small structures. One can also build intriguing optical structures by shaping liquid interfaces—part of a new field called optofluidics. For example, one can induce thermocapillary instabilities to shape and then solidify a nanofilm of molten polymer, thereby creating MEMS structures, photolithographic masks, or diffraction gratings. This 'topology on demand' may provide an inexpensive method for generating large-area arrays of photonic crystals."

Troian has spent the last 10 years working in traditional areas of fluid dynamics with emphasis on free surface thin films and their stability behavior. "Here at Caltech I plan on exploiting the beauty and power of interfacial stresses induced by electric, magnetic, and thermal fields to modulate the shape and response of small liquid-like structures with an eye toward micro- and nanodevices."

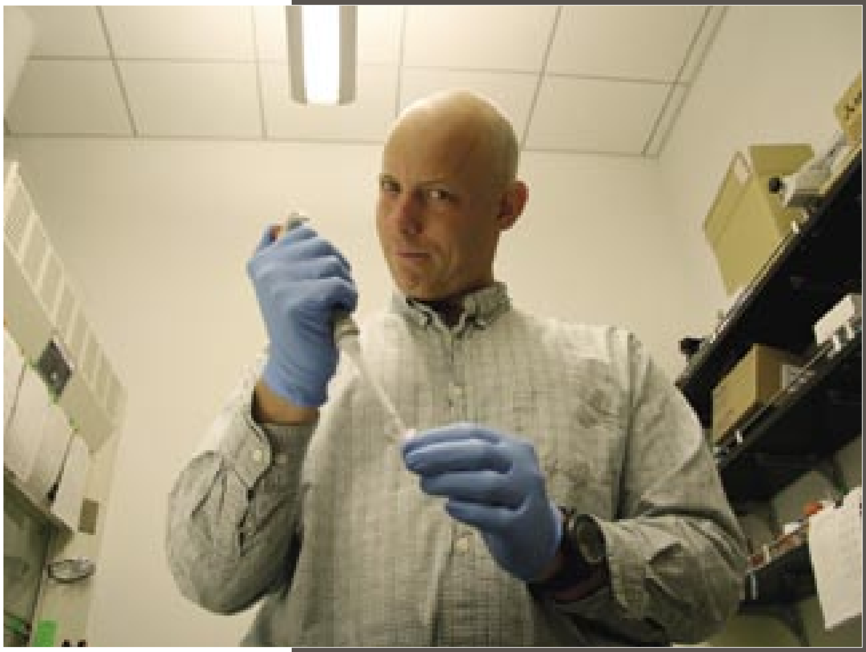
Ken Pickar, Visiting Professor of Mechanical Engineering, has been here for nine years, and during that time he has developed three outstanding courses for ME and the Division, E102 Entrepreneurial Development, E/ME103 Management of Technology, and E/ME105 Product Design. "Outside my family, Caltech is the core of my ex-

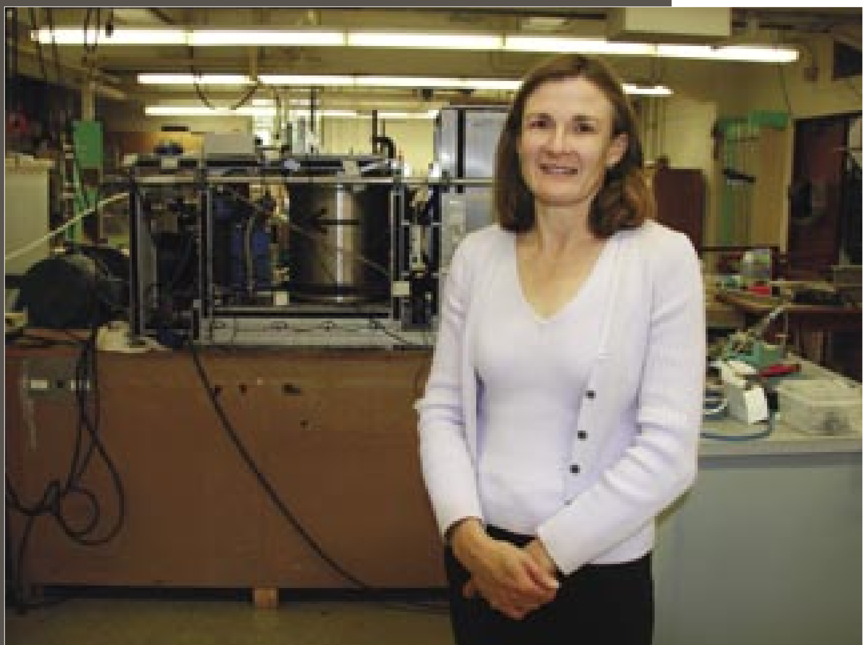
Rob Phillips

Professor of Applied Physics and Mechanical Engineering

In my heart I'm more of a physicist—which is what I am trained in. What I like is the application of mechanics to various things. Before I came to Caltech, I was working on how mechanics applies to materials. But I really have fun here working on how mechanics applies to biology.

What really changed everything for me was this one particular experiment by a group at Berkeley. What they did is grabbed onto a single virus, and they held it while the virus was packing its DNA. I was so impressed with that; I thought it was such an incredibly cool example of applying mechanical ideas to something in the biological realm. I said—honest—I've got to work on that, no matter what, and I've got to bail on my former life. Which is what I did.





Melany Hunt

Professor of Mechanical Engineering
Executive Officer for Mechanical Engineering

Caltech ME is still a special place—we still very much worry about how to educate students. What is the best way to get students interested not only in science, but interested in contributing to society? We aim to educate students in a way that results in building their confidence and their abilities so that they feel they are qualified to do a whole bunch of different things. Caltech does that in a unique way that is hard to find elsewhere—we pay close attention to the students and focus on fundamentals.

What I really love is hearing about what students do with their Caltech degrees—the range of things they do and the challenges they overcome using the tools of their engineering backgrounds. They don't feel limited by their engineering—they can and do find success in many different things. That's a great testament to Caltech.

istence right now. It has become the overriding factor in my professional life. What do I do? I teach three courses that are somewhat linked. All of them were driven by my reading of student demand."

"The Product Design course has evolved most profoundly. The course now is focused on the developing world, particularly rural Guatemala. The concept here is to take Caltech students, and all of our local brainpower, and apply them to a real-world problem that affects the over one billion people in the world who live on less than a buck a day. This kind of effort carried out in many universities over a long period of time is not characterized by a high success rate. You are building a product—that's tough for starters—for people you likely have no understanding of: their culture, what drives them, their living conditions."

"So what we've done is attempted to bridge this huge cultural and geographic gap by working with students from a Guatemalan university. All the teams have a student from Guatemala who is resident in Guatemala and free to travel on weekends into rural areas. They are the ones who are helping inform our work—that is, they are the ones who are helping to define the product, helping in the design, and testing whatever prototypes we are able to build in the very short 10-week sequence that we have for this. The students meet on Skype, an internet telephone service, several times a week, so there is bonding as a team. All my lectures are put on streaming video on the web. For the final exam the Guatemalan students are flown up here, partially paid by the Moore-Hufstedler Fund, for a period of 4 or 5 days. It's a new way of busting barriers between countries, cultures, and universities."

"We just finished the first semester where we had this close collaboration—and it has not been easy, but I would say it's been successful enough so that we are going to do it again and try and see if we can improve it." Pickar plans to take the class to a new level: in partnership with a professor at MIT he is applying for various grants to see if this model of having cooperative teams with people in-country and our own students is a good way of improving the "hit rate" of projects.

The desire to change the world for the better often marks a student's desire to go into mechanical engineering. **David Goodwin**, Professor of Mechanical Engineering and Applied Physics, was one such inspired student, and remains dedicated to solving both scientifically interesting problems, and those with more near-term application. "When I was a senior in college, there was an energy crisis in the U.S., and at that point I decided I wanted to do energy-related work. I found that at Stanford the energy programs were in Mechanical Engineering, and so I applied to that program. Shortly after I started, in about 1979, the nation's priorities changed, and funding for energy projects declined. Oil prices declined. I did finish my PhD on energy related projects, but during my postdoc positions I ended up working on other things entirely. Now, however, energy is once again a popular topic. I think we are at the point that while prices may fluctuate a little bit, they are never going to go back to being so low we can forget about it. Now there is an essential difference—we realize what we are doing to the environment through global warming. There's added motivation to develop new energy techniques that we didn't have in the '70s and '80s. A lot of my current work has applications to energy. In the last few years I've reentered the energy arena and over half my program is working on solid-oxide fuel cells. In that work I collaborate quite a bit with Sossina Haile [Professor of Materials Science and Chemical Engineering] in Materials Science, and colleagues at other universities."

"I've always done a lot of numerical modeling and simulation. There was an opportunity in the fuel-cell world: a lot of people are doing good experiments, but there is a need for better numerical simulations. It turns out that many of the things that you want to measure inside a fuel cell are very hard to measure, so numerical calculations can give you some idea of what might be going on—or help you to design better experiments. With the renewed awareness of energy issues, there is a lot of interest among the students, so I am fortunate to be getting a lot of student interest in my projects."

John Brady

Chevron Professor of Chemical Engineering and Professor of Mechanical Engineering

I am interested in complex fluids. Complex fluids are, for example, personal care products, printing inks, polymers, polymer solutions—all kinds of 'gunky' stuff. More formally, we call them multi-component materials in a fluid-like state. Often they are in the form of colloids—small particles dispersed in a liquid—and I try to understand their static properties. Can we form interesting structures? More importantly, I like to ask: How do they move? How do they behave? How do they flow?

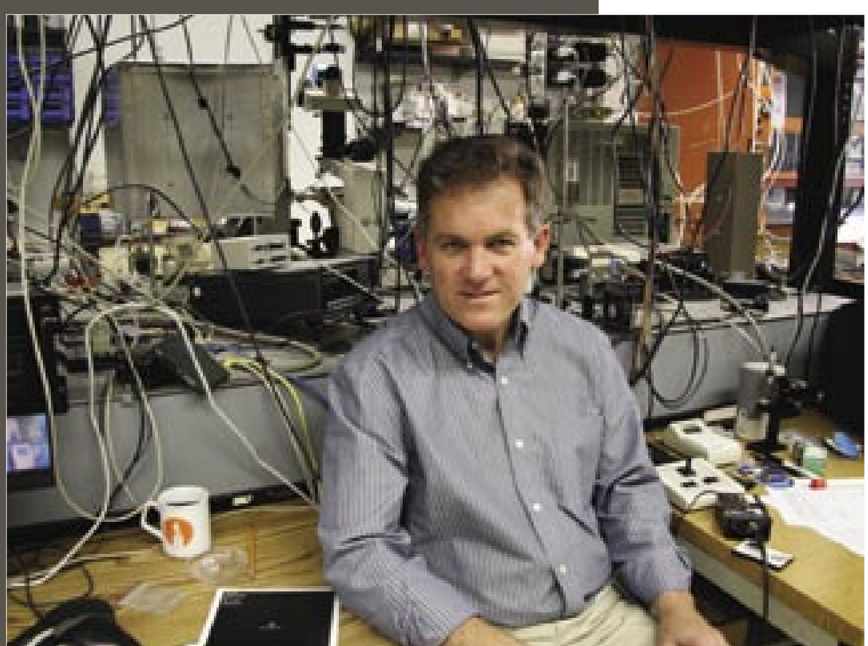
I've been doing fluid mechanics for a long time and have served on a number of thesis committees in ME, so joining the option, which I did in 2005, was a natural thing to do. I wanted to make my association more formal, and I wanted to become more involved in what goes on in Mechanical Engineering.

David Goodwin

Professor of Mechanical Engineering and Applied Physics

I think ME at Caltech is a little different than ME at other places. Our strength is at the interface of engineering and science. We don't do a lot of very applied and practical things that some other schools do—our unique niche is at the scientific end of the engineering spectrum. I was struck earlier this term when our new graduate students were here for orientation. We went around the table and asked them what they are interested in doing for research. And essentially every one of them said "micro-" or "nano-" something. Partly it's because we are interested in engineering at small scales, and we admitted those students. But I also think that illustrates one of our major directions: small things.

Within my own work, I think there's quite a potential for using some of the recently developed nanofabrication methods to develop much higher performance electrodes. Electrodes now are made from a random mish mash of powders that are baked to sinter the particles together. But I think that a more engineered approach, less random, would lead to higher performance. I am very interested in exploring how new nanofabrication methods can lead to higher performance fuel cells. And I think that we can make structures that just a few years ago would have been impossible to make.



The student side of the equation in Mechanical Engineering is tremendously important. **Joseph Shepherd**, Professor of Aeronautics and Mechanical Engineering, a recent joint appointment, has worked with ME students for a long time. "The nice thing about the ME program is that it is a very flexible program and gets students involved in research early on. The program attracts excellent students and I have worked with a number of them over the years. My joint appointment began in 2006, but one of my very first graduate students was actually an ME student. Since I arrived at Caltech in 1993, I've always had one or two ME students in my group."

Shepherd is interested in how structures respond to explosions. "We are working with Los Alamos right now—they have some metal cans that are used for special purposes, and we are studying the bending of these cans due to accidental explosions. In addition to solving their particular problem, we are trying to form rules in a very general way so that we'll have a set of ideas that we can use on other problems. We'd like a way to estimate the results for any mixture and any size pipe and any kind of explosion event—then we'll have something we can provide to the engineering community and the results will have widespread use."

Shepherd has joint projects with several ME faculty. "Dave Goodwin has developed a really great set of software tools called Cantera—this software allows you to do calculations on kinetics—and we've picked up on that and use it quite a bit, especially in a class on combustion that I teach." He also works with Tim Colonius, looking at problems concerned with the interaction of fluids and structures, and he has a program with G. Ravichandran, sponsored by the Navy, exploring the interactions between shock waves, bubbles, and solids in water.

Students are tremendously important to the work of **Yu-Chong Tai**, Professor of Electrical Engineering and Mechanical Engineering. "I have 17 PhD students and 3 undergrads. In my field, the job market is really good, so when students graduate, they are immediately stolen away.

We don't have that many postdocs! My students have to master all the theory, all the math and science, but they also have to master their hands, like a surgeon. They are able to operate many difficult machines and make devices beyond what conventional machining technology can do. That kind of student is attractive to so many technology sectors. My students have really broad backgrounds. I think that's really wonderful. That's actually the kind of group that I envisioned working with when I was young. They help each other, they teach each other." Tai and his students are inventing devices, particularly in the bio-implant area. "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 then putting it in the 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's low-power devices use micro and nano technologies. He and his colleagues have developed retinal implants that can allow a blind person to see a real-world image, not just light. "We are hoping that in less than two years, the devices that we designed here in the lab—that we have spent the last 10 years developing—will go into the human eye. That will be the biggest moment of my career."

Kaushik Bhattacharya, Professor of Mechanics and Materials Science, is one of the mechanical engineering students that passed through the Indian Institute of Technology, Madras in the 1980s, a time when two very influential professors were teaching there: Alwar and Ramamoorthy. "Anyone who went through IIT Madras in that era would know these guys. Phenomenal teachers. Many of the mechanical engineering students went into solid mechanics because of them, myself included."

