

# ENGenious

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



 **Micro Device Reliability Laboratory**



FALL 2003



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>.

### Division Chair

Richard M. Murray (BS '85)

### Division Steering Committee

Jehoshua (Shuki) Bruck  
*Gordon and Betty Moore Professor of  
Computation and Neural Systems and  
Electrical Engineering*

Janet G. Hering  
*Professor of Environmental Science and  
Engineering*

Thomas Yizhao Hou  
*Professor of Applied and Computational  
Mathematics*

Melany L. Hunt  
*Professor of Mechanical Engineering*

Ares Rosakis  
*Professor of Aeronautics and Mechanical  
Engineering*

Peter Schröder  
*Professor of Computer Science and Applied  
and Computational Mathematics*

Kerry J. Vahala (BS '80, MS '81, PhD '85)  
*Ted and Ginger Jenkins Professor of  
Information Science and Technology and  
Professor of Applied Physics*

P. P. Vaidyanathan  
*Professor of Electrical Engineering*

### ENGenious

#### EDITORS

Marionne L. Epalle  
Peter Mendenhall

#### ART DIRECTION/DESIGN

Jessica Stephens

#### PHOTO CONTRIBUTIONS

Steven A. Heller  
Peter Mendenhall  
Stephen Nowlin  
Nina Pratt  
Carolyn K. Swanson

#### PHOTO

Sallie Manson  
Briana Ticehurst

### Options

**AERONAUTICS (GALCIT)**  
[www.galcit.caltech.edu](http://www.galcit.caltech.edu)

**APPLIED & COMPUTATIONAL MATHEMATICS**  
[www.acm.caltech.edu](http://www.acm.caltech.edu)

**APPLIED MECHANICS**  
[www.am.caltech.edu](http://www.am.caltech.edu)

**APPLIED PHYSICS**  
[www.aph.caltech.edu](http://www.aph.caltech.edu)

**BIOENGINEERING**  
[www.be.caltech.edu](http://www.be.caltech.edu)

**CIVIL ENGINEERING**  
[www.ce.caltech.edu](http://www.ce.caltech.edu)

**COMPUTATION & NEURAL SYSTEMS**  
[www.cns.caltech.edu](http://www.cns.caltech.edu)

**COMPUTER SCIENCE**  
[www.cs.caltech.edu](http://www.cs.caltech.edu)

**CONTROL & DYNAMICAL SYSTEMS**  
[www.cds.caltech.edu](http://www.cds.caltech.edu)

**ELECTRICAL ENGINEERING**  
[www.ee.caltech.edu](http://www.ee.caltech.edu)

**ENVIRONMENTAL SCIENCE AND ENGINEERING**  
[www.es.e.caltech.edu](http://www.es.e.caltech.edu)

**MATERIALS SCIENCE**  
[www.matsci.caltech.edu](http://www.matsci.caltech.edu)

**MECHANICAL ENGINEERING**  
[www.me.caltech.edu](http://www.me.caltech.edu)

### Caltech Alumni

The mission of the Caltech Alumni Association is to promote the interests of Caltech as a world standard of academic excellence by strengthening the ties of goodwill and communication between the Institute, its alumni, and current students, and by maintaining programs to serve their needs. For more information on the Association and its activities, visit its website. <http://www.its.caltech.edu/~alumni>

### Support Caltech

<http://giving.caltech.edu>

### Comments?

[engeniou@caltech.edu](mailto:engeniou@caltech.edu)

**3 NOTE FROM THE CHAIR**

**4 SNAP SHOTS**  
'Round About the Institute

**6 NEW FACULTY**  
**New Arrivals, Joint Appointments, and Moore Scholars**

Michael Elowitz	Subra Suresh
Richard Flagan	Eli Yablonovitch
George Papanicolaou	Changhui Yang
Michael Roukes	Bernard Yurke

**8 IDEA FLOW**  
**DNA Tweezers, Motors, and Masks:** Bernard Yurke and Friends are Filling the Nano Toolbox

**10 RESEARCH NOTE**  
**Today's Internet is Just a Parking Lot:** New Algorithms Pave the Way for the Real Superhighway—Steven Low and the FAST Team

**12 GALCIT 75**  
**Graduate Aeronautical Laboratories:** Celebrating 75 Years of Experimental, Theoretical, and Computational Innovation

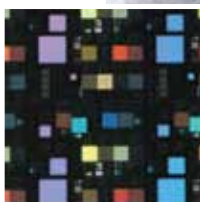
**26 EMERITUS**  
**Noel R. Corngold:** Many Many-Body Interactions  
by Paul M. Bellan



**28 OPTION PROFILE**  
**Control and Dynamical Systems:** From Cellular Systems to Gravitational Systems, and Almost Everything in Between

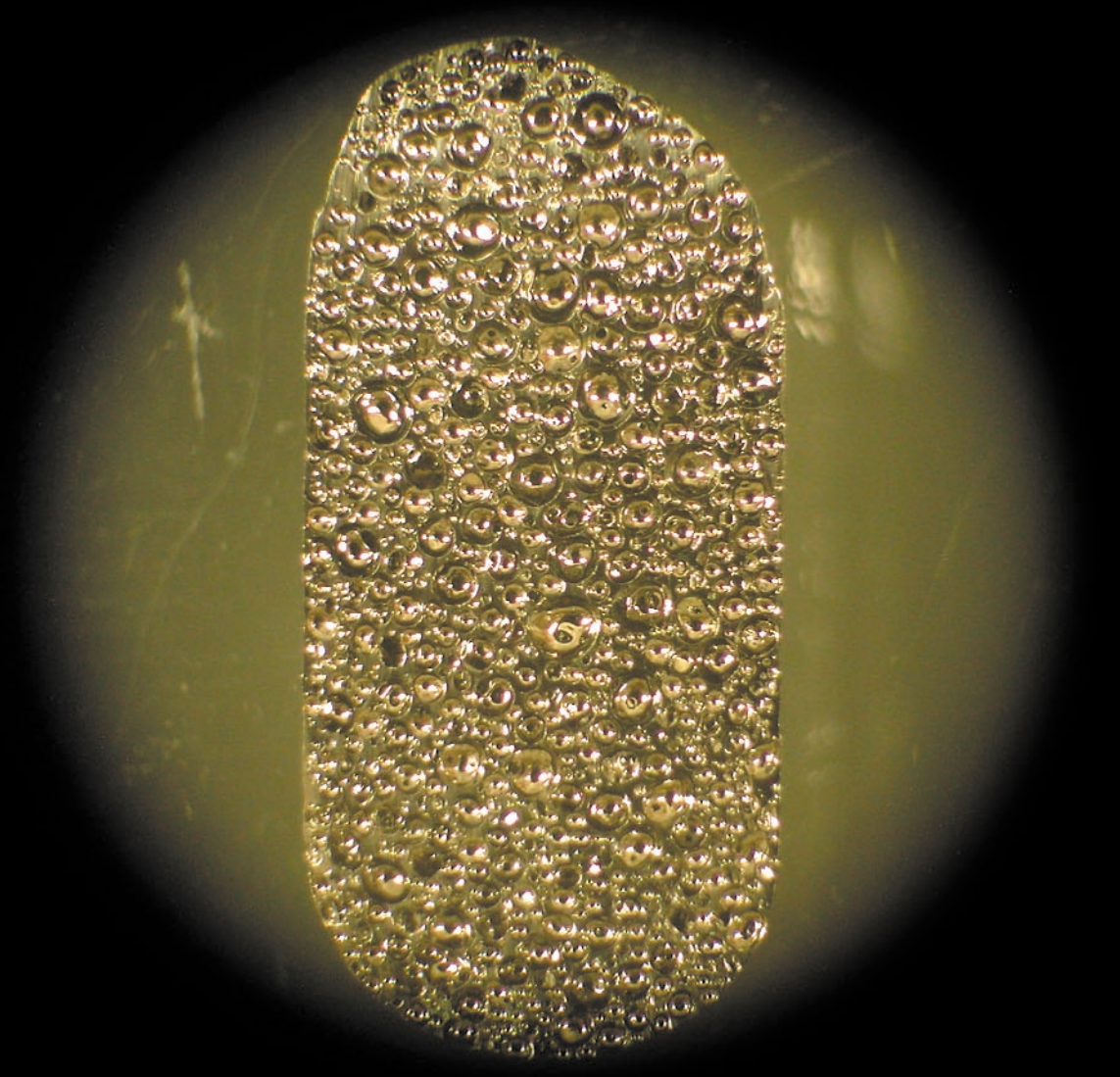
**32 CAMPUS RESOURCE**  
**More Than Getting Your Feet Wet:** SURF, the Summer Undergraduate Research Fellowship Program  
by Carolyn Ash

**34 ALUMNI**  
**An E&AS Who's Who:** Recipients of the Caltech Distinguished Alumni Award



**Cover Image:** GALCIT houses the only Class 1 clean room in the entire Caltech/JPL complex. It is the first installation in the Micro Device Reliability Laboratory. Ares Rosakis, Professor of Aeronautics and Mechanical Engineering, is shown suited up in this new facility. He and his colleague Subra Suresh from MIT (see New Faculty, page 6) have been studying stress and fracture evolution on the microscale, especially as they affect the processing and operation of thin-film structures in microelectronic and optoelectronic devices ("silicon chips") which are manufactured on 300-millimeter silicon wafers (detail, left). They designed a method to test the warpage and stress evolution in these large wafers and to investigate the issue of mechanical reliability through coherent gradient sensing (CGS) interferometry. CGS is a shearing interferometric method developed by Rosakis's group at GALCIT and applied to the study of a variety of mechanical problems. Based on this technology, a Caltech spin-off called Oraxion Diagnostics was formed and built the advanced prototype device that is currently used in this facility.

A generous gift from Betty and Frank Whiting in 2001 provided the seed funding that made the Micro Device Reliability Laboratory possible. Future plans for the expansion of the Laboratory include the installation of a variety of stress diagnostic and failure inspection instruments. This growing state-of-the-art facility will allow Rosakis and his colleagues to address the major mechanical issues confronting microelectronics, optoelectronics, and MEMS devices as feature sizes continuously decrease from the micron to the nanometer length scales.



## N O T E F R O M T H E C H A I R

*The Graduate Aeronautical Laboratories of the California Institute of Technology—of course we all know this as GALCIT—is celebrating 75 astonishing years on November 14 and 15th. **ENGenious** is joining the celebration by featuring the GALCIT faculty in this issue. They muse on the characteristics that have made GALCIT unique, and give a glimpse of current and near-term research. It's not too late to join the festivities yourself. If you are an aeronautics alum, a Caltech alum with fond memories of GALCIT, or an interested friend of the Institute, please visit the event website [www.galcit.caltech.edu/galcit75](http://www.galcit.caltech.edu/galcit75) to find the details of the program, see who will be there, and register. It will be a good mix of social activities and technical updates, and I look forward to seeing you there.*

*Also in this issue we visit my home option, Control and Dynamical Systems, and have the opportunity to learn more about the details of Steven Low's efforts to change the very nature of internet transmission protocols and Moore Scholar Bernard Yurke's work with Erik Winfree and Michael Roukes to continue filling "the nano toolbox."*

*I attended the East Coast campaign kick-off gala last month in New York City, and was pleased to see so many alumni and friends of the Institute eager to hear about the remarkable things happening on campus. Caltech has reached an impressive 62 percent of its campaign goal of \$1.4 billion through the vision and generosity of many people. This issue of **ENGenious**, from cover to cover, reflects the outstanding achievements that are possible when committed students, faculty, alumni, and friends of the Institute work together in the name of excellence.*

*Sincerely,*



**RICHARD M. MURRAY**

*Chair, Division of Engineering and Applied Science*



Image at left: A micrograph of "bubbloy," an amorphous, homogeneous foam of bulk metallic glass (BMG)  $\text{Pd}_{43}\text{Ni}_{10}\text{Cu}_{27}\text{P}_{20}$ . The foaming of metals is a challenge since foam is an unstable structure. However, metallic foams are known to have many interesting properties, offering high stiffness in conjunction with very low specific weight, high gas permeability, high thermal conductivity, and especially, high energy absorption capability. Dr. Jan Schroers, a recent post-doctoral scholar in Professor William Johnson's lab, along with graduate student Chris Veazey, invented a method to foam bulk metallic glass. Since the amount of energy that can be absorbed scales with the strength of a material, and since BMGs exhibit a yield strength of about 2 GPa (compared to 250 MPa for aluminum), a very large energy absorption ability is expected from BMG foams. Projected practical applications include possible use in the crumple zones of autos, for instance. This work is still in early developmental stages, but it has already moved into a Caltech spin-off company called Liquidmetal Technologies.



## 'Round About the Institute



Pictured above: Professor Christopher Brennen floats off the floor of the KC-135 microgravity research plane. Below left to right: graduate student Steve Hostler and post-doc James Cory.

## Suspended Students, Professor: Measurements Made in Zero Gravity

**The Deformation of Granular Material**, particularly the relationship between the stresses and the rates of deformation, has been the subject of some controversy and much discussion since R.A. Bagnold's observations 50 years ago. Earth-bound experimental measurements are fantastically difficult due to the action of gravity, which makes it almost impossible to sustain a homogeneous suspension of the grains.

For this reason, Professors Melany Hunt and Christopher Brennen devised a rheometer to fly in zero gravity in the NASA KC-135 airplane and to make measurements in that environment. The experiment was built by post-doctoral scholar Jim Cory (MS '98 APh, PhD '01 APh) with help from graduate student Steve Hostler. Cory, Hostler, and Brennen flew the experiment at NASA Glenn in June, doing three flights, each with 40 25-second intervals of zero gravity.