Bhattacharya works on problems somewhere between mechanical engineering and materials science. "When people think about mechanical engineering, they usually think about designing machines—cars, robots, devices. What I think of is the *materials themselves* in that same spirit. From a traditional mechanical engineering point of view, a material is some homogeneous blob of material. But

Michael Ortiz

Dotty and Dick Hayman Professor of Aeronautics and Mechanical Engineering

First and foremost, the aptitude, enthusiasm, and devotion to science and technology of Caltech's students are unparalleled. Caltech's student body is a national resource that feeds top talent into academia, industry, and the national laboratories. Another aspect that is increasingly rare and that particularly appeals to me in connection with my current focus on predictive science is Caltech's commitment to experimental science. As experimental programs at other elite institutions dwindle or are terminated outright at an alarming rate, Caltech's strength in experimental science becomes increasingly prominent. As a theorist, the opportunity to collaborate closely with leading experimental scientists is a luxury available at few other places and makes the Caltech experience unique.

if you look at it in some subscale, you will find that there are interesting features within the material and that's what gives us the macroscopic properties that we use. Materials scientists traditionally try and understand the substructure of materials. The difference is that today I can start understanding, analyzing, manipulating the substructure using a mechanical-engineering-like language. The material acts as the machine."

Along with one of his collaborators on the experimental side, Professor G. Ravichandran, Bhattacharya has worked for a long time on 'active materials,' piezoelectric or ferroelectric materials that do work based on some change in their structural qualities. "What is very interesting about these materials is that if you go to very small scales, scales of microns, the polarization is not uniform. Distinctive patterns are formed based on regions of polarization—and every material has distinctive patterns. The questions we are interested in are: Why does a particular pattern form and how can I manipulate it to get specific properties? That's our activity in active materials."

"One of the things that I am very excited about currently is a collaboration with Michael Ortiz and a group of students starting with Vikram Gavini. We're doing quantum mechanics, but at macroscopic scales." No material is perfect: materials have defects. Most of these defects are in parts per million or parts per trillion. So to compute them you need then to consider millions or billions of atoms. "We are developing methods to do these calculations at these levels. We ask the question: what aspects of this fine-scale behavior are important at the macroscale? Then we try and compute that directly. We write the down the detailed theory for everything, and then systematically coarsen the grain, shedding the information we don't need. We don't make assumptions or use multiple theories. We are just using one theory and computing it on a hierarchical scale. If you know that in a region the structure was nice and ordered, you only need to sample that area, you don't need to compute all the details. Near the defects, you need to get all the information. Our technique throws out a lot of redundant information."

Solid mechanics is very well represented in ME by Nadia Lapusta and Kaushik Bhattacharya, but through a process of 'mergers and acquisitions' in 2000, three joint appoint-

Joel Burdick

Professor of Mechanical Engineering and Bioengineering

I owe a great debt to a lot of the senior faculty—mentors like Chris Brennen, Allan Acosta, Frank Marble, Jim Knowles, Tom Caughey, and Ed Zukoski. When I was a young faculty member, they set the tone that you should be a gentleman and a scholar. They believed by their actions that people worked together and pushed the department forward. And this theme persists today: the faculty of the department really get along well. There are no politics. I actually enjoy going to ME faculty meetings. The faculty here have responsibility, but also feel ownership of the place. In larger schools you can feel more like just an employee.

ments of professors strongly associated with aeronautics and GALCIT—Ares Rosakis (Theodore von Kármán Professor of Aeronautics and Mechanical Engineering and the Director of GALCIT), G. Ravichandran (John E. Goode Professor of Aeronautics and Mechanical Engineering), and Michael Ortiz (Dotty and Dick Hayman Professor of Aeronautics and Mechanical Engineering)—took place. This brought enormous experimental expertise into the ME mix, as well as additional theoretical and computational acumen.

Professor **Michael Ortiz** comes to mechanics from the theoretical side. "The importance of modeling and simulation in the design and certification of complex engineering systems—traditionally based almost exclusively on testing—has skyrocketed in recent years, and this is likely to continue to become increasingly central in the future. For want of a better descriptor, the term 'predictive science' is used to describe this emerging field. As the complexity of engineering systems increases, our ability to test those systems thoroughly enough—and base their design solely on testing—steadily decreases or becomes impossible altogether. The resulting challenge is to develop our physical models and codes to a degree of fidelity such that we can reduce the number and complexity of integral tests required for certification. Of course, predictive science does not in any way diminish the role of experimental science, it enhances it. Carefully designed tests, tightly coupled to modeling and simulation, are more important than ever in order to validate models and codes and make code-based certification possible. The grand challenge of developing rigorous and reliable predictive science methodology combining modeling, simulation, experiment, and uncertainty quantification is one of the most interesting endeavors that I'm involved in at present."

Professor **Ares Rosakis** comes to mechanics from the experimental side, and at present is very excited about his collaborations with Nadia Lapusta in "experimental seismology," or laboratory earthquakes. "This research started about six years ago with Hiroo Kanamori [John E. and Hazel S. Smits Professor of Geophysics, Emeritus] and myself. We were looking at certain unusual earthquake

Richard Murray
Thomas E. and Doris Everhart Professor of Control and Dynamical Systems

I see very interesting feedback problems in biological machines. And we are now at the point at the organism level that we are able to probe into things like insects and other organisms much more deeply to understand how the machine works. There are applications, but I think it is interesting on a sheer scientific plane. At the cellular level, similarly, we are now able to probe in ways that we never were able to before, and therefore, we are able to design. So we can actually take the principles that we learn about how it works, and then design a new system using those principles. Synthetic biology is one of the areas I am interested in where Caltech is taking a reasonably early lead. My colleagues and I are interested in how to build things out of molecular machinery and to do so in a way that illuminates the biology that is going on. In the long run, the work may also be useful for developing therapeutic systems, detecting disease, and curing disease.

Guruswami Ravichandran

John E. Goode, Jr., Professor of Aeronautics and Mechanical Engineering

The ME department at Caltech is a very strong department, engaged in quite fundamental engineering science, with an eye toward application. It is also a very cohesive group that cares very deeply about undergraduate and graduate education. Students are provided with the opportunity to work on real-life problems and they have excellent classes. Programs like Erik Antonsson's ME72 class and the DARPA Grand Challenge with Richard Murray—these have really energized the students. And they also draw deep inspiration from the robotics program. There are all sorts of opportunities that are very attractive, very appealing to the undergraduates. They know the faculty cares about them. There is a sense of family.

ruptures that featured very high rupture speeds—speeds that were much higher than the shear wave speed of the material, in this case crustal rock. There was no direct proof that this could be happening—the seismological records were very unusual. We hired a student and constructed the experiments that mimic the rupturing earthquake in a laboratory setting. Kanamori provided invaluable guidance in designing these experiments with me so that they are relevant to seismology, and we produced miniature earthquakes in the laboratory. We demonstrated that highly unusual speeds of rupture are possible in nature, and we described the conditions leading to such unusual behavior. These experiments use high-speed photography, photoelasticity, and infrared thermography as diagnostics. This type of work is continuing now with both Kanamori and Lapusta. We are concentrating on the study of the 'crack-like' or 'pulse-like' nature of laboratory ruptures and their behavior when they encounter fault complexity such as forks, kinks, and jogs."

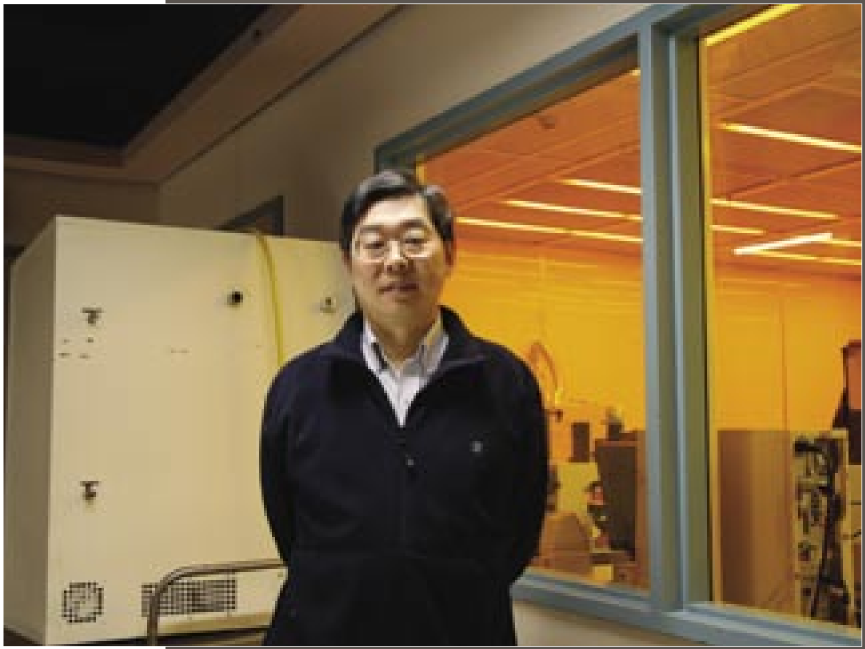
The fifth member of the ME "solids consortium" is Professor **G. Ravichandran**. As an experimentalist, Ravichandran determines if what the theoreticians say is possible is actually possible. "I work with a lot of ME students, and with Kaushik Bhattacharya. He's a theoretician, and I do experimental work, so we complement each other. He has made a number of predictions, particularly regarding active materials. People were very skeptical about this, but we have shown in the lab that in fact the behaviors Kaushik predicted are possible."

True to Caltech form, Ravichandran's collaborations extend across divisional boundaries, and he is now working with a group in Chemistry and Chemical Engineering on developing biomaterials based on protein engineering. "I have gotten very excited about that—cells can be thought of micromachines, at least in my very simplistic view." Ravichandran is working with David Tirrell, Ross McCollum - William H. Corcoran Professor and Professor of Chemistry and Chemical Engineering. They are jointly exploring cell-surface interactions, 3D cell migration in artificial extracellular matrix (aECM) proteins, assembly, and the mechanical properties of biomaterials. The goal is to move towards a comprehensive understanding of biological structure-function relationships in soft materials.

Rob Phillips, Professor of Applied Physics and Mechanical Engineering, has migrated over to the biological side. In fact, he is the one member of the ME faculty who now resides in the Broad Center for the Biological Sciences. His conversion is so complete that he serves as Option Representative for Biochemistry and Molecular Biophysics. Yet, many of his methods are still firmly rooted in mechanical engineering. "Our research uses physical approaches to understand the structure and function of living organisms and the macromolecular complexes that make them up. We are focused on the physical biology of the cell." Phillips is interested in a number of different phenomena involving the mechanical response of cells and the machines within them. "How do cells sense mechanical forces? That's a basic question. We know the mechanism of mechanosensation in bacteria is mediated by a protein known as Mechanosensitive Channel of Large Conductance (MscL). But how does MscL sense tension in the membrane? How do the elastic properties of the surrounding lipids affect the function of the channel? For that matter, how do the elastic properties of the lipids affect the function of any channel or transmembrane protein?"

To help bring students and colleagues deeply into the subject matter, in 2005 Phillips initiated "Physical Biology Boot Camps" and will be running his fourth camp this summer (with Richard Murray). He is also organizing a summer school and conference called "Nanomechanics: From Cells to Solids" that takes place in July 2007.

ME72 is a Caltech tradition, not just a class. Cheerleaders, the National Anthem, the final showdown in Beckman Auditorium… ME72 epitomizes many of the best qualities of Mechanical Engineering at Caltech. The course has been taught 22 times, and for 18 of those, **Erik Antonsson**, Professor of Mechanical Engineering, was presiding. "I was born a mechanical engineer. My father is a mechanical engineer. My mother's father was a mechanical engineer. My father's father did everything under the sun—never had the education to be engineer—but he certainly had the insight to be a mechanical engineer. He taught me a lot about the way things worked in the world. My mother's brother was a mechanical engineer. My older sister married



Yu-Chong Tai

Professor of Electrical Engineering and Mechanical Engineering

When I was a grad student at Berkeley, I saw a yellowed paper on a lab bulletin board announcing an EE search at Caltech. It was drafted by Dave Rutledge. It had been on the wall for at least two-and-a-half years. Then I did one thing right. I actually emailed Dave Rutledge asking if the position was still open. He said yes. We did not know each other at the time. He invited me to send in my information, and I did. Dave invited me for an interview almost instantly. So I came. I liked the people here. Paul Jennings, the Division Chair, told me "Tai, you come here, and we'll build you a lab." When I talked to faculty, basically they told me I could do anything I wanted. Less than one week after the interview they called me to ask me to come for another interview and offered me the job. From the time I saw the yellowed paper to the offer was less than a month. No regrets!

Kenneth Pickar
Visiting Professor of Mechanical Engineering

From everything that I can see—and I have talked to professors who have been here much longer than I have—ME is as strong as ever, is as well-positioned for the future as ever. This great array of talent here has kept the flame alive. When you are on top of so many areas, and when you do it for so long, there is only one way for you to go, which is down! But we haven't done that. The faculty here has kept the faith, and they have continued the tradition of Caltech excellence.

We are going to change—you can expect that ten years from now the things that people will be working on will be significantly different than the things that people are working on today. You can already see that beginning. Mechanical engineering as a profession has changed significantly over the last 20 years and it will continue to change. This is the only way that makes any sense; the word mechanical engineering has been around for a long time—it's been around for 100 years at Caltech. We've been able to maintain this discipline in a way that doesn't compromise the past, and yet doesn't get stuck in the past.

a mechanical engineer."

Antonsson has been the public face of the Mechanical Engineering Option over many years due to the magic of ME72—magic that extends off-shore, even beyond the boundaries of campus. He served as Executive Officer of the option from 1988 to 2002, catalyzing and provoking discussions, growing and inspiring the faculty. The ME undergraduate degree program was reestablished during this period. "This was important because it identifiably establishes our program and our students. It was a topic of considerable debate—and healthy debate—because it meant that we were making a long-term commitment to teaching the undergraduate program."

These activities were, of course, always accompanied by his research work. Antonsson and his group have been using genetic algorithms as a way to develop design solutions. "That's not unique—lots of people are doing that. But during the last couple of years we have recognized some of the fundamental limitations to this approach. We've realized that biology uses genetic information in a way that is very different from the way it is used in artificial evolutionary methods. And the difference is that the information in our genes is not a description of us, it is a recipe for us to grow and develop." This realization has led Antonsson to explore a new approach. The algorithms evolve sets of rules, and then the rules are handed to a simulation environment where individuals grow and develop. "At the end of that process we evaluate how well they performed. This more closely parallels evolution in the natural world, and is quite a radical difference in the way these methods are used and particularly the way they are used for solving design problems."

"We'd like to expand to attacking design problems where the designs have intrinsic complexity and therefore are difficult to solve by manual methods." Applications to environments like space offer complex challenges, for example. Solutions must perform at a very high level. "Now you start thinking about structural materials that change character or properties along their length—they might be flexible in some regions, stiff in other regions, and lightweight and hollow elsewhere. Bones—structural elements in biology—have exactly that character. They are not shaped like the rectilinear pieces you see in chairs and buildings—they are weird and complex. And they are also complicated from a materials standpoint. A long bone has an outer sheath of cortical bone that is very dense and stiff, and that sheath thins down at the ends. The hollow region of the long bones is filled with a kind of spongy bone that is almost like a closed-cell foam that takes up the space and provides other properties, but is lightweight. And they are hollow in the center. Bones are really quite complex. So we've thought about how to develop rules sets that would evolve in such a way that we could make things that would look like biological structures, like bones. What would we learn from that? That's the work that I am truly, deeply excited about."

Professor **Chris Brennen**, Richard L. and Dorothy M. Hayman Professor of Mechanical Engineering, has been closely associated with the lives of students on the Caltech campus far beyond his academic teaching and mentoring activities—which are prodigious by themselves. He has won three teaching awards, including in 2005 the Richard Feynman Prize, Caltech's most prestigious teaching honor. He was Master of Student Houses (1983-87), Dean of Students (1988-92), Executive Officer for Mechanical Engineering (1993-97), and then Vice President for Student Affairs (1997-2002). "I spent over 12 years in the administration of student affairs. Probably the most challenging job was the first one, Master of Student Houses; there was no staff in those days to deal with student problems. I had to deal with all kinds of things in the middle of the night. But particularly as you grow older you look back at those human moments—what you were able to do for particular students and students in general. I remember Richard Murray when he was an undergraduate. Richard was even faster then!"

"I'm at the age now where I don't have to worry about whether my research is respectable, or good enough to get tenure. I work on what I like to work on and I've always been interested in a very wide range of things. I've always worked on cavitation. It's such a pretty, visual subject. There are many applications of cavitation. Cavitation is a serious problem for artificial hearts for infants or adults. I am working on an NIH project trying to develop artificial

Joseph Shepherd

Professor of Aeronautics and Mechanical Engineering

I think the ME program is a very good program for the undergraduates because it gives them an exposure to actual mechanical things—they get to work on bits of hardware. I think the reason students like to come to a place like Caltech is because they imagine that they are going to be doing things with their hands. They are going to be building things, measuring things—doing something other than sitting in front of the video screen. So much of modern education has become very passive. ME at Caltech provides an outlet for students who are interested in working with technology in a hands-on way. And that is something that I hope we can continue as a tradition.

You can go anywhere and sit in classes—and you can argue that the classes here are better than those anywhere else. But I think the key point is that students have this wonderful opportunity to have interactions with the faculty who run these research labs. It's a fantastic opportunity. You learn so much working in a laboratory—not only learning about that specialty, but also learning how to be in a research group and what it's like to be on an exciting research project. That's where the tremendous advantage of Caltech lies.

hearts for infants, which is a big challenge. None of the artificial hearts work very well. I am working of course with Melany on booming sand dunes. I still do work on rocket engines. Cavitation is a big issue in rocket engines because the turbo pumps that are a key part of the engines cavitate like crazy. You have to manage that cavitation and make sure it does not become unstable and create serious problems."

"In ME, we have always striven to be at the very forefront of the new engineering—of the engineering of the future rather than working over the engineering of the past. I think we are very committed to teaching, especially the undergraduates. I fear that the commitment to the educational mission of this Institute has declined significantly, and that depresses me. ME has always had a tradition of marvelous teaching, and I learned a lot from my predecessors, such as Allan Acosta [Richard L. and Dorothy M. Hayman Professor of Mechanical Engineering, Emeritus], Rolf Sabersky [Professor of Mechanical Engineering, Emeritus], Ted Wu [Professor of Engineering Science, Emeritus], and Milton Plesset [Professor of Engineering Science, Emeritus], all of whom were devoted to students and great teachers.

"The *esprit de corps* among the ME graduate students is something I value. I think it is beneficial to them—they have tremendous pride in being part of ME. I guess I am a believer in what the social scientists call *social capital*—that is to say, you need to invest in your relations between people. And once you accumulate some goodwill, you have to be very careful not to squander it. It's harder to measure so scientists don't tend to believe in it. I have always believed in it because of my background. The benefits that accrue from social capital are in the end of tremendous value to the institution and to the department."

"I feel enormously fortunate to have been able to live out my career here at Caltech. Enormously fortunate with the colleagues I've had—seniors and juniors. I've had misfortune in my life, but I've also been very, very fortunate. And it's been a fantastic adventure being at Caltech. Hard to imagine I could have luckier in that regard. So I try to give back, as my mother, Muriel Maud Brennen, taught me I should always." ENG

Sandra Troian

Professor of Applied Physics, Aeronautics, and Mechanical Engineering

My office was in the Thomas building the year I was on sabbatical at Caltech as a Moore Scholar in 2004-2005. I spent many wonderful hours discussing topics like non-normality and stability of fluidic systems, Brownian motion, and quantum dot assemblies with the faculty there.

What I enjoy most is the strong emphasis on experimentation coupled with the fact that ME has some of the finest mathematicians around. One of the most important characteristics that attracted me to ME—and it is something that the ME departments everywhere should strive hard to maintain—is the basic focus on building structures of all kinds, from nanodevices to jet wings. Doing this job well requires passion and skill in understanding the fundamentals and the willingness and agility to learn the use of new tools and methodologies. Caltech knows how to do this right.

Stay in touch with ME at: http://www.me.caltech.edu

Powering the Planet

The Caltech Center for Sustainable Energy Research

Solutions to the most important energy problems hinge upon fundamental advances in science and technology. Ultimately, we as a society will have to replace fossil fuels for much of our energy needs, yet at the present time, we are not positioned to do so and continued short-term reliance on fossil fuels appears inevitable. Unquestionably however, the most abundant source of energy is the Sun. A group of Caltech researchers under the umbrella of CCSER—the **Caltech Center for Sustainable Energy Research**—contends that the most fruitful research directions will be ones that embrace these realities. Their approach rests on advances in three areas: the development of low-cost, ultra-efficient solar-to-electric conversion mechanisms; conversion of solar energy into stored chemical fuels; and the creation of low-cost, lightweight, and high-energy output fuel cells.

Last November, we sat down for a conversation with the principals of this new initiative—Professors Harry Atwater, Harry Gray, Sossina Haile, Nate Lewis, and Jonas Peters—to find out more about their approach and motivations.

ENGenious: On the CCSER website, you state that your aim is to transform the industrial world from one that is powered by fossil fuel to one that is powered by sunlight.

Harry Atwater: The question is: how realistic is that?

ENGenious: Yes, how realistic is that, and how are you going to do that?

Atwater: Ultimately, all energy on Earth emanates, directly or indirectly, from the Sun. Until now, we have used only the long-term storage media for solar energy, namely, decayed plant matter that has compressed under geological timescales to form fossil fuels. What we are talking about is transitioning from using these non-renewable *stored* forms of energy to things that are renewable on the same timescale as their use. We are really a *fuels* economy. The sources of renewable energy that have been developed to date, and which are undergoing development—wind power, hydroelectric, solar-electric—are, by themselves, are not capable of generating the fuels that power our transportation economy. Only about 20% of energy use in the U.S. is in the form of electricity, so it is not enough to generate electricity. Of course, it would be a worthy goal to generate all the electricity in the United States renewably—it's certainly not done that way now. But our ambition is even bigger, which is, essentially, to *displace* the carbon-intensive fossil fuel use with a carbon-free, non-carbon intensive solar-driven fuel cycle.

ENGenious: Why can't the current approaches to renewable energy meet our needs?

Atwater: The renewable energy infrastructure we have now for solar and wind is really nothing more than the outcome of the investment that we made in the '70s.

Harry Gray: Yes, and much of it was developing silicon photovoltaics. This is what we've got now. But it's just too expensive. It's 20-25 cents per kilowatt-hour. One of our objectives is to get the cost of electrical generation per kilowatt-hour down by a factor of five. If we could get it down to 5 cents per kilowatt-hour, the cost of producing large amounts of renewable electrical power for the country would come way down. We have estimated we could outfit the whole country now for solar, in the next couple of years, using existing technology, for about 5 to 10 trillion dollars. That's a rough calculation.

Nate Lewis: The problem with energy, really, is that people who experience it everyday don't experience it on the *scale* that we need to produce it. They don't experience the fact that, over the next 40 years, if you want to avoid even a doubling of carbon dioxide, after accounting for population growth and economic growth, you have to build the equivalent of a new nuclear power plant *every day for 38 straight years*. So all of a sudden, most of the "solutions" are in fact not solutions when you consider the needed scale.

Atwater: And there are material limits. Let's take the example of silicon solar cells. Suppose we were to spend 5 to 10 trillion dollars outfitting the U.S. with silicon solar cells. Currently, the front contacts on silicon solar cells are silver screen-printed contacts. It turns out that if you were to deploy solar cells on that scale, you would run out of all the silver on the world market. There are limitations.

Sossina Haile: When you start thinking about energy on a global level, you start thinking about *all* the ways in which the Earth is resource limited. When you start really thinking about global solutions, all of a sudden these material resources become a real problem. And along those lines, platinum is one that people are starting to think about in terms of either fuel-cell catalysts or electrolysis catalysts. There will not be enough platinum.

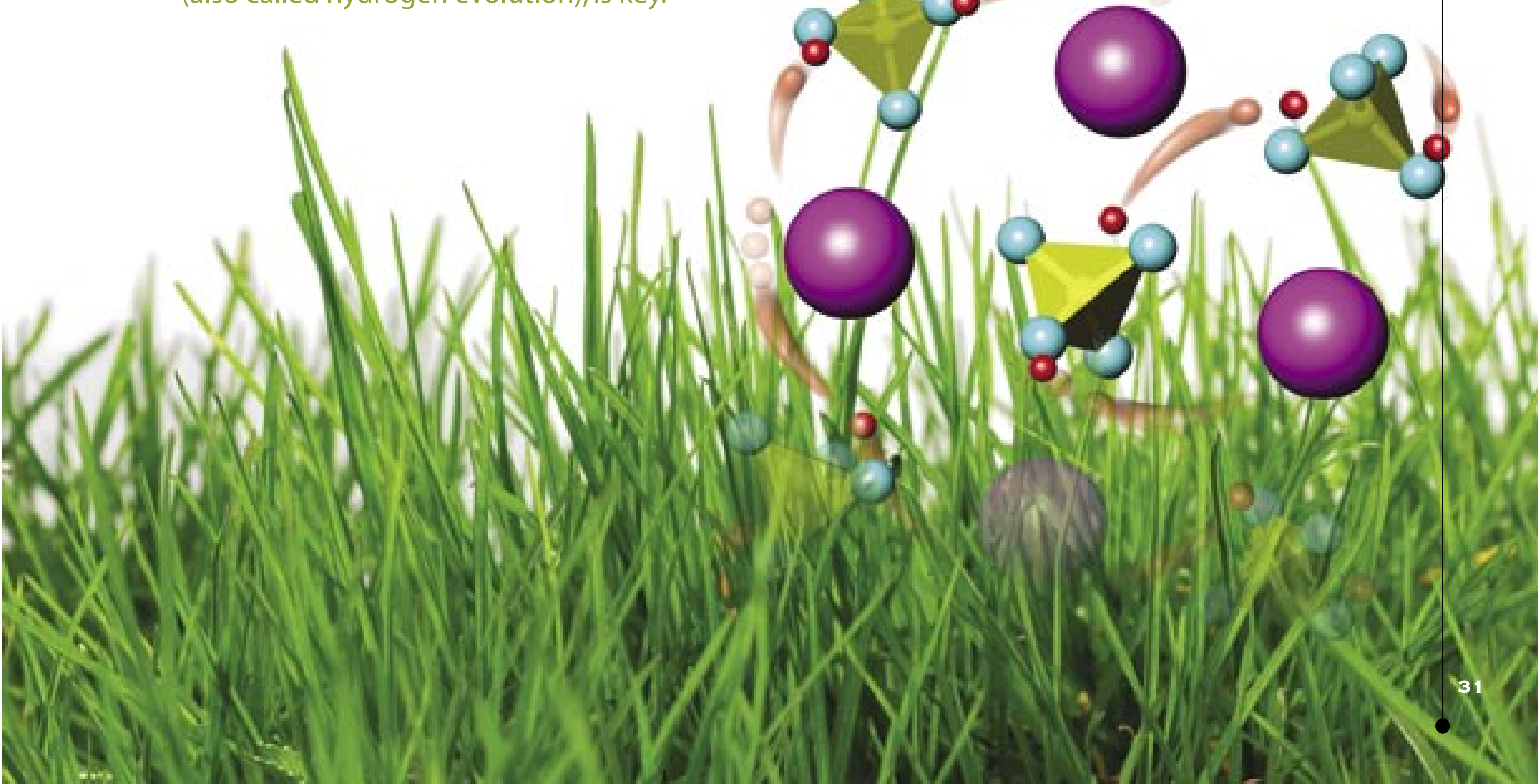
Atwater: Buy stock in platinum!

Haile: Platinum prices are skyrocketing, and it's all about hydrogen fuel cells.

Atwater: And then when we're successful in this CCSER initiative, you'll need to start shorting your platinum stock. [*laughter*]

Gray: One of Jonas's main areas of interest is replacing platinum with much cheaper, more available metal catalysts such as cobalt, nickel, and iron. That's one of the big areas of research in CCSER. Can we develop catalysts that are

Existing technologies cannot meet global needs because of efficiency and economic constraints, and well as the limited quantities of raw materials. This last constraint has led the CCSER group to place high on the priority list the development of catalysts made from non-precious metals. These catalysts will be designed to extract energy from water by pulling apart the two very strong hydrogen-oxygen bonds, rearranging them into weaker H-H bonds and a strong O-O bond. This results in making one really weak, high-energy fuel bond, effectively storing sunlight. This splitting of water, into a chemical fuel in the form of H_2 (also called hydrogen evolution), is key.



Left to right: Sossina Haile, Professor of Materials Science and of Chemical Engineering, Harry Gray, Arnold O. Beckman Professor of Chemistry, and graduate student Lisa Cowan.

closer to nature's catalysts, using much more abundant and biologically compatible materials? Because there is another angle on this—it's not only lowering the cost, it's also coming up with environmentally friendly materials. If the technology is going to be dispersed widely, then we can't have toxic metals all over the place. And so we need to use more of nature's kinds of metals, which are cobalt, nickel, iron, and copper.

Atwater: The things you have to do well—efficiently, and with abundant materials—are: absorb the light, convert that light to an electrochemical potential that's sufficient to split water, and then you have to catalyze hydrogen evolution from water by electrolysis.

Jonas Peters: So you are taking water and breaking it apart into hydrogen and oxygen. You shine light on it to break it apart. Then you've created a chemical potential. And when it comes back together, you get energy in the form of heat or light back again.

Haile: Or electricity.

ENGenious: Why is it so difficult to mimic nature's processes?

Gray: Because we don't know how to encapsulate these catalysts the way nature does. Nature encapsulates them in folded proteins in a membrane environment, and can keep them in place and manipulate their structures. We have not figured out how to do that yet.

Peters: There are basically dozens of details that count. *Every* detail counts. And nature has adapted an incredibly complex machinery to solve these really challenging chemical problems. We are still a long way off from actually being able to mimic nature.

Gray: If you look at an enzyme and ask how many weak interactions are critical in the function of the enzyme, it is something like 10^{15} weak interactions that are beautifully orchestrated in a folded protein structure. The weak interactions—things we call hydrogen bonds, van der Waals interactions, and so on—are orchestrated, tuned to work beautifully in these systems. What we do now is *cheat*. We use gold, and platinum, and rhodium, because on these surfaces you can get activation of bonds very simply. Whereas in a big enzyme framework, there's a whole orchestration of interactions that leads to the same thing with materials like iron in the center as the activating metal, or copper or manganese or cobalt or nickel. We haven't figured out how to do that yet in simple molecules.

Peters: Nature can't afford to waste energy when it does chemical transformations, so it has to tune all of its catalysts to operate right at the sweet spot where it's not wasting anything. Whereas humans, in the presence of abundant energy sources, can hit everything with a hammer. We use energy to "brute force" solutions in the chemical industry. That's how we get our fertilizers nowadays, and that's how we do can electrolysis. But the metabolic processes of nature cannot do that. So we, in the absence of energy, need to do the same transformations right at the thermodynamic sweet spot. That's hard. That's really hard.

ENGenious: On the bright side, since you are using sunlight…

Atwater: The resource potential of sunlight, relative to all of the other energy sources, is orders of magnitude larger—just considering the power striking the Earth or the power that can be derived. But it's a relatively low energy-density source, low energy-intensity source. That's why we need to cover large areas.

ENGenious: Are there other things you can accomplish once you have figured out how to split water?