The photographs give a slightly different meaning to the phrase "you are now free to move about the cabin."



New York City's Gotham Hall ballroom.



Alumni celebrating at the NYC gala (left to right): Dr. Jan W. Dash (BS '63 Eng), Dr. Dhiraj Kumar Sharma (MS '72 EE, PhD '75 EE), and Dr. Mirmira R. Dwarakanath (PhD '69 Ph).

## East Coast Campaign Kick-Off

**The Institute's** "There's only one. Caltech" fundraising campaign recently made its way to the Big Apple with a celebration dinner at Gotham Hall, a newly restored historical building in midtown Manhattan. Nearly 200 guests attended the gala event, which introduced alumni and friends on the eastern seaboard to the Institute's ambitious plans for the future.

The program included remarks from Ben Rosen (BS '54 EE), Chairman of the Board of Trustees, Wally Weisman, Vice Chairman of the Board of Trustees and Campaign Chairman, and President David Baltimore, as well as a screening of the campaign film, *Infinite Possibilities*. Adding greatly to the event was the presence of many Caltech faculty members and trustees who helped foster engaging conversations about the work of the campus community and beyond.

To find out more about the campaign, visit <http://one.caltech.edu>



Scott Fleming, team infrastructure lead, welding.



Computing team member Sue Ann Hong.

## How Hard Can It Be? Team Caltech Races in the DARPA Grand Challenge

**Where Are We Going?** Las Vegas. How are we getting there? Driving. Who's going to drive? No one! Bob, a 1996 Chevrolet Tahoe 4x4, will drive himself, alone.

How? Using GPS signals, several cameras, a laser measurement system, on-board software, and maybe just a little luck (we are going to Las Vegas, after all). What route will we take? We won't know until 2 hours before the race. One thing's for sure: we want to win.

Such are the knowns and unknowns surrounding the DARPA Grand Challenge race where \$1,000,000 goes to the team whose fully autonomous ground vehicle completes a course between Los Angeles and Las Vegas (225 to 250 miles) in the fastest time and in less than 10 hours. The race will occur on March 13, 2004. Only publicly available signals (e.g., GPS) may be used for navigation. Otherwise, the vehicle must be fully autonomous, receiving no other signals for navigation, path planning, obstacle avoidance, and terrain differentiation. Such a feat has never been done and will be extremely difficult and maybe impossible. But then again, until now we've never unleashed a team of tenacious Caltech undergraduates on the problem.

Over the summer, 23 students, mostly sophomores, and a handful of advisors (engineers and scientists from Caltech, Northrop Grumman, and JPL; including Alex Fax [PhD '02 CDS]) worked together on re-engineering Bob. With fall classes starting, a few of the team members have left to focus on their studies, leaving only 16 to finish the job.

If they win the race, future Caltech undergraduates will benefit from their spoils: all prize money will go towards undergraduate needs, including scholarships.

See how Team Caltech plans to bring home the booty at

<http://team.caltech.edu>

## Neuro: Art and Science Meet Again

**Once Upon a Time**, artists and scientists were one and the same. Then, maybe a couple hundred years ago, artists became artists and scientists became scientists. Both groups involved themselves in wide-ranging creative problem solving, but lots of things happened that started to separate them. Each group began asking different questions and seeking answers in different places. Call it the age of specialization?

A joint project of Art Center College of Design and Caltech's NSF Center for Neuromorphic Systems Engineering (CNSE) brought the two groups a bit closer together through a year-long collaboration exploring the CNSE's core mission of endowing machines with senses and sensory-like behavior. The resulting exhibition, NEURO, at Art Center's Alyce de Roulet Williamson Gallery and, of all places, the lobby of the Athenaeum, was a thought-provoking intersection of art, science, and engineering.

Stephen Nowlin, Director of the Williamson Gallery, and Pietro Perona, Professor of Electrical Engineering and Director of the CNSE, led a group of six artists and many Caltech faculty and graduate-student collaborators. "In tandem, art and science force shifts of perception we might otherwise never imagine," writes Nowlin in his essay on the NEURO website. Perona adds, "We thought that art might be a good vehicle to make our [scientific] ideas more accessible, and to provide some of our fellow citizens with an entry point into our laboratories."

To find out who did what, go to <http://www.artandscience.us>



Above (left to right): Professor Pietro Perona, Director, Center for Neuromorphic Systems Engineering and Stephen Nowlin, Director, Alyce de Roulet Williamson Gallery. Right: artist Martin Kersels and Professor Peter Schröder's project, "Science."

## New Arrivals, Joint Appointments, and Moore Scholars: The Faculty Scene

### New Faculty

**Michael Elowitz:** Assistant Professor of Biology and Applied Physics, Bren Scholar (joint appointment with Biology)

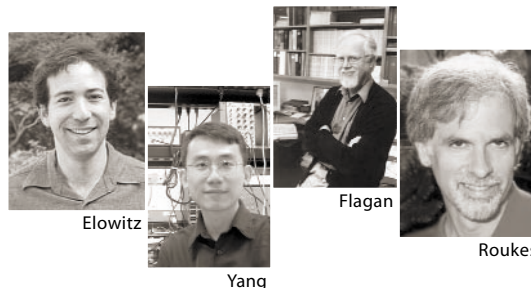
**Professor Elowitz's** interests are in biophysics, particularly gene regulation networks, biocomputing, and the origins of variation in living cells. Elowitz is interested in how cells process information and develop using circuits composed of interacting genes and proteins operating in the unfamiliar intracellular environment. He is equally interested in the opposite question of how novel networks can be engineered within cells to implement alternative cellular behaviors. Elowitz and his researchers will address these complementary questions together using a combination of experimental and theoretical techniques.

Elowitz received a BA degree in Physics from the University of California in 1992, and a PhD in Physics from Princeton University in 1999. Most recently, Elowitz was a fellow at Rockefeller University.

**Changhuei Yang:** Assistant Professor of Electrical Engineering (arrives December 2003)

**Professor Yang's** research area is biophotonics, the imaging and extraction of information from biological targets through the use of light. His primary interest is the application of novel interferometric and nonlinear optical processes for non-destructive biomedical imaging. He has developed a low-coherence interferometric phase technique that is capable of probing the small (nanometer scale) and slow (nanometer/second) dynamics of living cells. He is interested in applying the method to study the physical response of cells to subtle changes in their environment and the physical manifestation of cell-to-cell interactions and synchronizations. Professor Yang's other major research focus is in the development of molecular contrast optical coherence tomography (MCOCT). Optical coherence tomography is the optical equivalent of ultrasound tomography; it is capable of high-resolution architectural imaging of biological targets. Professor Yang is working on exploiting the photochemical properties of specific protein-based chromophores to introduce molecular contrast imaging capability into OCT.

Yang received his BSc (Physics, 1997), BSc (Electrical Engineering, 1997), BSc (Mathematics, 2002), MEng (Electrical Engineering, 1997) and PhD (Electrical Engineering, 2002) degrees from the Massachusetts Institute of Technology. Since graduation, he has worked as a post-doctoral fellow at ESPCI (Paris) and Duke University.



### Recent Joint Appointments

**Richard Flagan:** Irma and Ross McCollum Professor of Chemical Engineering and Professor of Environmental Science and Engineering (joint appointment with Chemistry and Chemical Engineering)

**Professor Flagan's** research focuses on understanding the role of atmospheric aerosols and related processes on air quality and global climate. This work elucidates the physical processes that enable pollen and other airborne allergens to penetrate deep into the respiratory tract where they may trigger asthmatic attacks. The research also advances aerosol technologies for the synthesis of nano-structured materials and devices. The common threads underlying these areas are an understanding of the dynamics and behavior of suspensions of small liquid or solid particles in gases, and the goal of advancing experimental methods for investigation of those particles.

Flagan received a BSE degree in Mechanical Engineering from the University of Michigan in 1969, and his SM (1971) and PhD (1973) degrees from the Massachusetts Institute of Technology.

**Michael Roukes:** Professor of Physics, Applied Physics, and Bioengineering (joint appointment with Physics, Mathematics, and Astronomy)

**Professor Roukes's** research activities are currently focused upon developing and using nanodevices in the exploration of single-quantum and single-molecule phenomena. The systems he and his group are building have a range of applications that span fundamental measurement, engineering, and biological and medical sciences. Recently they created a mechanical device that vibrates a billion times per second.

Roukes received a BA in Physics and a BA in Chemistry from the University of California, Santa Cruz in 1978, and a PhD in Physics from Cornell University in 1985.





Papanicolaou

Yurke

Yablonovitch

Suresh

## Moore Distinguished Scholars

### George Papanicolaou: Stanford University

**Professor Papanicolaou's** interests are in waves and diffusion in inhomogeneous or random media and in the mathematical analysis of multiscale phenomena that arise in their study. Applications come from electromagnetic wave propagation in the atmosphere, underwater sound, waves in the lithosphere, diffusion in porous media, etc. He has studied both linear and nonlinear waves and diffusion, in both direct and inverse problems. Papanicolaou is now working on assessing multi-pathing effects in communication systems, especially when time-reversal arrays are used.

Another recent interest is financial mathematics, especially the use of asymptotics for stochastic equations in analyzing complex models of financial markets and in data analysis.

Papanicolaou received a BEE from Union College in Schenectady, N.Y. in 1965, and his PhD in Mathematics from New York University, Courant Institute in 1967.

### Eli Yablonovitch: University of California, Los Angeles

**Professor Yablonovitch's** research focuses on optoelectronics, high-speed optical communications, nanocavity lasers, photonic crystals at optical and microwave frequencies, quantum computing, and communication.

Yablonovitch graduated with the PhD degree in Applied Physics from Harvard University in 1972. He worked for two years at Bell Telephone Laboratories, and then became a professor of Applied Physics at Harvard. In 1979 he joined Exxon to do research on photovoltaic solar energy. Then in 1984, he joined Bell Communications Research, where he was a Distinguished Member of the Technical Staff and also Director of Solid-State Physics Research. In 1992 he joined the University of California, Los Angeles where he is Professor of Electrical Engineering.

### Bernard Yurke: Bell Laboratories, Lucent Technologies

**Dr. Yurke** has been working at the forefront of physics in a number of areas, including low-temperatures physics, quantum optics, liquid crystals, biophysics, and MEMs devices. His current main interest is in constructing nanostructures and nanodevices using DNA. Past research projects have included the generation and detection of squeezed states at optical and microwave frequencies, the study of phase-ordering kinetics in liquid crystals, and force generation of microtubules. Yurke also is active in the development of quantum measurement schemes with phonons in nanostructures, and mechanical quanta in ultraminiature mechanical devices.

Yurke received BS (1975) and MA (1976) degrees in Physics from the University of Texas at Austin, and his PhD (1983) in Physics from Cornell University. Since 1982 he has been a researcher at Bell Laboratories, Lucent Technologies in both the Optical Physics and Materials Research Departments. He has been a Distinguished Member of the Technical Staff at Bell Labs since 1987. [See article by Dr. Yurke, page 8.]

### Subra Suresh: Massachusetts Institute of Technology (beginning May 2004)

**Professor Suresh's** interests are in nanoscale mechanical properties of engineering and biological materials, and in the connections between structure, properties, and function. He is the author/coauthor of two books, *Fatigue of Materials* and *Thin Film Materials*, both of which have been published by Cambridge University Press; coauthor of nearly 200 journal publications; and coinventor in approximately 15 patent applications. He has been elected a member of the U.S. National Academy of Engineering, a fellow of ASME, TMS, ASM and the American Ceramic Society, and an Honorary Member of the Materials Research Society of India. He has previously held the R. P. Simmons Professorship at MIT, the Clark B. Millikan Visiting Professorship at Caltech, and the Swedish National Chair in Engineering at the Royal Institute of Technology.

Suresh received a Bachelor of Technology degree from the Indian Institute of Technology in 1977, an MS degree from Iowa State University in 1978, and an ScD from the Massachusetts Institute of Technology in 1981, all in Mechanical Engineering.

## DNA Tweezers, Motors, and Masks: Bernard Yurke and Friends are Filling the Nano Toolbox

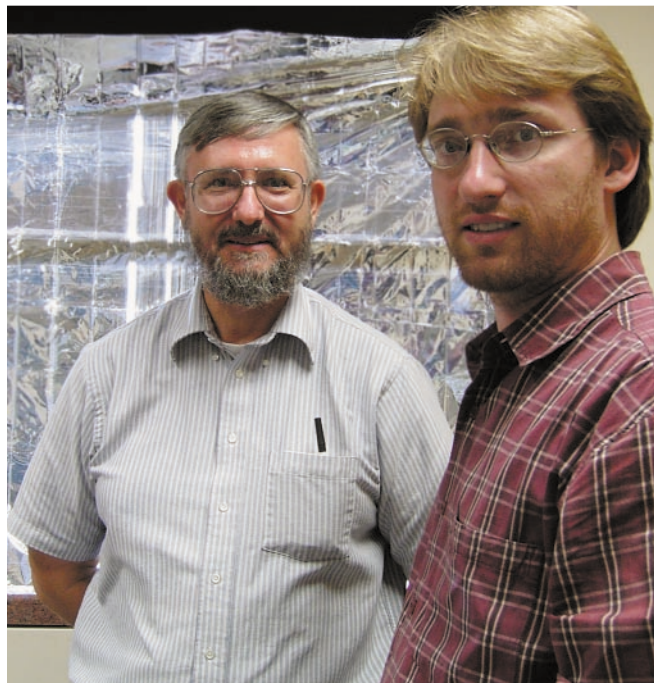
Bernard Yurke, who generally resides at Bell Labs as a Distinguished Member of the Technical Staff, is visiting Caltech as a Moore Scholar through September 2004. His scientific contributions span many fields, from cosmology to materials science, but here at Caltech he is pursuing his latest passion, using DNA to construct nanostructures and nanodevices. He shares with us the details of the projects he will be working on during his Caltech sojourn.