Haile: Certainly. You can get a little more radical and think about taking CO_2 and water and making a hydrocarbon out of it in the same way that plants do. Plants make all sorts of things, but they generally don't make much hydrogen (although there are bacteria that make hydrogen). They make all sorts of hydrocarbon compounds—starches and sugars, you name it—to build themselves. That would be the next level: taking solar energy and using it to do something interesting chemically. Once you've got solar energy and converted it into a useful chemical form, it's like having sunlight in your back pocket. Now you've got a fuel that you can use on demand when the Sun is not shining. You can put that into a fuel cell to get electricity. Electricity is only 20% of our energy use; but if you think about converting vehicles to use fuel cells, then that becomes part of the electricity side rather than just the fuel side.

Peters: There are, however, huge basic science issues.

ENGenious: What are the hurdles that have to be overcome?

Haile: There are essentially two devices required. One device takes in the sunlight and makes a fuel, and the other device, which has very similar components, is the one that takes in the fuel, and makes electricity. They're connected in the sense that many of the components are the same, but they have some differences and they run in reverse.

Peters: For each component, there are huge basic science problems. So when people will ask: what would it look like? You can't really say exactly because we haven't actually figured out what the components must be. There's a lot of individual work to figure out answers to basic science questions that we all have our distinct expertise in, but then these components have to work in an integrated way. So those are two separate challenges.

Atwater: By the way, one thing you might ask is: If plants are so great, why don't we just do biomass? Why bother with an artificially engineered device? While plants are wondrous machines in generating sugars and carbohydrates as fuel, they are relatively inefficient in terms of their conversion efficiency from the photons into stored energy. We can make solar cells now that are between 15 and 40% efficient in the photon-electron conversion, whereas plants are at 1% or less. Our goal is to develop processes to leverage an ability to make very efficient solar photovoltaic converters to enable the efficient production of fuels. Essentially beat nature at its game, even though nature is very elegant in the way it works.

> But our ambition is even bigger, which is, essentially, to displace the carbon-intensive fossil fuel use with a carbon-free, non-carbon intensive solar-driven fuel cycle.

Gray: The critical catalyst in this case is the one for water oxidation—it's the manganese part of plants. There's a little cluster of four manganese atoms in a structure we're still not quite sure of. Even though there's a lot of x-ray work right now, we're still not quite sure what it looks like. But it's a marvelous catalyst for oxidizing water to oxygen. Far better than anything else known that has any biological kind of metal in it. You can use platinum of course, as usual—or even better for this reaction would be ruthenium. One of our objectives is to build an artificial oxygen evolving catalyst, more or less working on nature's design and figuring out how we can do better. Once you get that—and that's a big technical hurdle, a huge hurdle—then we will be able to take sunlight, this catalyst, evolve oxygen from water, and the byproducts then are protons and electrons, which we can combine to make hydrogen fuel. Or we can also use these products to make ammonia from nitrogen, or methanol fuel to give to Sossina for her extraction through the direct oxidation of methanol to get electricity.

ENGenious: How long do you think it's going to take to solve that problem?

Peters: Well, people have been working on it for more than three decades. I would say that I don't think the ingenuity to solve the problem is lacking; I think people have thought very clearly about the challenge for a long time. But what has changed is that we're now much faster at being able to build catalyst structures and rapidly characterize them. We can make a lot more mistakes more quickly and learn from those. The other thing that has happened is that there's been a huge revolution in the understanding of biological structures through protein crystallography and biochemical techniques. So with those two things now where they are, we are better equipped to discover the basic science. Once you have the basic science you can make a much more accurate prediction about the engineering required. But until the step discoveries are made, how can you predict?

Once you've got solar energy and converted it into a useful chemical form, it's like having sunlight in your back pocket.

Lewis: Another approach we are taking in photon-electron conversion is to create very cheap solar-cell nanostructures to absorb and capture sunlight. My group is collaborating with Harry Atwater's group on an important part of that: how do you make and grow nanowire-based solar cells that allow you to have very long absorption length but very short collection lengths? The nanowires would be very impure from a materials standpoint, so very cheap as well. As chemists, we are trying to grow these using wet chemical methods. As materials scientists, Harry Atwater's group is trying to grow them using chemical-vapor-deposition methods. We know that we need to find a way to fool all the surface atoms into thinking that they are like the bulk atoms, or else all we're going to do is make a lot of heat. We are working on the chemistry of fooling those surface atoms.

ENGenious: This sounds like the kind of research that's really done only at research universities. Shell, for instance, is not doing this kind of research. Is that correct?

Atwater: Right. Precisely. I think in some sense, this problem, and the scientific challenges with it, mesh with some of Caltech's most appealing qualities: the ability to quickly get together in a very organic sense and have scientists from different fields work together in a small group using ingenuity and collaboration.

Gray: Caltech, I think, is uniquely set up to do this because of our small size. Chemists and physicists talk to engineers here on almost a daily basis. Students are close by. We know everybody. I know the people who work with Sossina, some of them quite well. And we've been able to kick ideas around, quickly, all the time.

Haile: Note that CCSER is not addressing *all* aspects of energy technology. We pick our problems. We've identified what we think is a viable solution that includes all the components of the solution. So if all these parts work, this actually would lead to sustainable energy for the planet.

Atwater: One thing just to set the stage here, to generate some perspective—there are many issues in energy technology, a whole portfolio of issues, that we are not covering at all. Issues like how would you use fossil fuels and sequester the generated carbon.

Gray: All the fission energy, all the fusion—all of that stuff we are not dealing with.

Peters: We're focused really on a single approach of what we think is the most exciting area of energy research.

Haile: A truly viable solution.

Gray: We think sunlight is the only answer.

Peters: One obvious thing is: if you *could* do it this way, wouldn't you want to know? And so that justifies working like the dickens. It's so obvious that if you could do this, you'd want to do it. So you'd better figure out if you can.

Gray: I think the honest answer to your first question about whether we can predict what's going to happen is this: we are working on very fundamental problems right now that must be solved. Come back and look at CCSER after about five years—we are laying the groundwork for the technologies of the future in this field. And after five years of CCSER, we should be able to say, well, we can't do it, because we haven't solved anything. Or, we cracked a couple of these things, and now we can predict, that by 2035—which is my own year on this by the way—that by 2035 the price of a kilowatt hour generated by solar will be the same as that generated by oil. That's my prediction.

Peters: I'm not sure. Five years is only one PhD-student length of time away. [*Note new unit of measure. Ed.*] I wouldn't say that in five years we would be able to know whether some of the key discoveries that need to be made are going to be ready.

Gray: I'm more optimistic and I'm talking about the whole world, not just our group. I believe that we'll have an oxygen catalyst within five years that will be working great. There's no doubt we're going to have the manganese structure.

Peters: That is what's important about having integrated efforts. You can capitalize quickly as step-wise discoveries occur elsewhere. Moreover, you can decide if something that looks good actually has relevance to the ultimate goal at hand. There are lots of proof-of-principle catalysts that actually are going to be irrelevant to ever having a functional system.

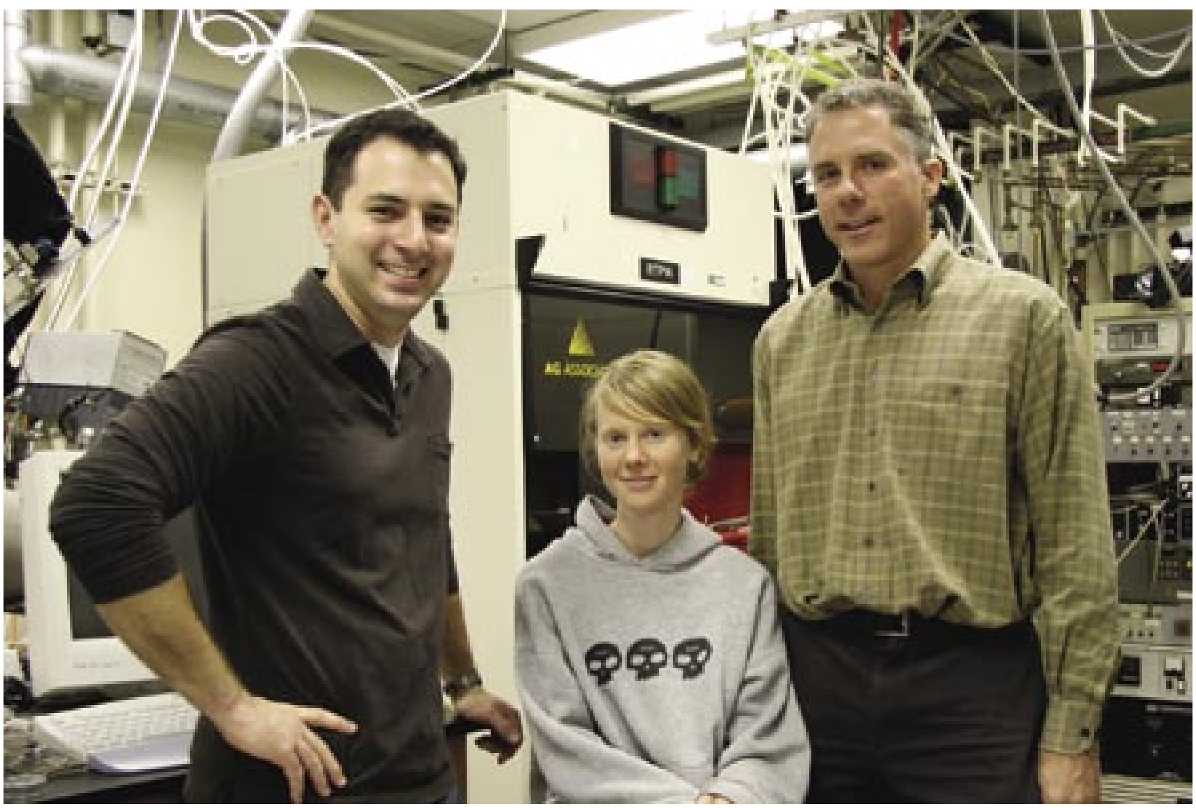
Gray: I believe we're going to see great investment in research in this area in the next five years, worldwide, because it's perceived to be a great problem.

Haile: There's an interesting challenge though. As you said, in the '70s, there was a lot of money that went into development and demonstration projects, but in areas where the technology was not yet ready. That's certainly the case in fuel cells now; there's a lot of development and demonstration technology. Money would, in my opinion, be better spent by solving the fundamental problems, rather than scaling up systems that you know already have problems.

ENGenious: What is different about the current environment than the one that existed in the '70s?

Atwater: Well, you know, if [the film] *The Graduate* had been made today, McGuire would have said to Benjamin: "nano." Nano-energy. Not plastics. [*laughter*]

Peters: It's clearly the case that the focus on global climate change is at an all-time high at the moment. So whether or not our interest in energy and climate change will wane with some new pattern that we'll go into in 15 or 20 years, the reality is that energy is a collector's item. Oil was only made once, and at the rates we need it, it will not be made again. We know that. Now, how long it's going to last,



Left to right: Dr. Michael Filler, postdoctoral scholar, graduate student Krista Langeland, and Harry Atwater, Howard Hughes Professor and Professor of Applied Physics and Materials Science.

nobody can exactly predict. But we've already done the rough calculation. We don't want to put a lot more CO_2 in the atmosphere if we can avoid it. So I think the difference is that people are acknowledging that we've got a situation here. In the '70s what drove it was the cost of fuel. I am not so worried about the cost of fuel—I'm more worried about how ugly this world will get when fuel gets scarce. Wars are created over this problem. And so most of us just look at it and say we don't want to live in a world where people are really scared about where their energy is coming from.

One obvious thing is: if you could do it this way, wouldn't you want to know?

Atwater: Scientifically speaking though, to come back to *The Graduate*—the understanding of nanoscale structures in matter and chemical reactions and of electron transport on the nanoscale are dramatically advanced beyond where they were in the 1970s. You could say we didn't know anything beyond very rudimentary things about nanostructures. All the reactions we are taking about—either the photovoltaic or photo-electrochemical reactions and the catalytic reactions—are really nanoscale phenomena. And we now have the theoretical, experimental, and synthetic tools to make nanostructures in an engineered fashion. That's a big difference.

Haile: It's true that all areas of science have advanced far from where they were in the '70s. And we're clearly able to leverage that—from the protein crystallography to the synthesis of exquisite structures that have exquisite function to the tools to be able to characterize them. On the other hand, we have this big impetus that we *know* we have to solve this, otherwise we really are not going to have a planet beyond this generation or two. Fundamentally we have to solve this. And the tools are in place for us to do that.

Lewis: The current situation is a perfect storm of three dollar a gallon gas prices, [Caltech Professor] David Goodstein's prediction that civilization as we know it will end in the 21st century if we don't solve the energy problem, and Al Gore bringing to the public's attention the climate and CO_2 connection.

Haile: We are now at CO_2 levels that the planet hasn't seen for 400,000 to 600,000 thousand years. If you plot CO_2 levels, they hover around 280 ppm for quite sometime, and then we hit the industrial revolution—boom. We are above 380 ppm now. If you look at plots of temperature, CO_2, and methane over the past 400,000 years, they all cycle. What's the cause of this 50,000-year cycle? Essentially, there's a slight change in the Earth's orbit every 50,000 years. So it's astounding, because now, this is the first time we are seeing CO_2 levels rise *before* the temperature rise. In all other cases it was that the Earth's orbit was changing a little bit, causing a change in temperature, and correlating with the increase of the concentrations in the atmosphere of CO_2 and methane. This is the first time we are seeing the CO_2 level rise *first*, and to such high levels, going up each year higher and higher. Who knows what's going to happen when you add the orbital cycle effect. It's scary, it really is scary.

Nate Lewis, George L. Argyros Professor of Chemistry.

Gray: I think there will be a catastrophe—in the next five years—a catastrophe having to do with energy availability. Just a little more of a glitch in the Middle East, and worldwide panic because there is no oil available. Long before global warming really knocks us off, there is going to be a crisis just having to do with the availability of fossil energy.

Haile: The other challenge is that whatever solution we want to implement will inevitably require energy as an input. So, if we're smart, we'll get on with it now while we have a reasonable amount of energy available.

Lewis: We know the CCSER approach encompasses physically allowed solutions. We know if we can find a way to make it happen, that there will be enough energy to keep everybody in the industrialized and the developing countries happy and independent. No other energy source allows that. We also know that we don't have that long, if you believe greenhouse gasses are the driver. Failure isn't really an option.

Atwater: Actually, I am profoundly optimistic. I see that the ability of humans to have such a big impact on climate can be turned around. Once we understand how to generate energy in a way that doesn't create that impact, or that offsets or mitigates that impact, we can do so on a scale that permits our planet to come back towards its natural state.

Gray: You asked what's new now compared to the '70s. If you look at the solar-fuel problem, there are three fundamental aspects. One is capturing all the light that reaches the Earth's surface—all the visible and near-infrared light. The second part is, once you capture it, to separate electrons and holes long enough to interface with catalysts to make fuel. We call that the electron-transfer part. And the third part is the catalyst. In the '70s, we didn't have any of the three solved. In 2006, we have the first two solved at least in concept. What remains to be solved is the catalyst part. But you see we've made *tremendous* progress in the other parts. And we can build nanostructures now to do all this, as Harry said.

Atwater: But currently they are not efficient enough.

ENGenious: What are the crucial problems in the fuel-cell domain that you need to solve?

Haile: We have to have a material, a membrane, that moves protons as opposed to moving electrons and holes. Like the photolysis systems, we also have catalysts on either side, but the catalysts are working in reverse relative to water splitting. Now in principle, if you have a good catalyst for oxygen evolution, it would also be a good catalyst for oxygen consumption. That's why we believe that if you make progress in fuel cells you make progress in water splitting and vice versa. Even though the functions are distinct, the catalyst components have lots of similarities. Getting back to the membranes, these materials in fuel cells are far less developed than the semiconductor materials for photovoltaics. A fuel cell only has to move one species, but it has to be very selective in moving that species. It should move no other species—no electrons, no water, no hydrogen, and no oxygen. For fuel-cell electrolytes, it's mainly a materials discovery problem.

Jonas Peters, Professor of Chemistry, third from left, top.

Atwater: We have silicon solar-cell solutions, but they're simply not low enough in cost per watt of power generated.

But if you could go to Home Depot and buy a gallon of [solar] paint and paint it on your wall or your roof, you'd feel pretty good about running your meter backwards.

The ways in which you make them more efficient actually involve discovering new materials as well. The efficiency potential of silicon solar cells is near its theoretical limit. Remember, efficiency is enormously leveraging in solar photovoltaics: everything has a *per area cost*. If you have a more efficient solar cell, the cost per unit area of the whole system goes down: the land, the module, the person that's there waiting to clean it every week. In the same way that the catalyst developers are looking for earth-abundant materials, we're essentially trying to create a whole new class of photovoltaic materials. The materials we have to work with now (other than silicon) are ones that were developed in the opto-electronics, laser, and telecommunications fields. Gallium-arsenide, indium-phosphide, and so forth—they are quite rare, and they are quite expensive to produce on the scale needed for photovoltaics. But there's a whole untapped potential for solar-electric generation using earth-abundant materials—things like oxides and sulfides of iron, copper, cobalt. We're beginning to think along parallel lines about how we can create earth-abundant solar photovoltaic materials.

ENGenious: What about the idea of "solar paint?"

Lewis: That's a Harry Gray, Nate Lewis idea. No one wants to pay 5 or 10 or 50 thousand dollars—the way it is now—to have solar panels installed on their roof. But if you could go to Home Depot and buy a gallon of paint and paint it

on your wall or your roof, you'd feel pretty good about running your meter backwards. So we know solar technology needs to be really cheap, because you have to cover large areas, and really simple. It has to self-assemble. You have to change—really disrupt—the current approaches. We know what we need to do, we just don't quite know how to get there yet. The other thing you need to think about: it's not just the United States. If it costs 10% more than someone making $500 a year can afford, China's not going to do it. If it's not affordable at the China and India price, then it's not going to be effective in helping to get clean energy to everyone that needs it and to everyone who's emitting CO_2 now. You've got to make it really cheap, not just "United States cheap."

Atwater: You shouldn't underestimate the fact that the amount of energy that we need to displace is so enormous that the capital investments that are required to do that are going to be enormous. In other words, if we actually make a serious dent in U.S. energy use, it will become the largest industry in the United States. It will become the largest employer, it will become the largest consumer of capital. We are talking about a new infrastructure that will be replacing a huge hydrocarbon fuel infrastructure.

Peters: When you look at trying to replace huge chemical technologies, whether it be Haber-Bosch chemistry for fertilizer or anything else, you don't actually replace those technologies until the economics are so slanted that suddenly you don't have a choice.

Atwater: Or there is some policy push—a combination of economics plus policy push.

Peters: A part of the motivation for everyone here is that we like to discover new things and apply them to interesting problems. And this is an enormously interesting set of scientific problems.

Gray: And we are blatantly using this as a recruitment device for young people. There's enormous interest in this area. We're going to be able to recruit some of the best young people here just because we have this synergy. If it were just individuals working on isolated problems, we couldn't do nearly as well. But I think working together on the big picture will entice a lot of kids to sign up.

Atwater: Students are the glue. Students are the joinery between groups and are the key to developing interstitial, interdisciplinary knowledge.

ENGenious: How long have you been thinking about these problems?

Atwater: I've been working on one aspect or another of solar renewable energy since I was a graduate student, and suddenly the world has also joined in recognition that this

Students are the glue. Students are the joinery between groups and are the key to developing interstitial, interdisciplinary knowledge.

is very important. I think it's an exciting scientific challenge—it's one of the most exciting science problems in the area of solid state materials and devices, and condensed matter physics—but it's also very important societally. I am now looking at the rest of my career thinking, what are the areas where I can have an impact not only scientifically, but potentially, on a problem where the applications would have enormous impact? That matters more to me than it did when I was an assistant professor.

Haile: I absolutely agree. I think that when we start off as foolish, bright-eyed, bushy-tailed kids, we have grand visions of how we are going to save the world. And then reality gets beat into us, and you have to do things that are not that grandiose, but are interesting scientific problems. And then at some stage, one starts to think back and say, wait a minute—what happened to my desire to save the world? And all of a sudden you say, how can I bring those two together? How can I use this incredible opportunity I had to learn all this great science, and use that for an important technical problem? It is a great way to draw in students because that is what they want also—they want to be able to use their technical skills to address important social problems—now more than ever.

Peters: [*with a wink*] I just want to make some money. I could care less. [*laughter*]

Gray: I've got 30 years of my life invested in this; to me it would be a great thrill to see someone really crack this. When I started in the '70s, I had to line up to get gas in Pasadena; literally, the gas lines at the corner of Lake and California went all the way around the block to Catalina and back down San Pasqual.

Peters: You'd use up all your gas in line.

Gray: I'd be reading journals thinking, I've got to do something. When I started I had this crazy idea that I could do better than nature. I really thought that I could build super molecules that would do everything—capture light, catalysis, everything at once. When we evaluated our solutions over the years, we found that they were tremendously limited in efficiency by crazy things that you couldn't control in these small packages. So nature wasn't that stupid after all. Nature had taken these three things that we've talked about—light capture, electron transfer, and catalysis—and separated them into pieces. But the younger people are going to solve this problem. The students we recruit are going to somehow figure out how to solve this thing, I am absolutely convinced of that. I'm excited about hopefully living long enough to see it. That's my goal. My goal is to live long enough to see this—and my other goal is to die funded. [*laughter*]

Lewis: We have to do this! It is not an option! I've been saying that for a long time. Everybody is repeating that mantra now, except maybe for the federal government. That's why it is so important and gratifying to have the Moore Foundation step in and get us off the starting block so we can move in that direction. ENG

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Alexis C. Livanos

Vision, Ethics, Passion, Transformation—The Shaping of a Leader in Aerospace

Alexis Livanos spent about a decade at Caltech, from the mid-1960s to the mid-1970s, earning three degrees (BS with Honors '70, MS '73, PhD '75) and then doing post-doctoral studies in applied physics. We had the good fortune to talk with Dr. Livanos about his travels from Greece to Caltech, through the aerospace industry, right up to his present position as corporate vice president and president of Northrop Grumman's Space Technology sector. His official biography will tell you about his expertise in the fields of advanced communications systems, technology and technology insertions, hardware design, and satellite manufacturing and production. You will learn that he has participated in the successful launch of more than 40 satellites. But that doesn't really get to the core of the man—his quick and forthright style, at turns funny, reflective, thoughtful, and thought-provoking. Our conversation was wide ranging, and we invite you to listen in.

ENGenious: What inspired you to become an engineer?

AL: The reason I came to the United States from Greece was because of NASA and the excitement of space exploration. My interest and passion in space started when I was 12 or 13, in high school—it was called Athens College. I was trying to figure out the equations governing how rockets moved. Eventually, I had the opportunity to choose Caltech and I came because of the Jet Propulsion Laboratory, and the climate. Later, I selected Fred Culick [Richard L. and Dorothy M. Hayman Professor of Mechanical Engineering and Professor of Jet Propulsion, Emeritus] as my advisor because he was in propulsion. After the first year in propulsion, I switched to lasers, then to electromagnetic theory, solid state physics, and finally to signal processing for earthquake prediction applications.

Spending a substantial amount of time at Caltech and importantly, having the opportunity to study many different disciplines in depth, is probably the best thing I have ever done because it prepared me for the breadth of the aerospace business. When I told Fred Culick that I wanted to work for Nick George [formerly Professor of Electrical Engineering and Applied Physics], it was perfectly okay. And when I told Nick I wanted to work for Amnon Yariv [Martin and Eileen Summerfield Professor of Applied Physics and Professor of Electrical Engineering], that was perfectly okay. This "sharing of students" is unheard of in academia. But it was of tremendous benefit to me, because if you look at my continuation from Caltech into industry, I followed the same path. The key is the ability to quickly *adapt* in an environment. Also key is having the ability and the intellect to cut through to the fundamental issues, address them and then not be bashful about asking a lot of questions.

ENGenious: What else about your Caltech education has influenced you?

AL: At Caltech I gained the ability to organize my thought process in a way that looks at all of the alternatives in a very methodical, logical manner. This has been absolutely invaluable. The second thing I value is the joy of research. Look at how we are pushing the technology here at Space Technology, in areas very similar to those in which Caltech is involved. We're involved in micro-electromechanical systems [MEMS], light-weight materials and large apertures, as well as high-energy lasers, advanced communications systems, and environmental sensors. Twenty years from now, all these technologies will be part of our lives. Pushing the envelope is part of what I learned at Caltech. In business, it's important that you have a fiscal responsibility toward your shareholders, but it's also important that you have the vision for the mission. These are highly complementary. The third thing I gained at Caltech is the ability to take science from one domain, apply the principles, and come up with a solution in a different domain. I think this is absolutely vital in terms of one's ability to invent and be successful.

ENGenious: Did you get anything from Caltech on the business side?

AL: Not during my formal career at Caltech, but I did attend one course at Caltech's Industrial Relations Center when I was working at TRW; it was called Managing Innovation. I thought it was an excellent course. I used some of that material and concepts to understand the balance between innovation, creativity, and the business of running the business. But the important thing to note is that Caltech teaches the ability to think. Once you learn that, you can apply it to return-on-investment calculations, contracts and pricing, profit margins, and regulatory and accounting requirements.

ENGenious: After Caltech, how did you decide to go into industry rather than academia?

AL: One of the pivotal moments of my career was when I decided that I really did not want to stay in academia. I always had thought that industry was tedious—but it is not like that at all! After my PhD, I started working with Bill Bridges and Amnon Yariv at Hughes Research Labs, and I just fell in love with it. Although I had an offer from Yale, I joined TRW in the very early 1980s. For the next 15 years, I followed the same pattern that was established at Caltech: I worked in diverse fields. I did program management, electro-optics, semiconductor electronics, digital electronics, radio and microwave frequency electronics, payloads, then structures. And that's how I grew.

I think another pivotal event was when I decided to venture into the "commercial world." While at TRW, I once tried to recruit an absolutely brilliant communications engineer who was working for Loral. But he recruited me! So I failed in that plan. Loral at the time had finished its divestiture of all of its defense businesses to Lockheed Martin. The company had an excellent track record in terms of performance. Space Systems Loral was doing commercial satellites, and I decided I wanted to try something new. I call this event "the MBA school of hard knocks." It was really an eye-opener. Going from a cost-reimbursable environment to a commercial environment was a different world, but it has given me the breadth and ability to look at

Vision, Ethics,

business in a different fashion.

But one constant throughout my career has been the importance of integrity—both ethical and scientific integrity—and respect. We must respect the technology and the system engineering aspects of the business, but also understand what "business" means, what shareholder value means, and understand how the two are interdependent.

ENGenious: What are your thoughts on the consolidation and evolution of the aerospace industry?

AL: Northrop Grumman's acquisition of TRW has been very successful. Our value comes from our culture, the way we do things, the kinds of people that we have, and our vision. When Northrop Grumman acquired TRW, they trusted and respected our set of values. Other mergers and acquisitions didn't have the same philosophy, resulting in cookie-cutter rules and constraints. If you homogenize everything, you get mediocrity.

The industry is evolving, which is healthy. I think there is a realization on the part of both the government—including the DoD and NASA—as well as the aerospace industry that we need to address workforce issues and our image. For the first time, I see a proactive stance to encourage the resurgence of our upcoming generation, from the 6th grade up, into the sciences. We are starting to get the "pull" mechanisms to grow. Now what is needed is the excitement, the vision. At Northrop Grumman, we are building the James Webb Space Telescope, which will travel 940,000 miles from Earth to the Second Lagrange Point (L2). It will image the universe as it was nearly 13 billion years ago, giving us insight into the formation of the first galaxies, planetary systems, and the evolution of our solar system. This project is really cool. It is forward-looking and visionary. This is what will grab the attention of students and draw them into the sciences.

Under the right leadership, the aerospace industry will regain that sense of pride, creation, the ability to improvise, and the ability to insert technology. I believe that all government agencies operating in space, including NASA, NOAA, U.S. Air Force, and the intelligence community are starting to make those changes that will attract a lot of bright people. I think we're going to get there. We're going back to the way things were done in the '60s and '70s, when there was a clearer vision and a closer working relationship between industry, government, and academia.

ENGenious: What is a typical day like for you?

AL: I arise around 6:00 a.m., and am at work usually around 7:30 a.m. A critical role for me is setting strategy for our company's performance and growth, so I spend a good amount of time in meetings with my executive and program teams. We also have critical reviews and it is my job to ask the hard questions on deliverables, schedule and cost. In addition to meetings with employees and customers, I travel to Washington, D.C. several times a month to speak directly to customers and key government representatives.

My personal style is to speak directly to the executives and engineers instead of exchanging emails. I walk the halls so I will know what we need to improve. I also meet with employees on a one-on-one basis and ask them what it is they are doing, and what ideas they have. Employee com-

Passion, Transformation

munication is really important. I'm more comfortable with informal communications—I don't write "directives." Ours is a non-adversarial environment, and I'd like to continue to grow and build the teamwork that we have at Space Park. I feel very lucky to be a part of this team.

ENGenious: What do you find most satisfying?

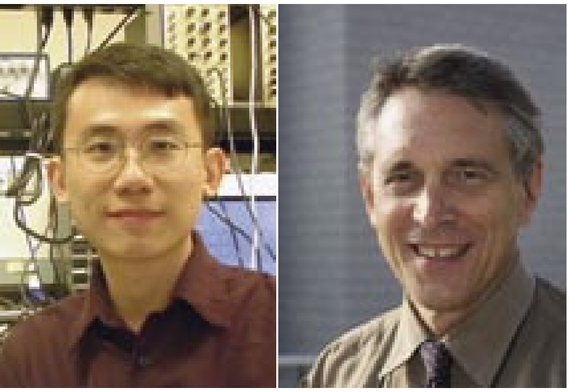
AL: Several things. I like being *immersed*. I don't manage by remote control. I like knowing what is happening and how I can help. And because of my affinity toward engineering and science, it is interesting to me to understand an issue in detail. People like the fact that management has a certain level of scientific or engineering curiosity and expertise. I can appreciate their work because I understand how difficult it is. So I'll talk to our teams in the laser lab, for example, and I'll ask them about wavefront quality, momentum shift, thermal dissipation, phase transition, and so on. This makes a difference.

Few things are as satisfying as good old-fashioned, hard-edged competition. I am absolutely energized by it. It's probably why I like doing the impossible, tough tasks. The truly big challenges are invigorating. In my view, consolidation has not eliminated the competitive drive at any company in our industry. So, I must be driven to win—not just compete—or someone else will be. That's a key strategy when you have talented employees.

One last thought about satisfaction—it also comes, believe it or not, from the Caltech motto: "The truth shall make you free." That simple statement inspired me as a student, and it pushes me forward now. It's part of the reason I continue to learn and personally evolve. Many people probably take it for granted today that the truth and perceptions really are one and the same, but it is perhaps one of the most important management lessons I've ever learned. The way others see you is more important than how you see yourself. This has not just changed my management style to be more participatory and more logical, but also has altered the way I look at the world—it has made life a lot easier.