**M**y research at Caltech is focused on using DNA to construct nanostructures and nanodevices, and is divided into two main areas of activity. One is directed toward the construction of free-running DNA-based molecular motors. The second is directed toward assembling sheets of DNA that could be used as contact masks for creating precisely patterned surfaces, specifically semiconductor surfaces.

A number of DNA-based devices that can produce repetitive motion have been described in the literature. Most of these motors are based on principles I illustrated with the construction of a device I like to refer to as molecular tweezers. The device consists of two double-stranded DNA arms that are connected by single-stranded DNA. This single-stranded section of DNA serves as a flexible joint that would allow one to bring the two arms together if one had eyes acute enough to see something that is seven nanometers in length and if one had fingers

dexterous enough to manipulate something that small.

We were able to close and open this device using a DNA-based motor. The motor consisted of two single strands of DNA, one



Dr. Bernard Yurke (left) and Professor Erik Winfree.

extending from each pincer end of the tweezers. A strand of DNA that I refer to as a “fuel” strand is able to hybridize with these single-stranded extensions to form double-stranded DNA. The process of forming these double strands pulls the arms of the device shut. The tweezers are returned to their open

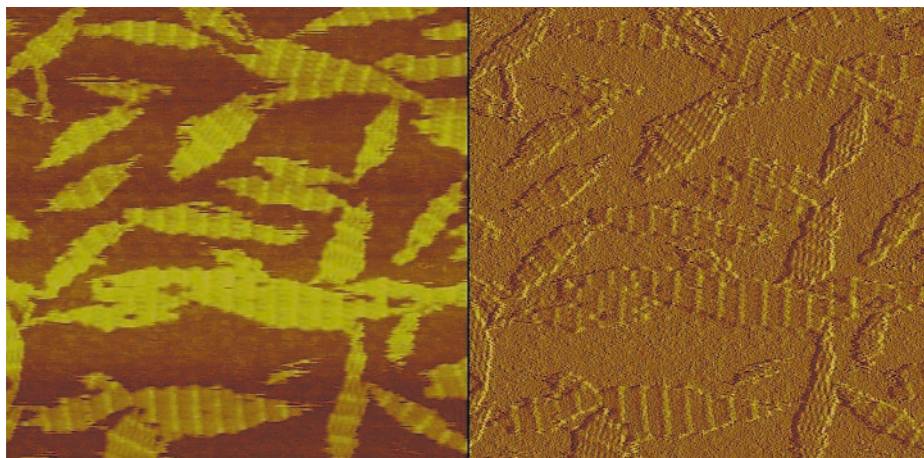
configuration by introducing the complement of the fuel strand. The complement is able to remove the fuel strand from the tweezers through competitive binding, thereby forming a double-stranded waste

product. DNA-based motors of this type are able to develop 15-picoNewton forces, which may sound really small, but biological molecular motors typically develop forces in the 5- to 30-picoNewton range.

The tweezers motor and others using the same principles are *clocked motors*. That is, they are driven through their sets of states through successive application of fuel and removal strands. If one adds the fuel and removal strands at the same time, these strands will mostly hybridize with each other directly without interacting with the motor. This

behavior is different from that of many biological molecular motors found in nature that are able to keep running because the fuel molecules are stable unless they interact with a molecular machine that is able to use the fuel.

The challenge is to devise DNA-based structures that can



The images above show atomic-force microscope images taken at Caltech this summer. One can make out the individual DNA tiles and the striped pattern indicates that these are AB lattices. Each image shows an area that is 689 nanometers wide.




operate like the fuel and removal strands but that do not interact with each other except through a DNA-based molecular motor. Erik Winfree [Assistant Professor of Computer Science and Computation and Neural Systems; PhD '98] and I have designed a set of DNA strands that should form such structures that are stable until a DNA strand with a specific base sequence is present. This special DNA strand would behave like a catalyst and could be used as the motor for a free-running DNA-based device. Much of my work here at Caltech will consist of measuring the reaction rates for various components of this device to debug and verify its performance. Perhaps such motors will allow a realization of Feynman's vision\* as expressed in his talk "There's Plenty of Room at the Bottom."

With the second project I hope to construct DNA-based contact masks that would allow one to pattern semiconductor materials

such that the smallest feature sizes will be on the order of 2 nanometers or better. This would be about an order of magnitude smaller than what can currently be done with electron-beam writing.

Winfree has shown that one can construct DNA-based tiles that assemble into two-dimensional sheets, often as large as 10 microns by 2 microns in size. The base sequence of the single-stranded extensions that serve to bind two tiles together through hybridization of complementary sequences can be chosen at will. That, in effect, makes the tiles programmable so that the DNA sheet that is assembled is a very complex tapestry. This tapestry can be decorated with gold particles. The complex pattern of gold particles could serve as a mask to produce patterns on some substrate that the DNA sheet has been deposited on. Erik's group has shown that DNA tiles can assemble to produce a variety of tapestries having patterns that are of interest in electronics. For example, on

paper, they have devised sets of tiles that will assemble into the kind of pattern that would be appropriate if one were trying to make an address demultiplexer, a typical integrated circuit. We hope to actually try out these sets of tiles to see how well they work in practice.

The tapestries produced by DNA tiles are easily imaged using an atomic-force microscope [see images at upper left]. This will be a major tool in our investigations. In this project I am also collaborating with Michael Roukes [Professor of Physics, Applied Physics, and Bioengineering] and members of his group to try to devise a lithography procedure that could transfer the tile patterns to a substrate. Since I am a Moore Scholar working in the Moore Laboratory, it is perhaps appropriate that I should be trying to push lithography to its ultimate limit.   

---

For further information see the websites for the research groups of Erik Winfree and Michael Roukes, Yurke's website at Bell Labs, as well the Feynman lecture at:

[www.dna.caltech.edu](http://www.dna.caltech.edu)

[nano.caltech.edu](http://nano.caltech.edu)

[www.bell-labs.com/org/physical\\_sciences/profiles/yurke.html](http://www.bell-labs.com/org/physical_sciences/profiles/yurke.html)

[www.its.caltech.edu/~feynman/plenty.html](http://www.its.caltech.edu/~feynman/plenty.html)

---

\*The prospect of mass-producing atomic-scale machines was first publicly envisioned in 1959 by Caltech Professor Richard Feynman. His lecture is now widely known, and serves as one inspirational cornerstone of today's nanotechnology research.



# Today's Internet is Just a Parking Lot: New Algorithms Pave the Way for the Real Superhighway—Steven Low and the FAST Team



**I**magine driving in the following manner. You fix your eyes twenty feet in front of your car. When you see no obstacle in sight, you slowly increase your speed. As soon as anything comes into sight, you slam on the brakes. Repeat as many times as necessary to reach your destination.

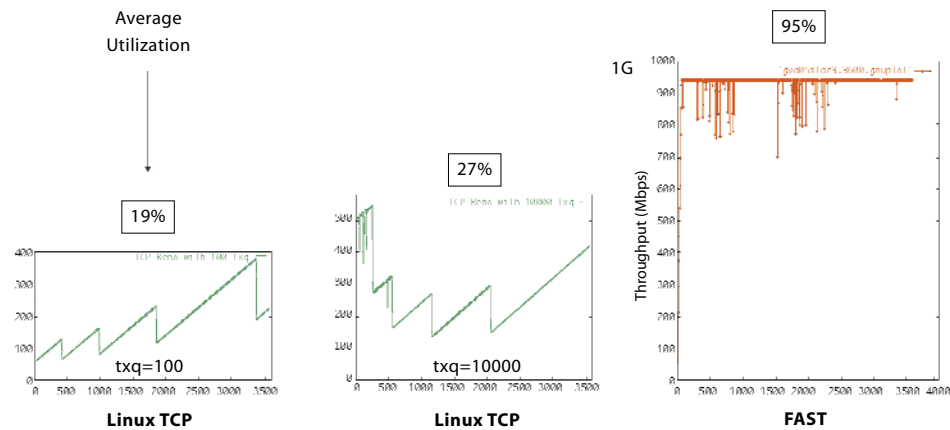
This is not a bad strategy in a parking lot, but it is not how you would want to drive on the autobahn, or on any high-speed roadway. When we enter a highway, we look near and far, front and rear, to sense the traffic flow around us and then converge quickly to the right speed. When sending and receiving information over the Internet, the current strategies used to control transfer speed are still designed for parking lot driving, while the infrastructure is being upgraded to superhighway mode. The FAST project at Caltech, led by Professor Steven Low, is changing that.

Here is the current state of affairs. The algorithm that controls

the sending speed is called the congestion control algorithm. It is a distributed algorithm designed to share the Internet among hundreds of millions of users. It consists of two sub-algorithms. One is a host algorithm, implemented by the Transmission Control Protocol (TCP) that modifies the sending rate in response to the amount of congestion in the path from source to destination. The second is a queue-management (QM) algorithm that implicitly or explicitly feeds back congestion information to the hosts. All currently deployed TCP algorithms are based on a scheme developed at Berkeley 15 years ago when most parts of the Internet could barely carry the traffic of a single voice call—and when the general public had no knowledge of the Internet's existence, let alone surfed the web. Since the mid 1990s, researchers have realized that this algorithm cannot scale to

any future network that must be able, for instance, to carry 1.5 million concurrent voice calls. The lack of a theoretical framework to understand the *underlying structure of the general problem* led to a tremendous variety of *ad hoc* tinkering with the TCP and QM algorithms, with limited success.

During the past five years, a rigorous theory of congestion control has started to emerge, based on work done at Cambridge University, the University of Melbourne, Caltech, UCLA, UIUC, and the University of Massachusetts. The theory covers the equilibrium and dynamic structure of large-scale networks under end-to-end control. One of the key components in the theory is Low's idea of interpreting the TCP/QM pair as a distributed primal-dual algorithm carried out over the Internet by hosts and routers in the form of congestion control, in order



to solve a global mathematical optimization problem. The iteration on the primal variable is carried out by TCP while the iteration on the dual variable is carried out by QM. The underlying optimization problem determines the equilibrium properties of the network such as performance, throughput, delay, packet loss, and fairness in resource allocation. It explains some intriguing phenomena observed empirically and provides practical guidelines for sizing network buffers.

With Caltech Professor John Doyle and Caltech alumnus and UCLA Professor Fernando Paganini (MS '92, PhD '96), Low has shown that the *current* TCP algorithm becomes unstable when feedback delay increases, and more strikingly, when network capacity increases! More importantly, the theory provides a framework to design and prove stable TCP algorithms that easily scale to large delay and network capacity.

With these new theoretical insights as a guiding light, Low's Networking Lab designed a TCP congestion control algorithm, called FAST TCP, that maintains high performance and is fair and stable. It was implemented in the Linux operating system. With Caltech Professor Harvey Newman, they demonstrated FAST TCP in November 2002 at the Supercomputing Conference in Baltimore, Maryland. The partners involved for this demonstration included Caltech's Center for Advanced Computing Research (CACR), Stanford Linear Accelerator Center (SLAC), European Organization for Nuclear Research (CERN), with support

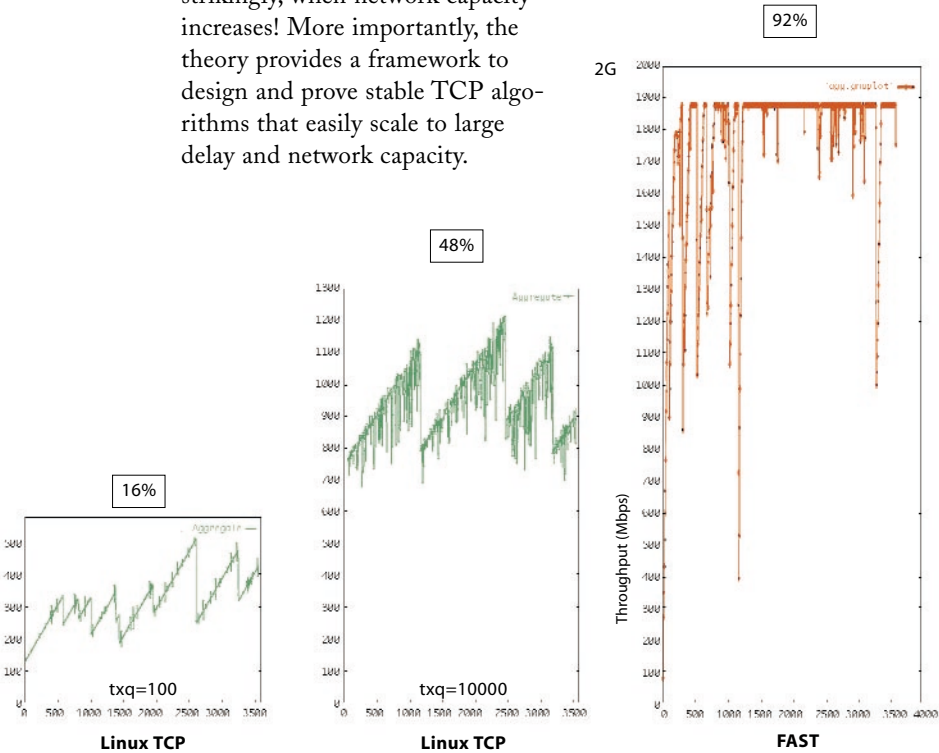
from DataTAG, StarLight, TeraGrid, Cisco, and Level(3).