And this all gets back to acting with integrity and honesty. If we want to be seen as being ethical, for example, there's no faking it—you are or you aren't. That's another way in which my Caltech education has influenced me—Caltech does a superb job of teaching the value of ethics and integrity. The Honor Code and learning to trust and have respect for intellectual property have provided for me a critical and solid foundation for this business. Part of that trust is built by communicating openly and honestly with whomever you are speaking with. Lay out the facts, help others see the truth about a problem or issue, and they will respect you for leveling with them. It gives you the freedom to make the best decisions and see clearly ahead. ENG

Dr. Livanos serves as the chair of GALCIT's Advisory Council, an external advisory and outreach committee. He is also chairing, with President Jean-Lou Chameau and JPL Director Charles Elachi, an international aerospace conference celebrating 50 years of space technology hosted by GALCIT. The conference will be held at Caltech in September 2007. For further information visit: http://www.galcit.caltech.edu/space50.



PROGRESS REPORT

Building a Microscopic Microscope

by Changhuei Yang and Demetri Psaltis

Do you see floaters drifting in your eyes when you look up into a clear blue sky? The floater phenomenon is the inspiration for our recent invention, *the optofluidic microscope.* The optofluidic microscope is a high-resolution, chip-size microscope that, remarkably, operates without lenses. It is already the world's smallest microscope, and we aim to make it the world's cheapest. The future use of the optofluidics microscope by bioscientists, clinicians, and doctors may mark a new era in discovery and healthcare.

Microscopes are ubiquitous in biology and clinical analysis laboratories. They are the workhorses of bioscience research and our surrogate eyes into the wondrous world of microbes and cells. Yet, since the development of the microscope beginning about 1590 by two Dutch spectacle makers, Hans and Zaccharias Janssen, then by Galileo and Antonie van Leeuwenhoek, the basic microscope design has undergone very few fundamental changes over the intervening centuries. In almost all microscopes, you can expect to find precise and expensive optical lenses and plenty of space for the light to travel and reshape itself—the long distance between the objective lens and the eyepiece lens isn't there for aesthetic reasons!

way to create small and precise optical lenses on chips easily. Second, the space requirements of conventional microscopy conflict with the size constraints of chip-based devices.

These difficulties aside, we can ponder "what if?" situations for miniature microscopes. An on-chip microscope implementation method can dramatically change the way we use microscopes. The application range of an on-chip microscope is wide and will be discussed below—at this junction, we would like to point out that a typical bioscience laboratory contains less than ten microscopes (size and cost are both factors in this). We invite the reader to consider the enhanced efficiency if the number of microscopes per laboratory is to increase by a factor of ten or a hundred.

Rethinking the Microscope

The antiquated nature of the conventional microscope design stands out even more in the context of the ongoing lab-on-a-chip research and development, in which laboratory instruments are being systematically miniaturized into chip-size devices. While a wide range of bioanalysis methods have been successfully miniaturized and implemented in a lab-on-a-chip format, there has not been a commercially viable approach to miniaturizing microscopy until recently. The difficulty is twofold. First, there isn't a cheap and efficient

To implement a cost-effective and commercially viable on-chip microscope, it was necessary to break with tradition, abandon the old microscope design, and rethink the whole imaging problem from the ground up. Fortunately, optical technology has come a long way since the 16th century, and we now have access to a broader range of devices than existed even 50 years ago!

To motivate this redesign process, let us enumerate the functions that the microscope must perform. There are three primary functions. First, a microscope should be able to replicate an image of the object onto a person's retina—or at least provide an image to an observer. Nowadays, electronic detector grids have been substituted in place of the retina in many optical devices. Nevertheless, the vast majority of microscopes still operate by relaying and replicating an object's image onto a sensor grid of some sort. Second, a microscope should be able to magnify the image so that objects are adequately resolved. Twenty-twenty vision roughly corresponds to a pixel size of about 5 μm on the retina. To resolve sub-micron features, magnification is invariably required. Third, a microscope should be able to select a specific plane in the object for imaging—this is called optical sectioning.

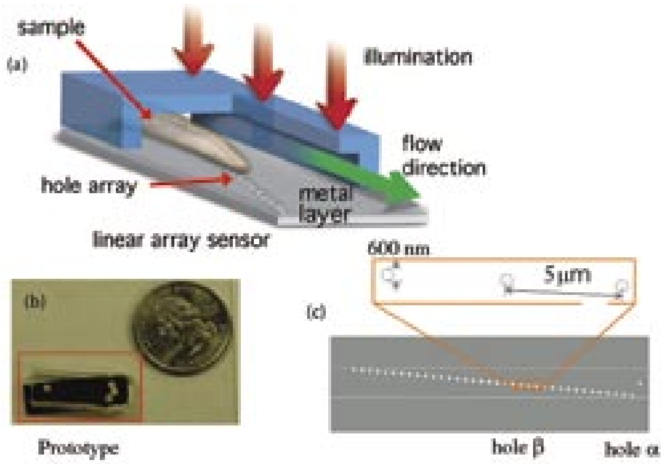


Figure 1. (a) The basic OFM scheme. The device is uniformly illuminated from the top. The sample passes over the hole array and blocks the light transmissions through the holes. (b) A prototype next to a quarter; the actual device is about the size of Washington's nose on the quarter. (c) The physical dimensions of the prototype. Holes a and b are both placed in the channel's center. By measuring the time difference between when the target first passes over each hole, we can determine the speed of the target by dividing the holes' separation distance with the time difference.

Drawing Inspiration From Floaters

What exactly are floaters? And why do we see them? For those of you who are unacquainted with the term 'floaters,' chances are you simply do not know them by name. Floaters are the spindly objects that float in your field of view and can be most clearly seen when you look up at a clear blue sky. Those highly resolved images are caused by debris in your vitreous humor that has gotten very close to your retinal layer. Under uniform illumination (such as that of a clear sky), they project clear shadows onto your retinal layer. Remarkably, the lens in the eye plays no part in this imaging process. To verify this, the next time you see floaters, try focusing and defocusing your sight. The floaters should remain equally sharp.

The floater phenomenon points the way to an imaging method that does not require the use of lenses or any other optical elements. Specifically, we can perform imaging by simply placing the object of interest directly onto a sensor grid, such as a CCD or CMOS sensor (this is the chip that is the heart and engine of your digital camera). By illuminating the object uniformly, a transmission image of the object can be directly recorded by the sensor grid. Recently, this strategy has been implemented as an imaging method by researchers at Stanford University and NASA Ames Research Center.

One must excuse the microscopists of the 16th century for not inventing this sooner—the only sensor grid available to them was embedded in the human eye, and there is no practical way of introducing objects of interest directly onto the retinal layer.

This direct-imaging approach has several advantages. First, the lack of optical elements in this arrangement implies that there is no aberration of the optical elements to worry about. Second, this is an intrinsically space-conserving method and as such is highly attractive as a chip-based microscopy method. However, this imaging method is non-magnifying and its resolution is fundamentally limited by the pixel size of the sensor grid. In other words, we can resolve two points on the object as long as they map onto two different pixels on the sensor grid: the denser the grid, the higher the resolution of this imaging system.

Unfortunately, this last characteristic is a disadvantage in practice. Currently the smallest available pixel size in a commercial CCD or CMOS sensor is about 5 μm, so this direct-imaging approach cannot be expected to perform better than a conventional microscope, which has a resolution range of about 1 μm to 0.2 μm. While we hope for the day when commercial CCD or CMOS sensor pixels will shrink in size by an order of magnitude, this day is unlikely to come soon since the creation of such sensors is hindered by very significant fabrication challenges. Until this day comes, is it possible to get around the problem of pixel size?

The Optofluidic Microscope Method Explained

The nascent field of optofluidics—the fusion of microfluidics and optical technologies—offers us a way around this problem. A new microscopy method, termed Optofluidic Microscopy (OFM), which we recently developed at Caltech, enables the imaging of fluid-immersible objects with microscope-level resolution (and as we shall see, super resolution as well).

An OFM device may be fabricated as follows. First, a layer of metal is coated onto a linear sensor array to block out

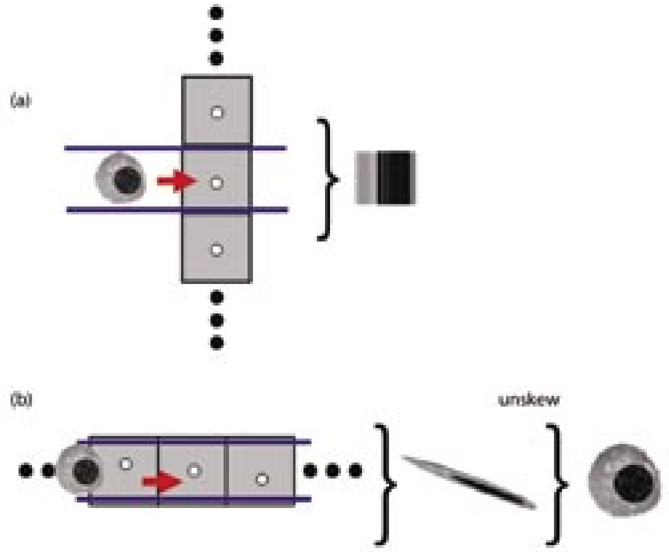


Figure 2. (a) Non-OFM technique. A transmission image of the object can be obtained by simply stacking up the transmission time traces collected as the object passes over the holes. To achieve high-resolution imaging, we need to space the holes closely across the channel. This particular arrangement gives poor image resolution as we cannot space the holes closer than a sensor-pixel width without mapping multiple holes onto a single sensor pixel. (b) OFM technique. The line of holes along the channel is skewed. This way, we can space the holes as closely across the channel as we want (in latitude), while at the same time ensuring that there is a unique 1-to-1 mapping of holes to sensor pixels. As the object will pass over each hole at different times, we need to correct for the time delays in the transmission traces prior to image construction. This is easily done by unskewing the traces based on the flow velocity of the sample (as measured with holes a and b).

light. A line of holes is then punched into the metal layer. Finally, a microfluidic channel is added on top of the entire chip.

In operation, the device is uniformly illuminated from the top and the target object is flowed across the array of holes via the microfluidic channel (see Figure 1). The time-varying light transmission through each hole constitutes a transmission image line trace across the object. By stacking the lines traces from all the holes together, we are able to construct a transmission image of the object.

The exact arrangement of the array of holes with respect to the underlying pixel grid is the key novel aspect of the OFM. Rather than placing them in a line exactly parallel to the flow direction, (for instance, in the absolute center of each pixel), they are placed only on the centerline of each pixel on the vertical axis. In the horizontal direction, they are *slightly* offset from each other—so a diagonal line with respect to the flow is created by the holes. Put another way, the longitude of the holes stays constant, but the latitude changes ever so slightly from one hole to the next. Assuming the specimen is rigid, each hole then captures information from the specimen at intervals that correspond to the *slight offset* of each hole from the previous (instead of intervals that correspond to the width of one pixel). By collecting images acquired *over time* of parts of the specimen separated by the latitudinal offset of the holes, and then reconstructing the image of the entire specimen, we get around the problem of pixel size. This is illustrated in Figure 2. Note that resolution may be increased by using smaller hole sizes and spacing them closer together in the horizontal direction.

Figure 3 shows OFM images of the *C. elegans* nematode acquired with our prototype in comparison with an image acquired with a comparable conventional microscope. The similar quality verifies that the OFM method is capable of delivering high-resolution images. Our prototype contains 600-nm wide holes that are spaced at 5-μm intervals. We note that as a demonstration unit, the metal layer of this device is not directly bonded onto the linear array sensor. Instead, the transmissions through the holes are projected onto a linear CCD array by relay optics. Recently, we successfully implemented an on-chip version (see Figure 4) and we are in the process of evaluating its performance.

Dual Advantage: Compact &

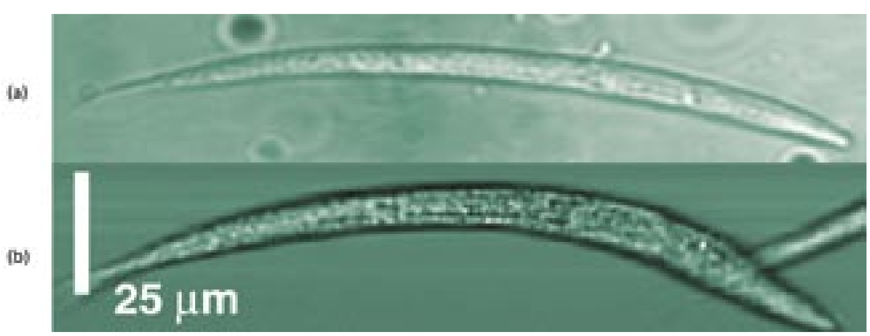


Figure 3. (a) A conventional microscope image of a nematode, *C. elegans*. (b) An OFM image of the same. Notice the tail end of his friend exiting the image at right.

This microscopy method does not perform image replication or magnification—two functions that are associated with conventional microscopy, and yet it is capable of delivering high resolution. More importantly, it functions as a microscope without the use of bulky optical elements. OFM

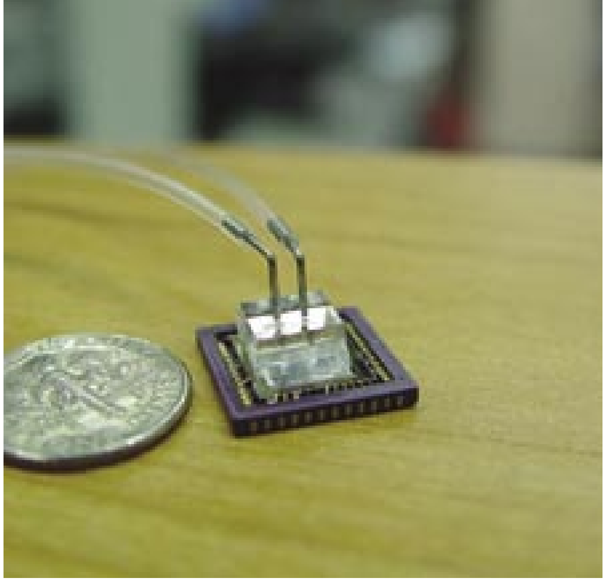


Figure 4. An on-chip implementation of the optofluidic microscope.

devices can be built onto chips with existing fabrication techniques and we estimate they can be mass manufactured at a very low cost (~ $10's).

Why Is An On-chip Microscope Useful?

The dual advantages of compactness and low cost open up a wide range of possible applications. For example, the OFM can be used in white-blood-cell-counting cytometry devices as image-based cell-type discriminators. Clinicians can use such units as disposable, point-of-care microscopes and battlefield medics can easily carry these devices out into the field. Health workers in rural areas can use cheap, compact OFMs as part of their regular toolkit,

Low Cost

easily carrying them in their pockets from village to village for malaria diagnosis. Further, the OFM can change the way a bioscientist tackles imaging problems. Potentially tens or even hundreds of OFMs can be fabricated onto a single chip. Such a device can be used to parallelize the imaging of a large number of microorganisms and dramatically improve throughput. Taking a long view, the OFM can even form the imaging component of a bio-compatible device that may be implanted into a person to provide continual monitoring of objects in the blood stream. Such a device may be useful for screening circulating tumor cells and other abnormal objects to provide early warnings of developing diseases.

Looking Ahead

In the context of expanding the capabilities of the OFM, there are three directions that we will like to explore over the coming year.

First, we would like to achieve super-resolution. A conventional microscope is limited in its resolution by the diffraction limit. Simply put, the projected image in a microscope is made up of propagative light rays from the object (in optical terms, these are far-field components) and is constrained in its resolution by the diffraction limit. In comparison, the OFM resolution is fundamentally tied to the size of the holes. As such, an OFM with small holes can, in principle, achieve resolution that is unattainable with conventional microscopes. We are in the process of demonstrating a super-resolution OFM.

Next, we are working on a fluorescence-capable OFM. Creating the equivalent of a fluorescence microscope with the OFM method is remarkably straightforward: we simply have to lay down a chromatic filter layer between the sensor and the metal layer. Another way to go about this is to start with a color sensitive sensor. Such a sensor has built-in filters.

Finally, we would like to demonstrate a phase-sensitive OFM. Creating a phase-imaging microscope system based on the OFM method is, again, remarkably simple. One approach will be to add a spacer medium between the sensor and the metal layer and punch hole pairs in place of individual holes. The hole pairs will function as miniature Young's double slits. By observing the interference pattern, we can determine the amplitude and phase of the transmission OFM image. In addition, this approach solves a problem associated with the OFM—the OFM does not provide optical sectioning capability; the plane of highest acuity is the plane immediately above the holes. With knowledge of the amplitude and phase distribution, we can actually compute the wavefront at any given plane. This will allow us to perform virtual focusing into the sample of interest. ENG

Changhuei Yang is Assistant Professor of Electrical Engineering & Bioengineering and Demetri Psaltis is the Thomas G. Myers Professor of Electrical Engineering.

The authors would like to acknowledge the dedicated efforts of Xin Heng, Xiquan Cui, and Lapman Lee for making the Optofluidic Microscope a reality.

For more information, visit these websites:
http://www.optofluidics.caltech.edu
http://www.biophot.caltech.edu
http://optics.caltech.edu

Virendra Sarohia

Bringing Academia to the Forefront of Space Research

In the rapidly evolving world of science and technology, isolation is suicide. Both Caltech and the Jet Propulsion Laboratory (JPL) know this well, which is why JPL continually looks to Caltech for the next generation of technological innovation to fuel future space missions. Collaboration between these institutions has been on-going in all kinds of ways since the founding of JPL. In fact, the origins of JPL can in part be traced back to the rocket work of GALCIT students in the 1930s, under the leadership of Theodore von Kármán.

The two institutions recently highlighted the importance of collaboration by creating a new position which provides a formal research and technology liaison. Filled by a GALCIT alumnus, Dr. Virendra Sarohia (PhD '75), this position is formally named Technical Assistant to the Chief Technologist, and resides in the Office of the Chief Technologist of JPL. The Chief Technologist of JPL is yet another GALCIT export, Paul Dimotakis (BS '68 MS '69 PdD '73), John K. Northrop Professor of Aeronautics and Professor of Applied Physics. JPL seeks partners to bring innovative contributions to what the Lab does best, one-of-a-kind missions. Caltech, with its emphasis on fundamental science and technology, has always been a perfect partner for JPL. In fact, the culture of JPL is deeply intertwined with the culture of the campus, uniquely so for a NASA lab.

The dynamic partnership between Caltech and JPL is instrumental in creating the aggregation of talented scientists and technologists JPL enjoys. Dr. Sarohia's goal is to build even stronger ties between faculty and students at Caltech and space scientists and technologists at JPL so that the flow of innovative ideas continues to expand.

From the vantage point of campus, there are enormous benefits to having JPL in your backyard. As Sarohia explains, "We expose the students to something *real* out there. Not all engineering schools have that. Space missions offer many engineering challenges—just name a discipline in engineering, and you will see it is required for spacecraft development: fluid and solid mechanics, materials, navigation, electronics, control, everything is there. It's like a candy shop."

The Divisions of Physics, Mathematics, and Astronomy, and Geological and Planetary Sciences have had long-standing connections with JPL through missions; but the number of collaborations between the Division of Engineering and Applied Science (EAS) and JPL was approximately twice larger than other divisions at Caltech in fiscal year '06. We are working on fundamental, nascent problems, that are generally not in the public spotlight, but whose results can form the basis of key mission technology developed years later. For instance, the collaborations of Professor David Rutledge (Kiyo and Eiko Tomiyasu Professor of Electrical Engineering and currently EAS Division Chair) with Dr. Sander Weinreb of JPL in microwave antenna technology have been outstanding. The Caltech experience as the world leader in array technology has fostered JPL development and acceptance by NASA of array technology for the next-generation deep space communication network.

On campus, Dr. Sarohia is literally centered in EAS, with his office on the third floor of Thomas. One of his very first action items as liaison was to meet with Richard Murray (Thomas E. and Doris Everhart Professor of Control and Dynamical Systems), then Division Chair, and the Division's steering committee. Murray asked Sarohia to pay close attention to (Theodore von Kármán Professor of Aeronautics and Mechanical Engineering and Director of GALCIT) Ares Rosakis's vision for a new master's program in aerospace engineering. "I spent lots of time with Ares developing the new aerospace masters program and I am very proud of it. The program resides in GALCIT and is multidisciplinary—we have remote sensing being taught, space propulsion, space optics, space structures, control, fluid and solid mechanics. It was exciting for me to help Ares and the GALCIT steering committee in the initial stages."

Starting in 2006, six JPL technologists became involved in the teaching of space science engineering courses. "As they are teaching, they are interacting with a bright pool of students. They are also looking for opportunities. They are kind of JPL ambassadors that can open up the door. One instructor has 10 or 15 students. Just imagine how many connections are made. You have to remember that each student has a campus faculty member as an advisor. And so we get campus faculty along with students interacting with JPL. That's a very rich source of connections."

"I am seeing lots of interest in the hands-on challenges of spacecraft engineering as part of graduate and undergraduate projects, and we are currently discussing a pilot project with Mechanical Engineering that would enable undergraduate students to do a senior thesis with a JPL comentor."

To further promote interactions, Sarohia has established a Caltech Faculty Seminar Series that takes place at JPL. Six to eight seminars are arranged annually, co-sponsored by the Offices of Chief Technologist and Chief Scientist at JPL. All of the initial speakers were EAS faculty members, including Joel Burdick (Professor of Mechanical Engineering and Bioengineering), Kaushik Bhattacharya (Professor of Mechanics and Materials Science), Richard Murray, and Sossina Haile (Professor of Materials Science and Chemical Engineering). Talks by Brent Fultz (Professor of Materials Science and Applied Physics) and Axel Scherer (Neches Professor of Electrical Engineering, Applied Physics, and Physics and Director of the Kavli Nanoscience Institute) are in the works.

Sarohia has been working at JPL since earning his PhD at Caltech in 1975. "The first half of my 32 years I was a researcher, interacting with campus very actively. There were students that came and worked at JPL in my group, in fact, a couple of them did their PhD in my group. Mory Gharib [Hans W. Liepmann Professor of Aeronautics and Professor of Bioengineering] was one of them." Later Sarohia got into space microelectronics, sensors, and eventually, management. In addition to his new role as liaison, he is a NASA program manager for the Long-Wavelength Detector Array Program. He is able to carry out his new responsibilities particularly well because of this long immersion in both the Caltech and JPL spheres. On fostering successful collaborations he says, "It is a contact sport. Creating good marriages on both sides of the aisle is the key to success. Two people have to really like the technical challenge—and they have to like each other so they can work together."

JPL reviews the research collaborations between campus and JPL on a regular basis. Over 250 science and technology collaborations were reported in 2006, with funding ranging from about $10,000 to several millions per collaboration. These exciting collaborative research efforts are characterized by the synergy of notably different talents adding a new dimension to the unique educational experience enjoyed by Caltech students, and lending JPL programs the fresh perspective of burgeoning young minds.

There are obstacles though. Post-9/11 regulations from the State Department "have not been very conducive to openness" Sarohia remarked. While the regulations are intended to protect U.S. interests and technology, they have had side effects: publications, presentation, and even people have to be "cleared," creating logistical barriers to the free flow of information that is the hallmark of academia. Moreover, JPL Director's Research Discretionary Fund (DRDF) seed funds for new initiatives are heavily oversubscribed. Combined with the general decrease of NASA technology development funds, many new JPL-campus interaction opportunities are lost. But Sarohia sees these as challenges to be solved, logistics to be negotiated.

Sarohia exudes a confidence and optimism that both organizations can help each other thrive, and he is devoted to that effort. "This is a dream job. I enjoy just the very fact that I work with younger people with limitless energy, and my goal is to reflect that energy into as many positive directions as possible." ENG

CAMPUS RESOURCE

Sherman Fairchild Library: Ten Years Later

by Kimberly Douglas

Ten years ago Caltech and the Sherman Fairchild Foundation dedicated the Sherman Fairchild Library in a forward-looking celebration of change and transition in libraries, given the ubiquity of computers and network technology. From the very beginning, designing a building that could be flexible in myriad ways was a huge challenge. There were the obvious limitations created by bricks and mortar, the issue of incorporating the library operations of six different engineering disciplines, and, of course, accurately predicting the future. The initial vision included not only increasing digital content, but also providing tools to manipulate that content. Students and researchers were expected be actively engaged in digital authorship.

In the early 1990s, following many years of generous contributions to the Institute, the Sherman Fairchild Foundation aimed to memorialize Sherman M. Fairchild, "scientist, businessman, inventor" at Caltech. A namesake library incorporating the anticipated innovations in libraries seemed appropriate. Fortunately, President Thomas Everhart and Professor Brad Sturtevant, Chair of the Faculty Building Committee, successfully convinced the Foundation that its benefactor's memory would be well served by such a new library, balanced somewhere between a traditional repository of physical materials and on the cutting edge of "virtual" technologies.

In Internet terms, 1997 was an era ago. Amazon was a baby, there was no Google, no wireless access, let alone a blogosphere. Ten years later we look back and realize that we've migrated through a number of different operating systems, CPU boxes of different shapes, and a plethora of portable technologies. Remember the Zip drive?

In the Sherman Fairchild Library (SFL), we have responded to this evolution by offering access to more computers and software tools, always cognizant of the principle of distributing computer productivity software and network access throughout the print collection. It is important to mingle print and electronic resources to encourage integration. The innovation of check-out notebooks in the fall of 1998 added another dimension, and in 2001 wireless access came to the SFL through the generosity of the Lee Center for Advanced Networking. Macs and Linux machines have been added to the inventory, along with newer PCs, to continue the practice of adopting and extending the offerings as technology and the community's needs and behaviors evolve.

While technology is an undeniable driver, the library's purpose and look and feel is very much rooted in human needs. As we look over the building with the passage of time, the work of the Committee and the Moore Ruble Yudell architects has stood up well. In large part this is because the human aesthetic was not lost or supplanted by technology. Professor Brad Sturtevant (who passed away in 2000) and the architects were insistent that the interior design be conducive to study and interaction, both with other humans and with digital and print content. At one point, many remember, there was a plan for a fireplace on the third floor. While it did not come to fruition, it served as a symbol, a shorthand, of the kind of comfort and place envisioned for extended reading and study.

One of our goals at this point in time is to remain at the forefront of leveraging digital technology and the new models of publishing scientific material for the benefit of our community.

The third-floor reading room continues to be a sought out destination with its lounge chairs and high ceiling. A recent Moore-Hufstedler grant funded the Leisure Reading collection located here; now you can find novels and magazines to peruse as you are recovering from the Annals of the Institute of Statistical Mathematics. Even the second floor, a very quiet space with no keyboard clicking allowed (as requested by students in 1999), remains popular, particularly at exam time. In 1998 the students asked for longer hours, until 4 a.m., for exam periods—a request honored. Not long after, benches were added to the third-floor balcony to provide appropriate seating for students who had otherwise been enticed to sit out on the ledge!

This past summer, what was originally a photocopy room on the second floor was renovated to create two more



group study rooms. With support from the Friends of Caltech Libraries, wall-mounted flat screens and controllers were installed to further support group collaboration.

While one naturally focuses on the building and the physical environment to celebrate ten years, the gift of the library included the creation a whole new digital environment that has also thrived and changed the way the library serves the Caltech community and, in fact, the world-wide education and research enterprise. Not long after the Sherman Fairchild Library opened, an invitational conference on scholarly communication hosted on campus concluded that the new network-based technologies certainly allowed the distribution of research content to be decoupled from the peer-review and editorial process. While the scholarly community still struggles with a model to act on that observation globally, the Caltech Libraries implemented an open source digital repository application, Eprints, to provide the platform for Caltech scholarship to be presented via open access protocols to the open Web.

Our resulting digital repository, CODA (Collection of Open Digital Archives), contains Caltech theses, faculty research papers, technical reports, and even books. Since 2003, PhD students are required to submit electronic theses—and the library has a program to scan and mount all Caltech theses retrospectively. Already there are 2,750 PhD theses in the digital archive; of these 2,000 are openly accessible. Faculty members, particularly those in Engineering and Applied Science, have also submitted over 6,000 papers and reports, as well as 21 books in electronic format for digital archiving and reliable presentation via the Web.

This platform has also served other units on campus in bringing their content to the open web. The Caltech Archives uses the CODA to present its Finding Aids and Oral Histories; the Public Relations Office presents the archives of Engineering and Science.

Persistent URLs, digital format migration, metadata, intellectual property, cyberinfrastructure… all these have entered the lexicon of the modern librarian as we face the future of technology and access to scholarship. One of our goals at this point in time is to remain at the forefront of leveraging digital technology and the new models of publishing scientific material for the benefit of our community. All the while, of course, retaining a human touch.

Our community, it turns out, extends well beyond Caltech to anyone around the globe who has interest in the kind of scholarship Caltech generates. In this way, the Sherman Fairchild Foundation gift, combined with the vision of the original building committee, has redefined what it truly means to be a library.

Kimberly Douglas is the Caltech University Librarian.

Visit the library on-line at:
http://library.caltech.edu

Library staff and their families gathered at the Los Angeles Zoo, July 2006.

RESEARCH NOTE

Biochemical Logic: Submerged Circuits of Floating DNA

by Erik Winfree

Digital logic and water usually don't mix. But that's exactly what we are trying to do. Recent work in our lab, lead by postdoctoral researcher Georg Seelig and graduate students David Soloveichik and Dave Zhang, demonstrates a new method for creating logic circuits out of DNA that work in a test tube—taking chemical input and producing chemical output. Because these circuits operate under conditions mimicking an intracellular environment, this research may be a step toward designing a "micro-controller" for biological cells and other complex chemical systems.

Our circuits work in water because they are based on chemistry, not electronics. Rather than encoding signals in high and low voltages, these circuits encode signals in high and low concentrations of short DNA molecules. The chemical logic gates that perform the information processing are also DNA; each gate is a carefully folded complex of multiple short DNA strands. When a gate encounters the right input molecules, it releases its output molecule. This output molecule in turn can help trigger a downstream gate—so the circuit operates like a cascade of dominoes where each falling domino topples the next one. However, unlike dominoes and electronic circuits, components of these DNA circuits have no fixed position and cannot be simply connected by a wire. Instead, the chemistry takes place in a well-mixed solution of molecules that bump into each other at random, relying on the specificity of the designed interactions to ensure that only the right signals trigger the right gates.

Making use of this molecular mechanism, we constructed gates to perform all the fundamental binary logic operations—AND, OR, and NOT—that are the building blocks for constructing arbitrarily complex logic circuits. To demonstrate that the circuit elements can indeed be combined and cascaded to compute complex functions, we created a series of circuits, the largest one taking 6 inputs processed by 12 gates in a cascade 5 layers deep (see Figure 1). This is not large by the standards of Silicon Valley, but it demonstrates several design principles that could be important for scaling up biochemical circuits.