The current TCP typically achieves an average throughput of 266 Mbps, averaged over an hour (a single TCP/IP flow between Sunnyvale, California and CERN in Geneva, Switzerland over a distance of 10,037 kilometers). This represents an efficiency of just 27 percent. Using the standard packet size that is supported throughout today's networks, the FAST TCP sustained an average throughput of 925 Mbps and an efficiency of 95 percent—a 350 percent improvement—under the same experimental conditions. With 10 concurrent TCP flows, FAST achieved an unprecedented speed of 8,609 Mbps, at 88 percent efficiency. More importantly, the FAST protocol sustained these speeds using standard packet size stably over an extended period on shared networks in the presence of background traffic, making it “backwards compatible” and adaptable for deployment on the world's high-speed production networks.

Low and his team are working with academic and industry partners to further test the FAST TCP in real applications. The first users will probably be those in academia requiring terabyte data transfers on demand, high-energy physics (HEP) research groups, for instance. But stay tuned! This new superhighway may be making its way to your neighborhood next.

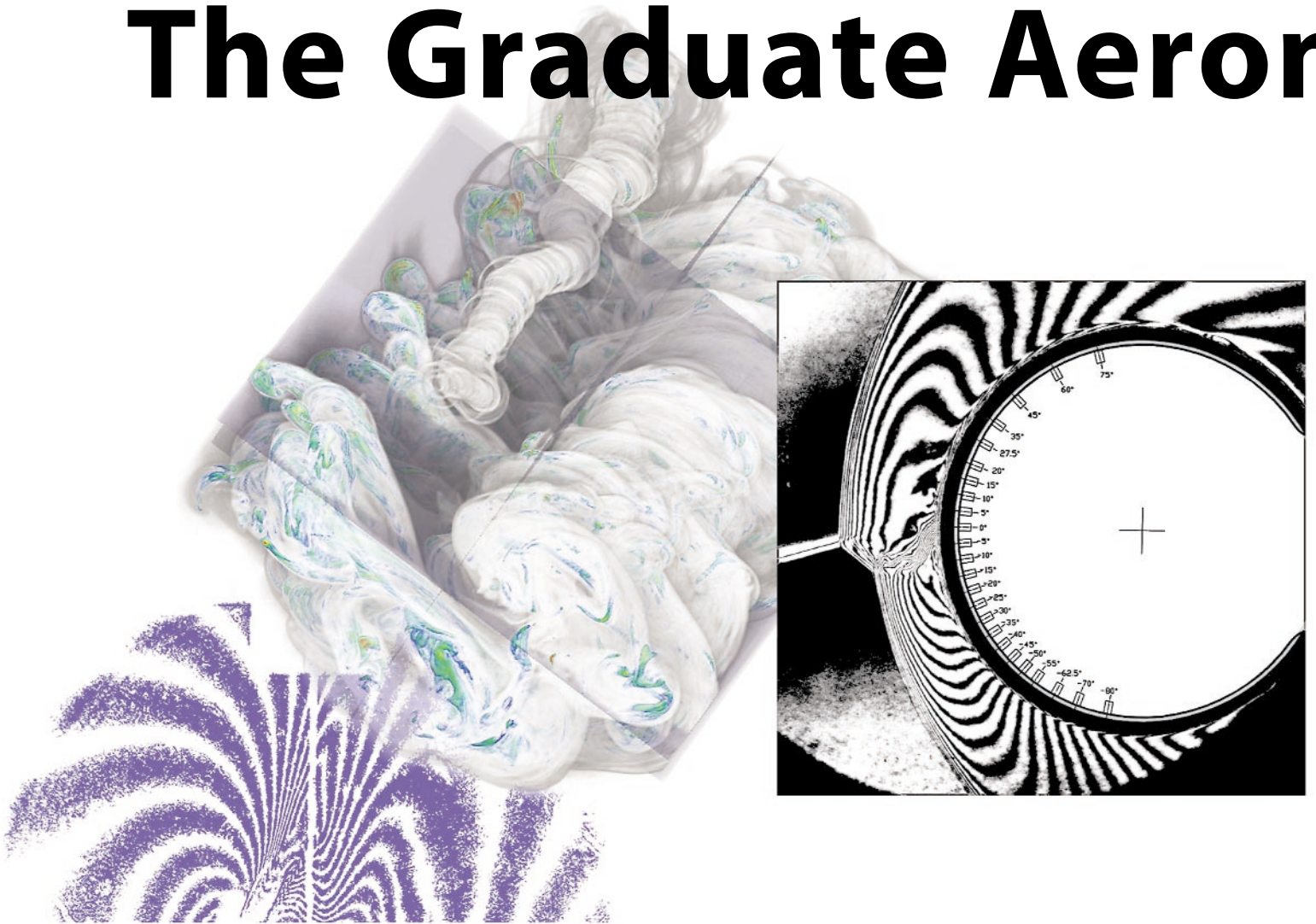
*Professor Steven Low is Associate Professor of Computer Science and Electrical Engineering at Caltech.*

For further information visit:  
[netlab.caltech.edu/FAST](http://netlab.caltech.edu/FAST)



The figure above shows throughput traces for FAST and Linux TCP with percentage utilization. The x-axis is time (sec), the y-axis is aggregate throughput (Mbps). The FAST traces are in red. The txq number refers to the size of buffer memory in the Linux kernel used to mitigate the mismatch in the network card's transmission rate and the CPU processing of packets.

# The Graduate Aeron



*On the occasion of the 75th Anniversary of the founding of the Graduate Aeronautical Laboratories of the California Institute of Technology—GALCIT, that is—we took the liberty of talking with each of the faculty members about the current direction of this world-renowned research group and the factors that have led to its unique—some say unparalleled—position in the world of fluid mechanics, solid mechanics, and combustion research. It is well known in the scientific community that GALCIT is the birthplace of a large number of ideas, new theories, innovations, and scientific discoveries. It has established a long tradition of leadership in its chosen fields. However, GALCIT's ongoing obsession with the scientific foundations of fluid and solid mechanics has ensured that this 75-year old intellectual powerhouse shows no signs of advanced age.*



# aeronautical Laboratories

Celebrating 75 Years of Experimental, Theoretical, and Computational Innovation

**A**s Professor Mory Gharib deftly explains, “the same principle that guided GALCIT’s early research efforts still governs today—find the most challenging unsolved problems, the *show stoppers*, and attack them before the rest of the scientific community even has them on their radar screen.”

Each generation has its own mix of show stoppers, and the original areas in which GALCIT worked revolved around aeronautical applications. The lab was founded in 1926 as the Guggenheim Aeronautical Laboratories with a \$300,000 grant from the Daniel Guggenheim Fund for the Promotion of Aeronautics (Caltech was one of seven schools that were so funded). Hans Liepmann, the third Director of GALCIT, speaking at GALCIT’s 50th Anniversary celebration, noted:

[Daniel] Guggenheim stated clearly that his endowment was not intended to be permanent, but that he thought aeronautics, then in its infancy, would be raised to a state where support would be guaranteed from both private and government sources. [...] it would have been absolutely out of the question to raise that money for that purpose at that time from the government. Congress would have never permitted such a strange venture. The legislators would have just laughed, because at that time, flying was often barnstorming and the accident rate on the few existing airlines was something like one fatality for 1,300 miles, a number that has only been reached at times by private automobiles.

Its first director, Theodore von Kármán, a pioneer in both fluid and solid mechanics, began visiting Caltech in 1926, but made a firm landing in 1930 to direct GALCIT full time. As recorded by Clark Millikan, the second Director of GALCIT, von Kármán spent the fall of 1926 at the California institute advising its staff regarding the educational policies and experimental

facilities of the new graduate school and laboratory. During this visit the essential features that characterized their subsequent development were largely worked out under von Kármán’s leadership.

The initial focus on the applications of fluid and solid mechanics to aeronautics blossomed, and by the end of the Second World War, observed Liepmann, “GALCIT was the only school in the nation equipped to tackle the problems arising from the explosive development of aircraft and missiles to transonic and supersonic speeds and finally into spaceflight.” In fact, the burgeoning aerospace industry in Southern California was catalyzed, supported, populated, and maintained by GALCIT (and Caltech) with cutting-edge research, unique testing facilities, and top-notch graduates. Aerospace companies were founded by Caltech and GALCIT alumni, led by our alumni, and served as

## origins

home to creative thinkers, inventors, and engineers who succeeded in transforming society by breathtaking advances in communications and transportation. A particularly unique institution “spun-off” from GALCIT is the Jet Propulsion Laboratory (JPL), which put the first U.S. satellite into space and continues to this day leading the country’s unmanned space program. Von Kármán was JPL’s first director.

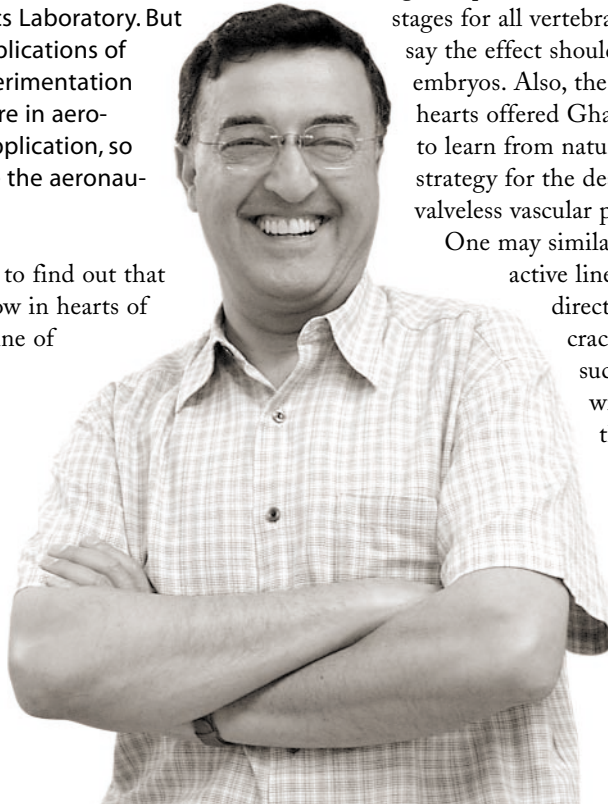
# breadth

**E**

ven as early as the '30s, '40s, and '50s, the pioneering research undertaken by GALCIT faculty and colleagues spanned a wide range of interests outside of the aeronautical envelope.

**A. Rosakis:** As a matter of fact I have been told that von Kármán himself was arguing about calling GALCIT basically a center of applied mechanics—the Graduate Applied Mechanics Laboratory. But at that time, the biggest applications of mechanics, theory, and experimentation in both solids and fluids were in aeronautics. That was the star application, so it made sense to emphasize the aeronautics part.

Today, one may be surprised to find out that investigation of the blood flow in hearts of embryonic zebrafish is one line of research in GALCIT. Mory Gharib is carrying out this extraordinary work with colleagues Scott Fraser, who is Rosen Professor of Biology, senior research fellow Jay Hove, and post-doctoral scholar Reinhardt Köster. By surgically blocking the flow of blood through the hearts—these tiny beating hearts are less than the diameter of a human hair—the researchers were able to



demonstrate that a reduction in “shear stress,” or the friction imposed by a flowing fluid on adjacent cells, caused the growing heart to develop abnormally. The results demonstrate for the first time that the very action of high-velocity blood flowing over cardiac tissue is an important factor in the proper development of the heart. Because the early development of an embryonic heart is thought to proceed through several nearly identical stages for all vertebrates, Gharib and his colleagues say the effect should also hold true for human embryos. Also, the studies of embryonic zebrafish hearts offered Gharib’s team a unique opportunity to learn from nature how to develop a proper strategy for the design of an optimal artificial valveless vascular pump for medical applications.

One may similarly be surprised to learn that an active line of inquiry in GALCIT is directed toward exploring dynamic crack formation in geomaterials such as the Earth’s crust—otherwise known as earthquakes—and that this research has shown that cracks can propagate at supersonic speeds.

**Rosakis:** I remember my second year in GALCIT. I was asked to give a talk in geophysics by Professor Hiroo Kanamori [John E. and Hazel S. Smits Professor of Geophysics], and I spoke about dynamic fracture of

## Morteza Gharib (PhD '83)

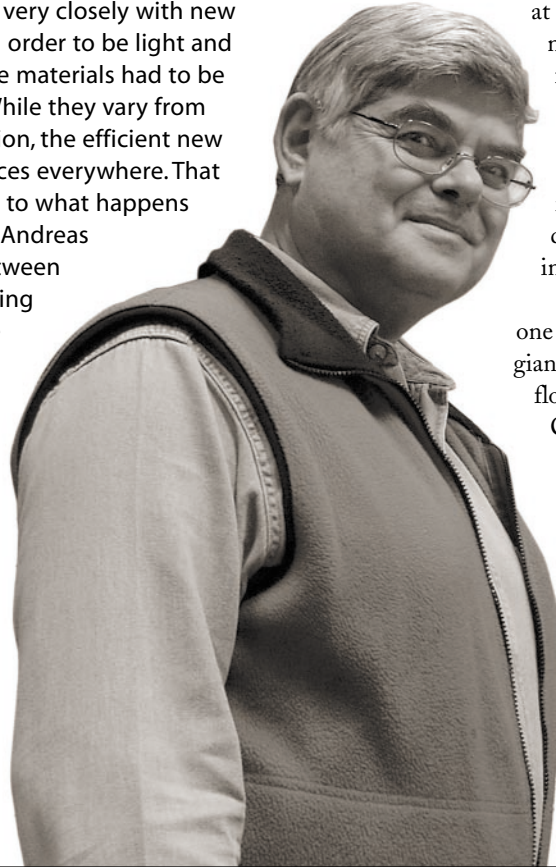
**Hans W. Liepmann Professor of Aeronautics and Bioengineering**

*Professor Gharib’s principal research interests are vortex flows, biofluid dynamics, wake flows, free-surface turbulence, bioengineering, and quantitative visualization.*

If I see that the boxfish can do better control than a 747, I drop all this rigid stuff! One of the experiments we are doing aims at understanding how a boxfish stays next to a coral reef, the sharpest object you can imagine, in high turbulence, but keeps a distance of one millimeter. And doing it by having seven fins that are flapping and creating vortices here and there, keeping the fish right there, dead accurate. This problem is a combination of fluid mechanics, flexible compliant structures, and control. The future GALCIT will be tied to these new areas, and I think the next wave of smart propulsion devices will be based on the biomechanics of flying and swimming. But we need to learn how nature engineers these things.

Another area I am working in is free surface flow. My group is studying problems associated with the wakes of big ships. Last May we went on a ten-day field trip with a Naval research vessel. We have a Caltech camera under the boat to see what the propeller is doing. How is the propeller generating bubbles? How do the bubbles end up in the wake? The Navy spends \$200 million per ship. These ships are radar-proof and stealth, but the wakes are not: you know exactly where they are. You don’t see the ship—you see the bubbles. That’s why we are helping them understand the mechanisms of wave breaking. Is it possible to remove an observable wake? It’s possible.

engineering materials. He said to me: have you ever thought about applying these same principles to different problems with different length scales, that is, earthquakes? It took me about ten years to follow his suggestion, but I finally did. And it has been a very, very interesting ride. During this same period, engineers starting working very closely with new composite materials. In order to be light and efficient and strong, the materials had to be made of composites. While they vary from application to application, the efficient new structures have interfaces everywhere. That situation is very similar to what happens in geophysics. The San Andreas fault is an interface between two plates that are sliding against each other. The engineering application is mimicking part of the geophysical application. Also the San Andreas fault separates two pieces of material that have been sliding for centuries. So they are not exactly the same material anymore to the right and left. All mature faults, for example, are composed of different properties on one side



compared to the other, like a composite is. So here are applications that are very similar.

The high-speed cameras used in Rosakis's lab show that shear cracks in interfaces propagate as fast as 7 kilometers per second. One of these cameras operates at 50 million frames per second, which is necessary since these shear cracks are faster than the fastest supersonic jet planes. This work has practical applications not only for materials engineering, but also for geophysics, because there is reason to believe that certain large earthquakes feature rupture that propagates intersonically along the geological fault.

Considering even larger scales, one may think that the dynamics of galaxies, giant whorls of matter, and other cosmological flows may be a concern only to those in Caltech's astrophysics corridors. Think again. The computational theoretical fluid dynamics work of Tony Leonard and Dale Pullin has application here, as well as in more down-to-earth applications such as climate studies and ocean dynamics problems.

**D. Pullin:** I am presently interested in turbulence, and although fluid dynamical flows can be simulated on a computer, there are limitations. One limitation is that turbulence involves a very vast range of

## Paul Dimotakis

(BS '68, MS '69, PhD '73)

### John K. Northrop Professor of Aeronautics and Professor of Applied Physics

*Professor Dimotakis's principal research interests are fluid physics, the dynamics of turbulence, and high-speed propulsion.*

I came to Caltech from Greece as an undergraduate freshman. The plan was to study nuclear engineering and return to Greece to build a nuclear reactor. But I fell in love with physics and the Feynman lectures. So I thought well, whatever I am going to do professionally, I am going to study physics first and answer some of my questions. So I got my first degree in Physics. I then got my Masters in Nuclear Engineering, per plan. By then, I had met Hans Liepmann and was enchanted by his intellect and enthusiasm for science. So then I said, well, it doesn't really matter what your degree says, so I switched to Aeronautics to study with Hans Liepmann. I did my thesis research in low-temperature physics and superfluidity. The Applied Physics option got started in the meantime, so my PhD is actually in Applied Physics, which better described my research.

I now work in fluid mechanics, turbulence and turbulent mixing, combustion, chemical reactions, and high-speed propulsion, among other things. But I only took one course in fluid mechanics as a student. The feeling at the time, and to a large extent this is still the case, is that you come here to be educated, not to be trained. You are educated when you understand how nature works, how the world works, and how to think; and if you learn these things, you can actually do anything. And that is the same sense I try to transmit to students that I work with. I like to think that GALCIT graduates can do anything.



eddies. Turbulence is about eddies. And there is not just one eddy in a turbulent flow, there are billions of them, and they're all of different length scales. Further, turbulence occurs everywhere: in the intergalactic medium, in the interior of stars, probably in star formation processes; it occurs in environmental fluid mechanics, on the scale of climatology; it occurs locally in environmental flows over mountains, it occurs at the interface between the ocean and the waves, it occurs inside the ocean; it occurs in turbulent combustion, inside a jet engine, in the boundary layers on 747s. It's a very important problem.

It would be nice to have a simulation tool that could deal with these problems, for obvious reasons. But unfortunately, because of the huge range of length scales, even with the world's biggest computers, we can't really do it in a faithful way. So one of the areas that I am interested in is called large-eddy simulation. This is an attempt to try and compute turbulent flows without resolving *all* of the length scales. Maybe in 20 years, because Moore's Law is working out pretty well, we will have the computational capability.

Dealing with turbulence in the presence of a wall has turned out to be a very, very difficult problem. It's actually a bit of a bottleneck at the moment. Take the computation of a very simple flow, the flow past a sphere, at large Reynolds numbers. The very best we can do at the moment, resolving all the scales, is probably flow at a Reynolds number of 10,000. And that's pushing it a bit.

Let's take an example. A golf ball flies at a Reynolds number of 50,000 – 100,000. So we are not even close. The roughness of a golf ball means that the turbulent boundary layer near the surface of the golf ball is very complicated. And it is also spinning, which is a further significant complication. You can't hit a smooth golf ball much more than about 100 yards. Tiger Woods couldn't hit a smooth golf ball out of the backyard. But he can hit a dimpled one 300 yards.

That's an example of how

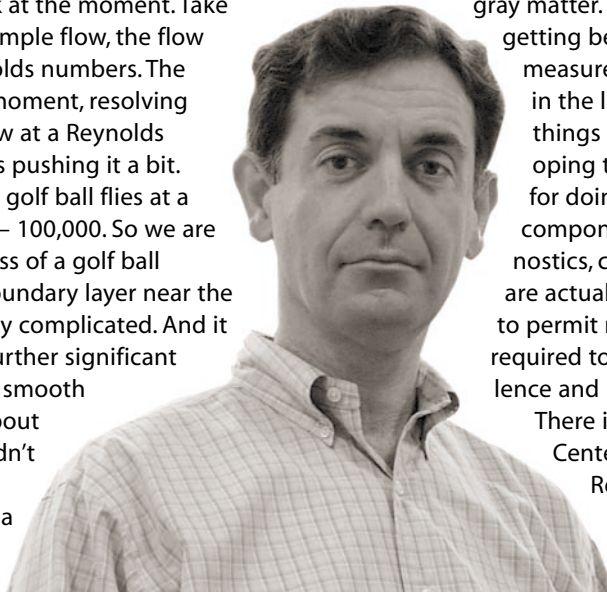
the behavior of the turbulent boundary layer profoundly affects behavior. If, in the next 10 years, I can do a faithful numerical simulation of the flow past a sphere, even a smooth sphere at a Reynolds number of 100,000 or a million, I'd be reasonably happy.

Professor Dimotakis, who also considers turbulence in his work, concurs and adds more to the mix:

**P. Dimotakis:** What is different about what is coming? There are two things. To "solve" the turbulence problem, we must appreciate what it is that makes it a problem, and a difficult one at that. And in the case of turbulence and turbulent mixing, what makes it difficult is that this is an unsteady, three-dimensional, non-linear phenomenon. And I need to add one more element: it is all those things but it also encompasses an enormous range of space and time scales. If it weren't for the latter, we would just put it on a computer since we understand the equations. The combination puts it out of reach of traditional analysis.

What is new and different is that we have computers that are getting larger and will eventually be large enough to handle this problem, with some help from gray matter. In addition, experiments are getting better. We are now able to measure in three and four dimensions in the laboratory. That is one of the things I've been involved in: developing the methods and technology for doing this. So that's the other component: experimental tools, diagnostics, coupled with computers that are actually getting powerful enough to permit recording of the kinds of data required to describe and analyze turbulence and mixing.

There is joint project with Caltech's Center for Advanced Computing Research (CACR) that we have been working on for three years. We will soon have the means of acquiring up to



## Michael Ortiz

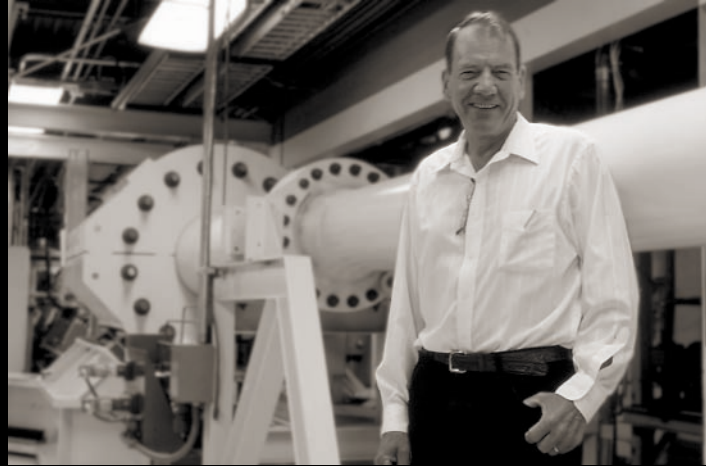
### Professor of Aeronautics and Mechanical Engineering

*Professor Ortiz's research interests are in computational solid mechanics.*

I don't do experiments. I draw the line there. That's the one thing I don't do. But, you know, you asked me why I came to Caltech. One of the real attractions of Caltech is that it has maintained strength in experimental mechanics and experimental sciences in general, which is becoming more and more unusual at other institutions because it's expensive. There's an economic incentive for emphasizing cheaper things like computers and computation. But Caltech has done a very good job actually in maintaining strength in the experimental area. That is really unusual and really unique. And I have colleagues like Ravichandran, Knauss, and Rosakis who have devoted all their careers to experimental science. I'm in very good company. We have very good working relations where they do the experiments. Of course they are capable of doing modeling and theory themselves and they do. But often we collaborate and we combine efforts.

# Hans Hornung, Director

One of the unique aspects of GALCIT has been the position of Director. There have been four Directors in the last 75 years: Theodore von Kármán, Clark Millikan, Hans Liepmann, and most recently, Hans Hornung. Hans Hornung was director from 1987 until this year when he stepped down to return to research full time. During Hans's tenure as Director there were many changes to the faculty and physical plant. Five new faculty members were hired within the first eight years of his arrival at Caltech. The lower floors of the Guggenheim building were



twenty *terabytes* of data in a short time. This will allow recording of three-dimensional data from flow that occupies about one cubic foot. We will be recording up to  $10^9$  measurements per second. And that is roughly what it takes to capture such phenomena. If you have not been able to see what the phenomenon is that you are trying to describe, well, you are not likely to do a good job describing it. So this is what is changing and what will be different in the next few years.

The breadth of GALCIT's work has been only hinted at. We look at a couple more examples that harken back to the "aero" in GALCIT.

**F. Culick:** I am working principally on unsteady chemically reacting internal flows, or combustion instabilities as this area is known. Understanding and controlling unwanted unsteady motions in liquid rockets, gas turbines, solid rockets, afterburners, and ramjets have been my areas of research, really beginning with my thesis work. The crux of the problem is that a great deal of energy is being released in a relatively small volume, with almost no losses, and this energy is being converted into unwanted, nonlinear motions of fluid. It's a tough problem. My group attacks it with both theoretical and experimental investigations. I also work in other areas, notably propulsion systems.

**M. Ortiz:** My particular interest is in space structures. The two main challenges there are surveillance and energy. By surveillance, I refer broadly to large-aperture optics. We want to build structures, lenses in space, which have sizes in the kilometer range. It is very difficult to deploy those structures, stabilize them in space, and then get them to work as desired. These requirements really challenge traditional concepts in structures. We are used to thinking of structures as working in gravity here on Earth and they're typically designed to *withstand* gravity. Now we're thinking of very large structures in the *absence* of gravity. These structures cannot be tested on Earth because they're too large. We cannot achieve zero gravity conditions on Earth anyway. You have to have confidence in the design and that the deployment sequence is going to work, because launching these things is very expensive. I see an important role there for modeling and simulations. It's a very exciting area. I am also interested in ideas that might allow us to capture solar energy and beam it down to Earth. This is an area where GALCIT in particular is going to play a very significant role. And there are very obvious connections to JPL with both of these projects.

**J. Shepherd:** We are working with companies who are building new propulsion devices based on explosions—pulse-detonation engines (PDEs). It is a very

completely renovated with the removal of the venerable 10-foot wind tunnel. The T5 Hypervelocity Shock Tube was built, as were the Ludwig Supersonic Tube, the John W. Lucas Adaptive Wind Tunnel, and the Lees-Kubota Lecture Hall. In the GALCIT tradition, Hans was a working director, managing an extensive research program in hypersonics, teaching classes, many of which he initiated, and also mentoring post-docs and students, 15 of which received PhDs working under him and several more are in progress today. Hans has carried on the tradition of excellence in research and teaching that past directors established, and like them has won many honors, including the Ludwig Prandtl Ring and election to the Royal Aeronautical Society.