While biochemical circuits have been built previously, both in test tubes and in cells, our implementation is novel in that the circuits' functions rely solely on the properties of DNA base-pairing—no biological enzymes are necessary for their operation. This allowed us to use a systematic and modular approach to design the logic circuits, incorporating many of the features of digital electronics.

One especially important design principle in digital electronics is signal restoration, which ensures that even if signals deviate slightly from the ideal levels representing 0 or 1, due to noise or imperfect manufacturing of components, the signals can be correctly interpreted and restored to the ideal levels. This principle was critical to the digital circuit revolution. With restoration, components did not have to be perfect: if a gate outputs a slightly smaller or larger signal than intended, the downstream components have no trouble determining the intended output of the gate. This allowed the components to get small and cheap, and to be robust to electrical noise. Similarly, we were able to implement signal restoration in our biochemical circuits by designing special thresholding and amplification gates that produce output strands at either a very low or a very high concentration, depending on whether the input was above or below a threshold level. By implementing digital logic in chemistry, our circuit was able to produce the correct output even when "noise" was introduced and not all gate molecules performed perfectly (see Figure 2).

> [We are also] inspired by an indirect attempt to understand the hypothetical "RNA world," a time four billion years ago when all the major tasks within primitive cells were carried out by complex RNA molecules.

Another critical aspect of digital electronics is the standardization of signals. This allows components such as microprocessors that are created by different companies and for different purposes to be hooked up any way an engineer wants. This is a challenge for chemical circuits. Because chemical circuits operate in a well-mixed solution, hook-

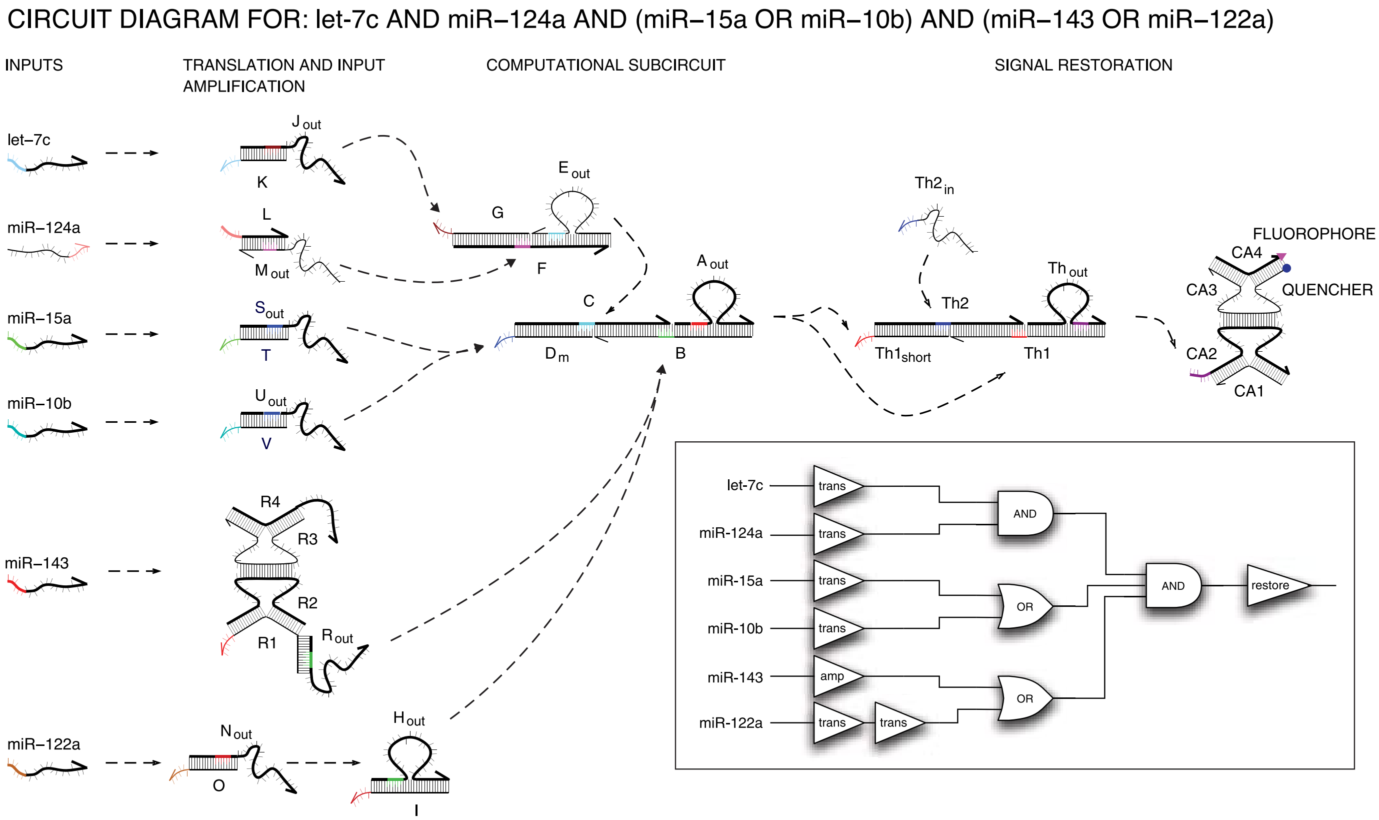


Figure 1. Circuit with 6 inputs (far left) processed by 12 gates in a cascade 5 layers deep.

Digital Logic and Water?

ing up components cannot be done simply by wiring them together; the molecules themselves must be redesigned to interact with the intended inputs and outputs. Fortunately, this is a systematic process in our circuits: the logic gates themselves have a modular design with independent input and output domains. For example, this makes it easy to design "translator gates" that can be used to wire together pre-existing components that use distinct molecular signals. This modular design is especially helpful for interfacing with existing biological components. We demonstrated this by using microRNA sequences, part of a recently discovered genetic control system in biology, as inputs to the circuits. Being able to "read in" microRNAs as inputs and to process information contained in specific microRNA expression patterns may become a powerful way of detecting specific cellular abnormalities, such as the exact type of cancer in a tissue sample or even in vivo.

While they incorporate design principles from digital logic, these biochemical circuits are not meant to solve the math problems computers are so remarkably good at. Compared to modern electronic circuits, these circuits are painstakingly slow and exceedingly simple. Rather, our work builds on and contributes to the fast-growing discipline of synthetic biology, in which the engineering of biochemical circuits—ranging from genetic and metabolic networks to signal transduction cascades—is directed toward creating circuits that take molecules as input and produce molecules as output. These efforts will enable a new generation of

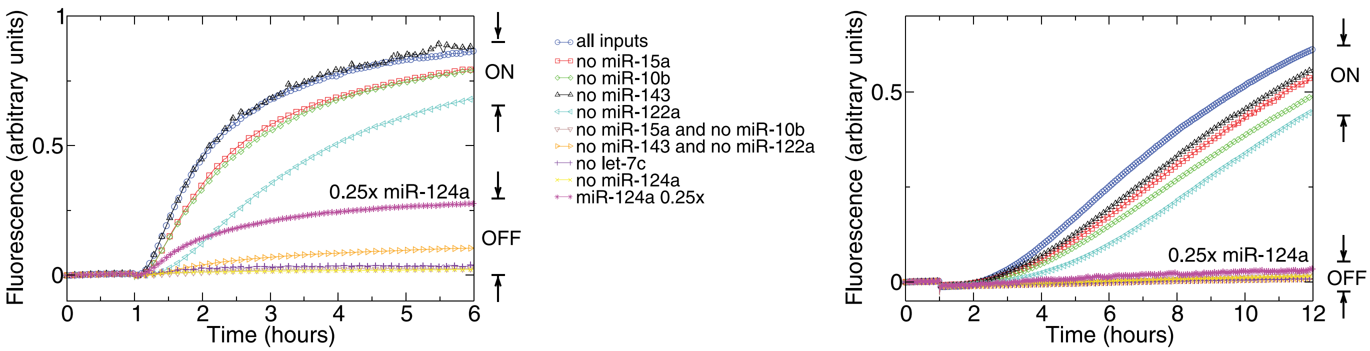


Figure 2. The graph on the left shows circuit function without the restoring element; the magenta trace shows simulated "noisy" input, leading to an output that is partially between the ON and OFF levels. On the right, with the restoring element, the "noisy" input is suppressed.

technologies for embedding "intelligence" in chemical systems, with potential bionanotechnology and biomedical applications. In such engineering endeavors, it is certainly worthwhile to see what we can learn from the construction of electronic circuits. After all, digital logic has arguably changed the way we live more than any other invention in the second half of the previous century.

This discussion might lead you to think that our motivation in creating these biochemical circuits was purely technological. Partly true. But it was also largely inspired by an indirect attempt to understand the hypothetical "RNA world," a time four billion years ago when all the major tasks within primitive cells were carried out by complex RNA molecules. This hypothesis implies that although proteins may be better at many chemical tasks, and have now largely taken over, they aren't absolutely necessary: nucleic acids can do the job also, be it catalyzing chemical reactions, carrying information, or serving as structural molecules. This changes the bias about what kinds of chemistry are necessary for engineering complex and functional molecular systems.

With that perspective in mind, the immediate stimulus for our work was the convergence of several research threads. Dave Zhang, interested in engineering biological circuits, had been pondering the origin of life and wondering what the simplest self-replicating molecular systems might be—which led him to the idea of designing cascades of DNA-DNA interactions, the precursors of our "translator gates."

Meanwhile, David Soloveichik, lost in the clouds of theoretical computer science, was fascinated with how simple chemical reaction systems could compute, and he recently analyzed the computational power of molecular automata created by Benenson and Shapiro at the Weizmann Institute of Science. Finally, Georg Seelig, who has spent the last year characterizing a novel DNA-based catalyst, was looking for ways for his fundamental work to find applications to biomedical therapeutics—with the dream of contributing to efforts developing "smart" drugs to cure cancer or other diseases.

Exactly how these threads combined and led to the genesis of our DNA logic gates and circuits may forever remain shrouded in mystery, but I distinctly recall when, not much more than a year ago, David and Georg emerged from Georg's office with big smiles and announced, "We have to go to dinner." We designed and ordered the DNA strands for an AND gate—and a week later the strands arrived. A few days after that, the very first experiments showed that the system worked exactly as predicted!

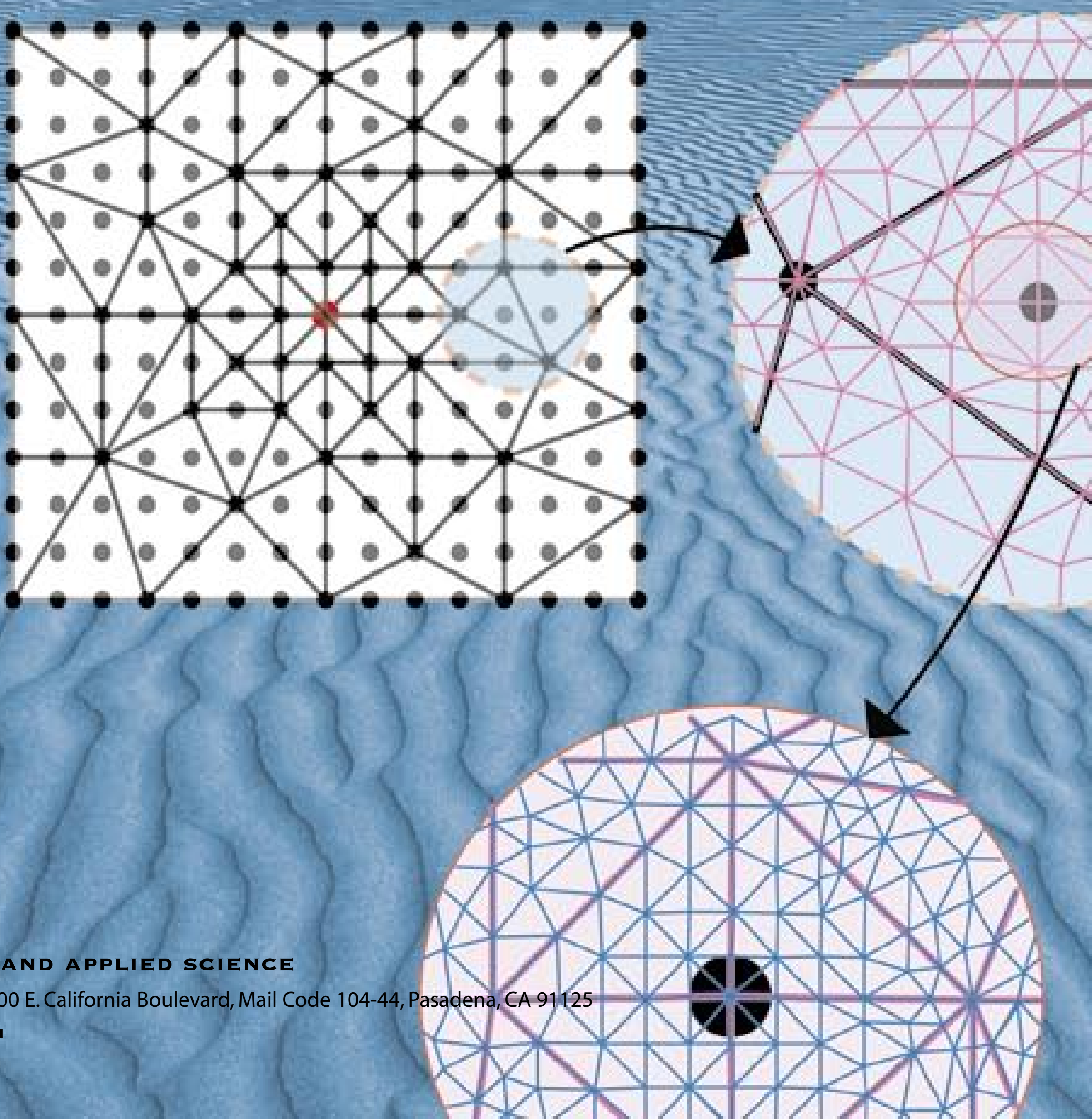
In about two weeks, we had gone from inspiration to a minimal publishable unit. I've never had that experience before or since. It clearly told us that we were on the right track, and that if we pushed it we had a chance to demonstrate something significant.

Where is this going? Our work is part of a broader vision for engineering the DNA nanotechnology systems being developed by Ned Seeman (at New York University), Niles Pierce (here at Caltech), and others. Ultimately, we'd like to be able to program biochemical circuits. Silicon computers are programmed by defining, in a high-level language, how to perform a task, and this specification is then translated by a compiler to create an executable binary file that runs on the CPU. Similarly, it now seems possible to give a high-level specification for the logical function a DNA-based circuit should perform, and to automatically compile it into DNA sequences for the required logic gates, which work in solution. E N G

Erik Winfree is Associate Professor of Computer Science and Computation and Neural Systems.

Learn more about the DNA and Natural Algorithms Group at:
http://www.dna.caltech.edu

Not to be confused with a nifty hood ornament, the 6-meter parabolic reflector on the roof of the Moore Laboratory is a prototype of the antennas that are needed by the thousands in very large arrays being considered for deep-space communication and radio astronomy (see http://www.skatelescope.org). The reflector was produced by a unique aluminum hydroforming process. This method provides a precise, structurally strong, and inexpensive shell structure in a fast (10-minute) stamping process. Two more antennas of this type are at JPL and are part of tests of a prototype array operating at 8.4 and 32 GHz for space communications. Working on this project are Dr. Sander Weinreb, Faculty Associate in Electrical Engineering, his colleagues at JPL, and graduate students at Caltech.



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