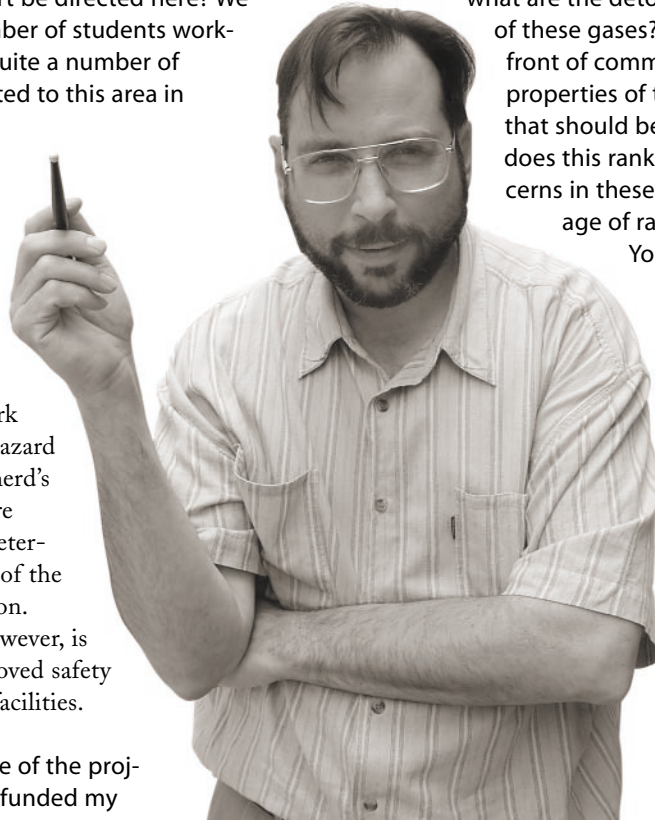
Hans's athletic abilities are known throughout the campus—he is a formidable opponent in tennis and played on the Aeronautics soccer team until it hurt too much. (Actually we hear he'll be out on the field again this season.)

In recent years, Hans has become quite interested in using computation to study fluid mechanics and has this to say about numerical simulation: "One of the developments that is extremely rapid these days is the capacity of computers. In 10 years' time, computers will be so much more powerful and things we only dream about now will be able to be simulated on the computer. At the moment three-dimensional simulations are things for which you need huge machines, powerful machines. Three-dimensional turbulence is actually four-dimensional because of time. And because you need to resolve very fine scales and very large scales at the same time, the computational problem is enormously difficult. At the same time, I think the development of diagnostics will help us measure things in much more detail and so our ability to make models of processes in nature will increase enormously. GALCIT is the place where this is going to happen."

interesting idea, but like many new ideas, it's not really clear how well this is going to work. So we are carrying out very basic research on several aspects of this concept so that we can give them some guidance. Should they be spending millions of dollars on this? We are doing the same thing for our government. We are working with the Office of Naval Research to determine if PDEs are something we should be investing the R&D budget of the country in. Should more funding and effort be directed here? We have a large number of students working on this and quite a number of publications related to this area in the last 5 years.

Shepherd and his students have been active in many areas concerned with explosions and detonations, and much of their work has centered on hazard mitigation. Shepherd's investigations were instrumental in determining the cause of the TWA800 explosion. Lesser known, however, is his work on improved safety of nuclear waste facilities.

**J. Shepherd:** One of the projects that initially funded my



laboratory was an interest in understanding the hazards in a nuclear waste storage facility in Hanford, Washington. Up in Hanford they have several hundred tanks that are each full of millions of gallons of toxic and radioactive waste. And it is sitting there cooking, chemically reacting. You can have releases of flammable gas, and there are mechanisms for ignition, so you can have explosions inside those tanks, which are partially full. And so one of the things we've studied is: what are the detonation and combustion properties of these gases? And then I do things like testify in front of committees about what we think the properties of these gases are. Is this something that should be of the greatest concern? Where does this rank? You have many, many types of concerns in these types of facilities. What about leakage of radioactive material into the ground?

You are also worried about contamination of workers, long-term waste storage, explosions, and so on.

There is a long list of issues that you have to evaluate, and we provide some input into that. We try to provide *scientific* input. Our goal is to give them data, and to analyze that data and apply it to their situation. The consequences of our experimentation are far-reaching.

The people in GALCIT are constantly inventing new gadgets. Measurement devices, shock tubes, image-capturing systems, the list is endless. The precision is daunting.

## Joseph Shepherd (PhD '81)

### Professor of Aeronautics

*Professor Shepherd's research interests are in combustion, explosions, and shock waves with a particular interest in basic processes in flames and detonations with application to evaluating explosion hazards.*

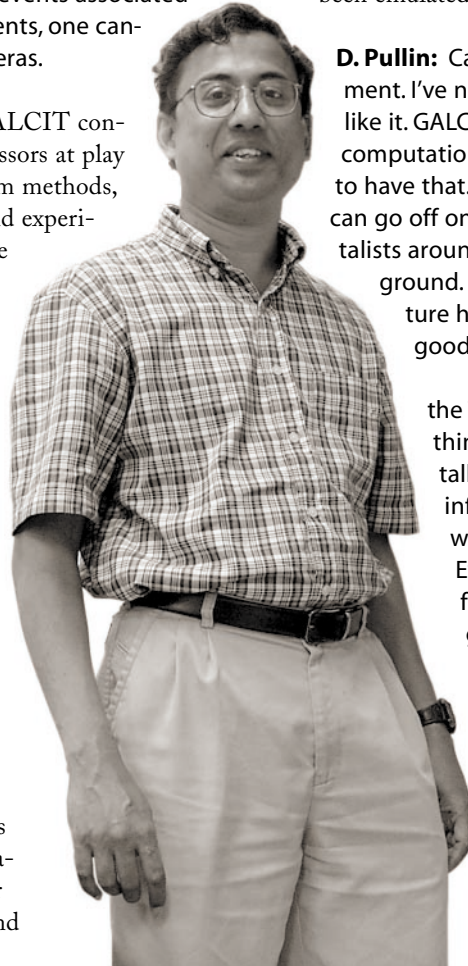
The experiments we do are a kind of magic act in glass, steel, and electricity. We spend weeks, months, sometimes years building these facilities so that we can have a few millionths of a second where we can very precisely control the conditions and then take an image. Then, to really understand that, we have to do it over and over again with different substances, probing the flow, and looking at it in different ways. It is a very special kind of experimentation; you can never sit and watch the flow like you can in the low-speed water channel and say "Oh, look, there's a vortex." The only way you can see anything is to use this very elaborate instrumentation. Everything has to be done in just the right order and a precise sequence of events takes place. You do that just right, and bang—you get this beautiful picture of the flow. And now you have learned something about how nature works. And that's really what we're after.

I came to Caltech as a graduate student because I was in love with physics, and everyone knew Caltech was the best place to do that. Almost by accident I wound up studying fluid mechanics under Brad Sturtevant—and have been doing it ever since. When I was offered the chance to come back as a faculty member in 1993, I jumped at it because I knew first-hand the research environment in GALCIT and how great the students are.



**G. Ravichandran:** One of the things we do is develop new, one-of-a-kind instruments. Recently we developed a camera that takes thermal pictures at a million frames per second. The need was related to basic experiments that we were doing to understand failure under dynamic conditions. That is, where the cracks or the shear failures propagated at very high speeds, on the order of one to several kilometers per second. In order to visualize the thermal events associated with those dynamic failure events, one cannot use ordinary thermal cameras.

The breadth of the work in GALCIT continues to expand, and the professors at play are inventing on all fronts: from methods, to tools, algorithms, devices, and experiments. They are active in all the areas that the Division of Engineering and Applied Science has identified as core intellectual thrusts for the next decade: computational science and engineering, nanotechnology, global environmental science, bioengineering, and information science and technology.



**T**he GALCIT tradition of bringing together the best theoreticians and experimentalists, and then letting them fly in their own directions of discovery has both left a legacy and created a playground for future players that is hard to find

anywhere else in the world. GALCIT, like its sister departments in the Division of Engineering and Applied Science, strives to do a few things extraordinarily well, attracts the very best people in each chosen area, and provides them with an unparalleled environment for research. This has led to GALCIT having a visible impact out of proportion to its size, the best faculty, the best students, and a unique approach that has been emulated by others.

**D. Pullin:** Caltech is an unmatched research environment. I've never seen, never come across, anything like it. GALCIT has a nice balance of experimentalists, computationalists, and theoreticians. You really have to have that. A group of theoreticians, by themselves, can go off on a tangent, for years. Having experimentalists around helps you keep your feet on the ground. And of course, the intellectual temperature here is very high. The students are very good, so good they keep us on our toes.

Perhaps the best feature of the group is the Tuesday Research Conference. It's something we all contribute to, and it keeps us talking. It is intended to be a relatively informal forum for presenting unfinished work and ideas about future work. Everyone attends: students, post-docs, faculty, and visitors. And because we are generalists, we can all respond to each other's interests. That contributes to the unique environment here. It really *makes* the environment. There is a community, a very stimulating one at that.

**G. Ravichandran:** When I first came to GALCIT, it was a new culture for me. What particularly struck me was the camaraderie between students and

## Guruswami Ravichandran

### Professor of Aeronautics and Mechanical Engineering

*Professor Ravichandran's research interests are in mechanics of materials, dynamic deformation and failure, wave propagation, micro mechanics, composite and active materials, and experimental mechanics.*

GALCIT is a very special place, especially for the experimental side of things. This is one of the few places in the world where the experimental sciences are very strongly supported and encouraged. This is because of the historic precedents of how the wind tunnels were developed and how they supported the aerospace industry during the time of von Kármán; they were always doing large-scale experiments and really using experiments to understand the physical world around them, first in the aeronautical sciences, and later on evolving into mechanics. That provided a culture that has been built on for 75 years. This has brought forth a certain energy, a synergy to encourage experimental work, and colleagues who appreciate experimental work. And there is also close interaction with colleagues who do simulation and modeling. This is really a singular place where the experimental sciences are thriving.

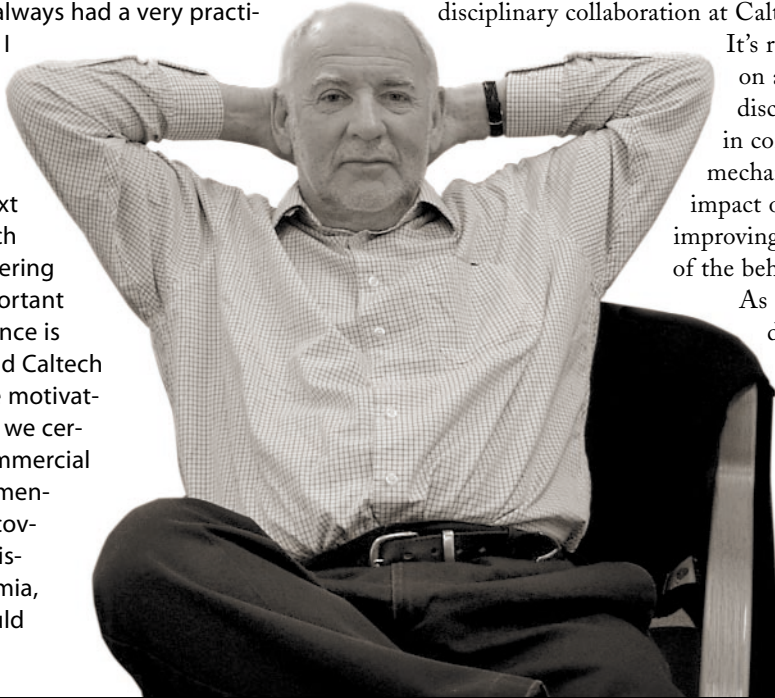
# experimental

# m

the people here, the family atmosphere. People got along and people seemed to know everything about each other's research. Ideas were flowing freely. People were not operating in an isolated manner. And what I found particularly interesting was that it was very easy to interact with people from other parts of campus. It still is.

**F. Culick:** I've been here a long time. I am probably the only one still here who knew both Millikan and von Kármán. The outstanding thing from the very beginning has been the quality of the students and the quality of the faculty. It's important to realize that the entire faculty is good, not just two or three. That's always been important for GALCIT.

The other crucial element is the relation between the research we do and its application. While my work in particular has always had a very practical bent—at one point I was consulting to all the rocket companies simultaneously—it is always done in the atmosphere and context of fundamental research and science, or “engineering science.” This is an important point. Engineering science is really where GALCIT and Caltech excel. The work may be motivated by applications, but we certainly are not like a commercial lab. Without the fundamental science that we discover, develop, and then disseminate out of academia, engineering *per se* would not go far.



**W. Knauss:** One of Caltech's—and GALCIT's—strengths is the high caliber of its students. While my colleagues don't necessarily and uniformly want to admit it, Caltech wouldn't be so excellent if we did not have this pool of outstanding students. We can do a much greater volume of high quality work here because we need to spend relatively little time with detailed guidance of graduate students. There is also a closeness, a camaraderie among the students and advisor which derives, in good part, from the fact that we are small and that makes GALCIT unique.

Embedded as it is in another unique institution, the California Institute of Technology, GALCIT benefits from collaborations with other academic disciplines.

Professor Ortiz puts it quite clearly: “The fact of interdisciplinary collaboration at Caltech is not just ‘talk.’

It's really true. We work on a daily basis across disciplines.” Ortiz works in computational solid mechanics. The direct impact of his work is improving our understanding of the behavior of materials.

As a necessary intermediate goal, he is improving methods in computational mechanics and computational science in general. His algorithms, for instance, seek to make more efficient uses of computers. His efforts

## Dale Pullin

### Professor of Aeronautics

*Professor Pullin's research interests are in computational and theoretical fluid mechanics, vortex dynamics, compressible flow and shock dynamics, turbulence, and large-eddy simulation of turbulent flows.*

I was actually an applicant to GALCIT—I was accepted as a student at GALCIT many years ago—I've still got the letter. But I didn't come—I went to England instead. I don't know why I went to England. L.A. had very bad press, of course, still does—remember this was in 1971, before the Internet. Much later, as a professor, I came here to visit for six months on a sabbatical. And it turned out GALCIT had a vacancy, and they wanted someone who was interested in both theory and computation. Often people do one and not the other. And L.A. was not as bad as I thought it was; it was actually quite interesting. And indeed, I always like to reinvent my life every 10 years, so an opportunity comes, you take a risk. I thought, why not? I've been here 12 years now. When you get to my age... well, let's not get into that yet.... In any case, I quickly found a superb research environment here at Caltech.

ode

in this regard have made some impact on mathematics, and with respect to his collaborators in this area he mentions, “We shouldn’t forget, I’m a

real fan of mathematics. I think it’s the grease that makes everything possible. So we interact very closely with card-carrying, hard-core mathematicians.”

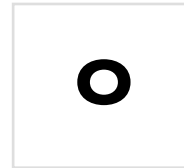
The collaborations between GALCIT and various groups on campus are varied and endless. Another to note is that between Professor Ravichandran and his newest partners.

**G. Ravichandran:** Most recently, in collaboration with my colleagues in Mechanical Engineering, Applied Physics, and Materials Science, I have been working on *active* materials. Active materials are materials that respond to external electro/magneto mechanical or thermal mechanical loads and they can change shape. So they can be used for active control of structures. For example, for a helicopter blade, you want to deform the surface during flight to adapt to the aerodynamic conditions. This is really a dream—but I believe it will happen. So we study material behavior for actuators for novel applications.

We apply an electrical voltage on a ferroelectric material, and at the same time we subject it to mechanical loading via stress. This causes the material to change shape; as it generates strain, it is doing work against the stress, and you have work output, so it can be an active device. When we take off the voltage the

material deforms again due to the stress and you can have a cycling actuator. There is a broad range of applications one can envision. It can be used in adaptive optics for use in astronomy, and so on. My role in this project is to demonstrate the principles in such an active device.

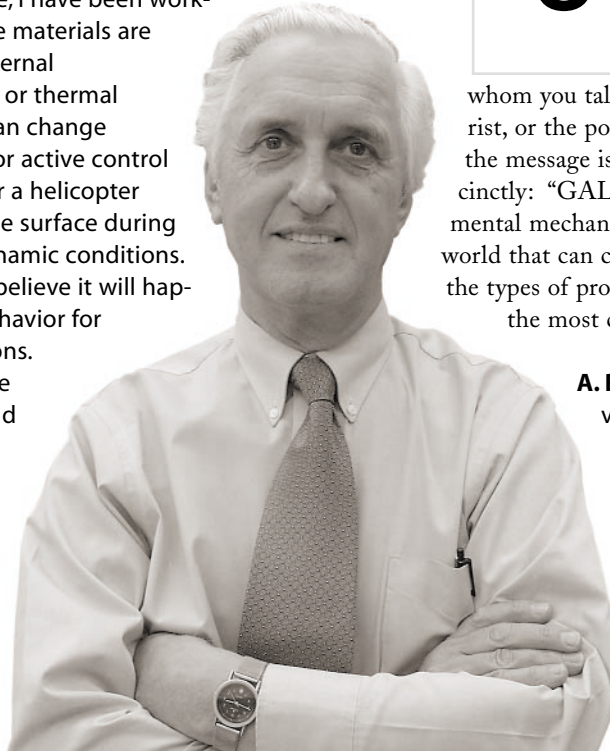
The interactions are not limited to projects between faculty members. As Professor Leonard explains, “If a student in another department happens to be interested in what you are doing, there are no barriers at all. I had a PhD student in physics; several in mechanical engineering, and one in applied mathematics. It’s great!”



ne of the particularly unique aspects of GALCIT is its strong experimental mode. No matter

whom you talk to in GALCIT, a pure theorist, or the pointedly experimental types, the message is the same. Gharib puts it succinctly: “GALCIT is the mecca of experimental mechanics. There is no place in the world that can come close. The quality and the types of problems we investigate are at the most challenging frontiers.”

**A. Rosakis:** At GALCIT, we are very proud of our experimental facilities. They are unique, and they are extensive. We have managed to keep them in an era where computation is taking over the world. And although the development of computer facilities is an excellent thing, in certain cases this has been at the



## Wolfgang Knauss (BS '58, MS '59, PhD '63)

### Theodore von Kármán Professor of Aeronautics and Applied Mechanics

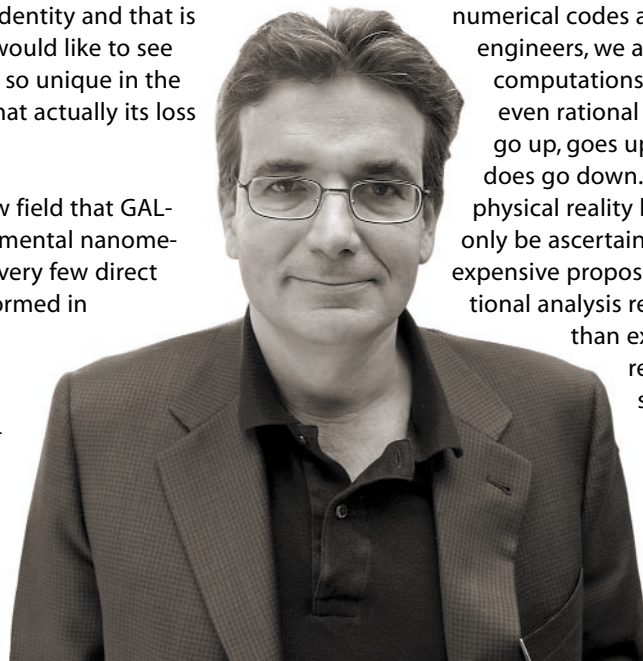
*Professor Knauss's research interests are centered in solid mechanics.*

In the early 1980s, I became aware of the need to pursue materials issues at smaller and smaller size scales. It was extremely hard then to convince people of the need for this field—the phrase “nanomechanics” was to appear a decade later. I was very lucky to get \$30,000 from the National Science Foundation to build, over a two years’ time span, a Scanning Tunneling Microscope to study deformations at the nanoscale. And today this kind of research is just the accepted thing. Colleagues fight for the millions in research funds in this area. But this kind of situation has always been a problem if you pursue a view of what’s going to be needed in the future: if you’re too early, support is tough to attract. However, Caltech has been an excellent place because it fosters reaching one’s potential. If you do things well and honestly, no one interferes.



expense of the observation of reality. Computational analysts like my colleagues Michael Ortiz and Tony Leonard are developing very advanced codes that are capable of doing things that are unprecedented. However, as they would admit themselves, they are not observing reality. So advanced experimental techniques that have high fidelity and use high-resolution diagnostics are absolutely necessary. It is true that in mechanics, both in solids and fluids, the trend is to go towards theory and computation, rather than experiments, because experiments are expensive. It is a simple explanation. They are difficult, dirty, and expensive. However, at GALCIT, we have managed to preserve our experimental identity and that is one of the things that I would like to see continue. Our position is so unique in the country and the world that actually its loss would be a great crime.

**W. Knauss:** A totally new field that GALCIT is exploring is experimental nanomechanics. There are really very few direct experiments being performed in the nano range. Instead, everything is done by inference from what is measured on a considerably larger scale, and to deduce properties or behavior with the aid of those inferences, assumptions are a necessary evil. It has always



seemed terribly dangerous to make these assumptions and then apply the results without the direct experimentation background.

Let me cite a recent experience as an example. One of my students performed measurements of the (frequency dependent) volumetric compliance of a polymer. This deformation process was then simulated via a molecular dynamical computational model. Upon comparing experiment with the computations, the two differed very significantly—they were in the ballpark, but not close enough even for rough engineering purposes. Where GALCIT excels is in supplying *both* experiments and computational capability to fine-tune

numerical codes and make them accurate. As engineers, we are often asked to put faith in computations because they all *look* fine or even rational in the sense that what has to go up, goes up and what should go down, does go down. But how *close* we come to physical reality by computational means can only be ascertained via experiment. This is an expensive proposition, and because computational analysis renders “results” more quickly than experiments, the trend in

research—and funding—is on a seemingly unstable slope towards computation. My biggest worry is that the experimentalists are beginning to disappear in solid mechanics. If GALCIT has a mission it is the perpetuation of the proven syner-

## Ares Rosakis

### Professor of Aeronautics and Mechanical Engineering

*Professor Rosakis's research interests are in the mechanics of solids, dynamic failure, impact mechanics, and the reliability of microelectronic components.*

These days, in addition to aeronautics, we have space applications, which are traditional to aeronautics, but we also have the micro and the nano worlds, which are full of solid mechanics and microfluidics problems, and then we have geophysics. In my own research, I started with the engineering scale, went to the large scale with geophysical research, and recently I have been working with very small length scales, in particular microelectronic components such as thin-film structures on flat substrates, interconnects, and optoelectronics—basically things that are baked on a wafer. These become microchips in your computer. We are concerned with how small we can make these components. It turns out there is a physical limit which is dictated not by the electronic performance, but by the strength of the thin-film materials.

Through the years I have investigated materials on many orders of magnitude: from microns to hundreds of kilometers. This really reflects the philosophy of GALCIT. Mechanics—whether its fluid mechanics, solid mechanics—is continuum mechanics. There are very powerful tools that we work with at all of these length scales. One of the biggest strengths of GALCIT both in the research and in the teaching of graduate students has been to lay down the fundamentals in mechanics. And it does not matter what the application is. The application could be aeronautical, it could be space, it could be geophysical, it could be everyday engineering, it could be microelectronics. But really the fundamental principles are the same.

gisms of experiment and analysis in both solid and fluid mechanics. As a final reminder in this context it needs to be remembered that new physical phenomena are only found in the laboratory.

**G. Ravichandran:** I am an experimentalist—sometimes I do computations, but I am primarily interested in experiments. I always liked to build things and see things work. I am interested in physical phenomena rather than doing things on the computer or with paper and pencil. I am a hands-on person and that's what fascinates me. As part of our ferroelectrics work, we have experimentally validated a theoretical prediction. Kaushik Bhattacharya [Professor of Mechanics and Materials Science] first made the prediction of how to achieve large strain in these materials. But his was a thought experiment, on paper. One has to understand what are the principles behind the concept, and whether one can even make this idea work. What can be imagined is not always possible to implement. So we are doing a reality check on these thought experiments. That is one role of the experimentalist. The other role is to discover new phenomenon that have not yet been predicted by theory. The theory then catches up. This doesn't happen often, but there are quite a few examples. It's a very important part of the mix.

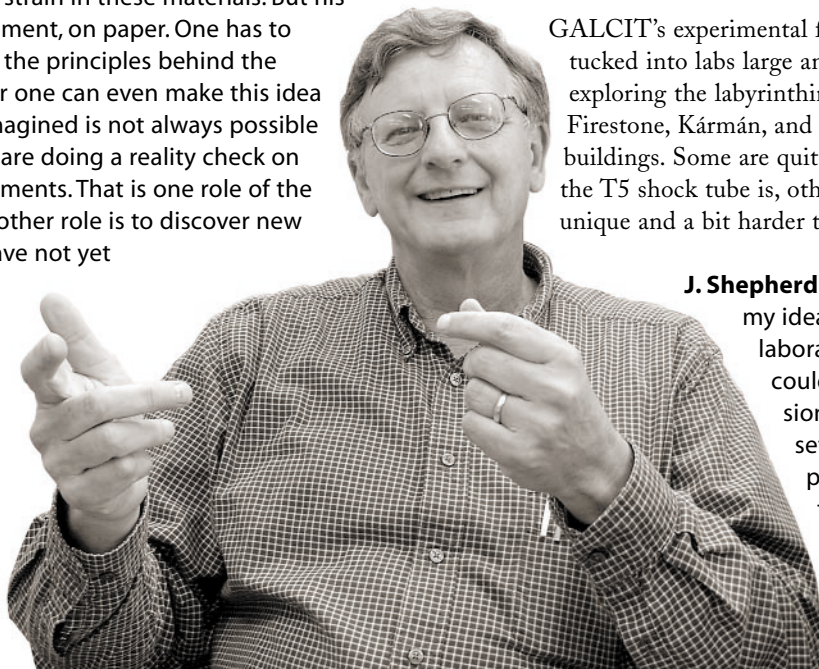
Very striking is that the thing which is

most attractive to the theorists is this practical, “down and dirty” work at which GALCIT excels.

**A. Leonard:** GALCIT is very strong experimentally. That is what makes it great. And that's one thing I think that we all agree on; even the computational people agree that we have to keep this going. In today's climate it's hard to do that, but we've got to, we can't just follow the crowd. The experiments that [Professor Emeritus] Don Coles was doing in the 1970s were the things that really attracted me to this place. He was doing experiments on turbulent spots in laminar boundary layers. They were really neat experiments, and I just happened to be trying to compute these same things at the time.

GALCIT's experimental facilities are tucked into labs large and small, found by exploring the labyrinthine corridors of the Firestone, Kármán, and Guggenheim buildings. Some are quite well known, as the T5 shock tube is, others are absolutely unique and a bit harder to find.

**J. Shepherd:** When I came, my idea was to set up a laboratory where we could study explosions in a university setting. There are people who do that around the world, but it's a fairly unique activity. Most people view



## Anthony Leonard (BS '59)

### Theodore von Kármán Professor of Aeronautics

*Professor Leonard's research interests are centered in computational fluid dynamics.*

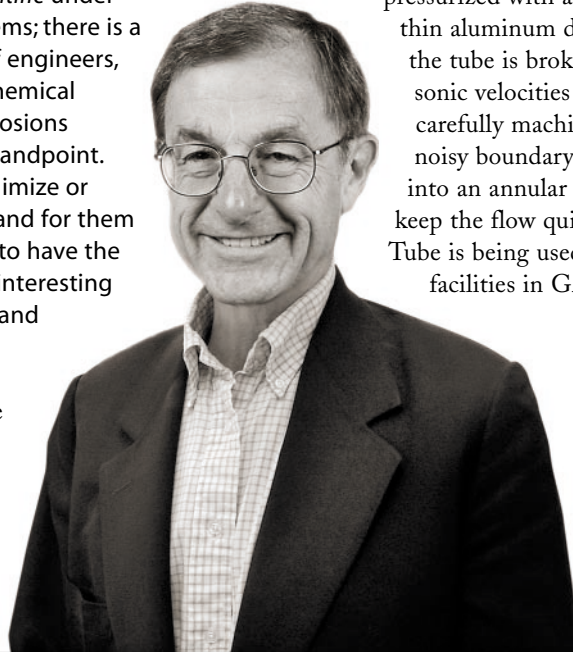
I was an undergrad here from '55 to '59 in mechanical engineering. I didn't get to know too many of the GALCIT people. I remember being sort of happy to leave, because it was really a tough four years. But then I think after awhile you start to remember the good things. So I always had a good feeling, definitely a good feeling, about Caltech. Then I went into nuclear engineering as a grad student. I worked in this field for 10 or 12 years, including being an assistant professor at Stanford. But nuclear engineering went downhill in the early '70s. However, I had started getting more and more interested in fluid mechanics and managed to land a senior post-doc position at NASA's Ames Research Center. This was really a terrific job for me. And then an interesting thing happened at Ames. They had a fairly new director, Hans Mark, who wanted to move into an essentially untouched area: computational fluid mechanics. This allowed me to really develop this new interest of mine in depth. I don't know the exact history because I wasn't here, but GALCIT decided they wanted somebody in computational fluid mechanics. They didn't have anybody; it was just too new. I came down to campus as a visiting professor in '83, and I came back in '85, full time. So it was a perfect match. The whole deal just fell into place. It was very serendipitous. It was an unusual path back to Caltech.

explosions as something that is hazardous and they are a little reluctant to think about setting up a lab inside a building. We built this lab in order to look at problems that are both of scientific interest, and of interest to industry. We have to pay the bills. So we have always looked to practical problems—crashing

# people

airplanes, explosions in chemical plants, hazards inside of nuclear waste storage facilities. The goal, though, is to have a *scientific* understanding of these problems; there is a very large community of engineers, including those in the chemical industry, who study explosions from a very pragmatic standpoint. They simply want to minimize or eliminate the problems and for them what's interesting is *not* to have the explosion; for us, what's interesting is to have the explosion and study it.

New to GALCIT are the Lucas Adaptive Wall Wind Tunnel (AWT) and the Ludwig Tube. The Lucas AWT was made possible by a generous gift from the Richard M. Lucas



Foundation. It uses adaptive wall technology in the test section to reduce and even eliminate the need for data corrections required in straight-wall tunnel tests. While the tunnel is operating, pressure measurements are taken along the floor and ceiling of the test section; combined with the current displacement profiles, a one-step predictive algorithm determines the required wall contour for the current model configuration and adapts the walls to match. The system effectively “tricks” the air into thinking it is in an infinite flowfield, rather than confined by the walls of the tunnel.

The Ludwig Tube is a Mach 2.3 facility that provides clean supersonic flow with relative ease and low cost. It is ideal for universities as it allows students the possibility to do experimental work at supersonic regimes without a complex facility to support. The device is the ultimate in simplicity, consisting of a tube pressurized with air and an evacuated tank. When the thin aluminum diaphragm separating the tank from the tube is broken, the flow is accelerated to supersonic velocities for about one-half second inside the carefully machined nozzle at the end of the tube. The noisy boundary layer on the tube walls is diverted into an annular slot at the end of the tube in order to keep the flow quiet inside the nozzle. The Ludwig Tube is being used not only for teaching, but like many facilities in GALCIT, as a research tool as well.

**T**he most important product that GALCIT has produced, however, is its people. Approximately 2,000 people have graduate degrees from GALCIT, and they have gone forth to all parts of the world to make their mark. The

## Fred E. C. Culick

**Richard L. and Dorothy M. Hayman Professor of Mechanical Engineering and Professor of Jet Propulsion**

*Professor Culick's principal research interests are in combustion, active control of combustion dynamics, nonlinear acoustics, and propulsion.*

In 1980 I started working in applied aerodynamics: teaching courses, doing a lot of historical research, and starting out on a project that is just now in its finishing stages. It really goes back to a day in 1977 when I took a boys' ice hockey team down to San Diego for a pair of games. In between the morning and the afternoon games, I visited the San Diego Aerospace Museum to see the *Spirit of St. Louis*, the plane Lindbergh flew solo, non-stop across the Atlantic. When I was there, I saw a replica of the 1903 Wright *Flyer*, and had an epiphany of sorts. My adventures into finding out just why that airplane looks the way it looks—it's highly unstable, and in fact what I think helped the Wright brothers the most is that they didn't know just how dangerous it was—have taken me on a ride that has lasted two decades. In that time I built a 1/6 scale model of the 1903 *Flyer* which was tested in the GALCIT 10-foot wind tunnel, and have been involved in building two full-scale replicas in conjunction with AIAA projects, one of which I hope to fly before the end of this year. I have found it a fascinating endeavor to explain an historical object with current theoretical understanding and experimental techniques. This research niche—applying modern understanding to the behavior of older airplanes—has been very enjoyable.



Brazilian, Indian, and Chinese space programs all began with significant leadership by GALCIT graduates. You will find many GALCIT graduates as professors in universities across the U.S. and throughout the world, as well as in the top echelons of government labs and industry.

**P. Dimotakis:** And if you ask me what is different about GALCIT, I would say it is this philosophy that what we strive to impart to the students is a very fundamental and a very broad-based understanding in mathematics and physics, as well as engineering principles and fluid mechanics and solid mechanics, and so on. There is a continuum of types of knowledge one needs so that one is productive not only at the time one graduates, but also 10, 20 years later. That is a very sobering thought. In case it is difficult to imagine 20 years out, I invite students to think back 20 or 30 years and to imagine that they had graduated then, and now they are called upon to contribute to bioengineering, to space physics, to high-energy lasers, to failure analysis—you name it. Would they have received the tools and educational background to make such contributions? Did they receive them then, and are they receiving them now? Well, GALCIT graduates did. The testimony to that is that if you look at many of the new technologies and many of the new thrusts in science and engineering that were initiated in the last 10 to 20 years, many of them have GALCIT graduates behind them. The development of the chemical laser, for instance. And, in some measure, GALCIT graduates contributed to the development of inertial-confinement fusion and laser fusion. These could well be the power sources of 50 years from now. Many of the challenges and limitations in how well one can hope to convert hydrogen and deuterium into helium and energy have to do with shockwaves and gasdynamics. The compression takes place by a converging shock that is driven by umpteen lasers ablating an outer shell. Not many people understood the gasdynamics of how to do that—but GALCIT graduates helped do that. You will find GALCIT graduates doing all kinds of things. Some of them are in the aerospace world, but probably not the majority.

**A**

nd so GALCIT is poised for the next 75 years, balanced on long-standing organizing principles and unbounded imagination.

**F. Culick:** My thesis supervisor at MIT had been a GALCIT student for a while, and he eventually earned his PhD elsewhere with H.S. Tsien [PhD '39]. So my connec-

tion with GALCIT in this respect stretches way back. When I arrived in the early 1960s, most of the then current faculty had been here a long time and constituted really the first generation of GALCIT. I have seen all the incarnations of GALCIT over the decades. In some respects, the place is still the same, still guided by the same aspirations and goals it was founded with. But we are suffering from the same problem most universities are suffering from these days—we are more and more buffeted by external influences, and this usually comes down to funding. Time spent raising money detracts from cultivating the closeness that we have always treasured.

**G. Ravichandran:** GALCIT has adapted in a unique way to the current and future universe of ideas in the sense that for 75 years it has evolved. You cannot be stationary and be successful. We have adapted to new ideas and generated new ideas. We also look into the

future

future and reach out. This is what keeps the place alive. This has been brought about by a culture based on fundamental science with an eye toward practical applications.

**P. Dimotakis:** The philosophy of von Kármán, still embraced today, guides us. If you want something that is lasting, that will be at the forefront 20 years from now: don't train people, educate them. There is a difference there that is not so subtle. This is what sets GALCIT apart.

It's important to capture people's imagination. It's important to work and contribute to frontier areas, because those capture the imagination of young people and ultimately that is what it's all about. ■ ■ ■

---

*The GALCIT 75 Anniversary Celebration will be held on November 14 – 15, 2003.*

For more information please see [www.galcit.caltech.edu/galcit75](http://www.galcit.caltech.edu/galcit75)

## Noel R. Corngold: Many Many-Body Interactions

by Paul M. Bellan

**N**

oel Corngold was born in Brooklyn in 1929, grew up there, and fully expected that his career would be entirely on the East coast. He went to Columbia for his bachelor's degree, and then ventured, in what at the time seemed far afield, to Harvard for his PhD. California was definitely not on his mind. When he was in high school, it seemed that Noel was destined to be a chemist and like many of his generation he played around with sulfuric acid and mixed various concoctions in test tubes in his family kitchen (when his parents were out of the house, of course).

However, while taking some courses after high school at the equivalent of a junior college, he asked his chemistry teacher so many questions about what the electrons were really doing that the teacher said "If you keep asking questions like that, you go across there to the physics department and you ask them." Which is precisely what Noel did.

Much to the surprise of those who would meet Noel later and know him as a theorist, Noel did an experimental PhD. Harvard sent him to Brookhaven National Laboratory where he helped to measure the magnetic moment of the neutron. The measurement was a great success, much more accurate than the competition, but Noel decided at that time that he would rather fight equations that don't want to be solved rather than equipment that does not want to work.

After his PhD, Noel worked at Brookhaven Laboratory with a small group of theoretical and experimental physicists, concentrating on neutron physics. This was a golden era that resulted in many important publications and the start of many influential careers in nuclear reactor physics. Noel became an expert on the physics of large numbers of neutrons in reactors and during that time wrote several seminal papers on this topic.

Noel pulled up stakes in 1966 and came to Caltech to work on nuclear engineering. This period was the peak of optimism about nuclear power, a heyday where everyone believed that nuclear power would be too cheap to meter, even that every family would have a nuclear-powered automobile.

Caltech's nuclear engineering program, though short-lived, attracted superb students; several went on to become prizewinners

and distinguished alumni. But the national mania for nuclear engineering waned in the 1970s and Noel turned his attention to other situations where he could apply his expertise on the complex dynamics of large numbers of interacting particles. Plasma physics is just such a field and in the late 1970s, Professor Roy Gould [BS '49, PhD '56] was just building a small tokamak at Caltech (a tokamak is a device with a toroidal magnetic field configuration which is very good at confining hot plasma). The new ideas of chaotic mechanics were beginning at that time and Noel, together with a student, took one sample of noise from the tokamak and, by doing what was extreme number crunching for the time, managed to assign a fractal dimension to the tokamak turbulence. More recently, Noel has explored some of the peculiar theoretical features of the pure electron plasmas produced in another experimental device constructed by Gould.

Although neutron physics is only one of Noel's interests these days, the nuclear engineering community is still very appreciative of his work and this year the American Nuclear Society awarded Noel its Eugene P. Wigner Reactor Physics Award for his pioneering theoretical work on how neutrons behave in reactors. His nuclear colleagues also recently published a special issue of the journal *Progress in Nuclear Energy* titled "A Collection of Papers to

Commemorate the 70th Birthday of Professor Noel Corngold."

Noel has served on too many Caltech committees to remember (being a member of the boards of the Athenaeum and of the ill-fated Baxter Art Gallery were particularly entertaining), and presided as the unofficial administrative head of the Applied Physics Option for fifteen years, all the while keeping in good cheer. Noel has taught many courses over the years and in particular, introduced more than a generation of graduate students to the intricacies of thermodynamics and statistical mechanics. On a personal note, Noel is a great believer in the virtues of the bicycle and most often comes to his office via that means of transportation, all decked out in bicycle regalia. Noel has become both an expert on wine, and more than a slight art maven via the influence of his wife, Cynthia, who is an artist and art therapist.

Noel asserts that he will never retire, hoping always that one more "nice problem" lies ahead to be grappled with. The only possible diversion is the new—and—unique grandson, 18-month-old Wally who, Cynthia agrees, is both "handsome and brilliant." 📷 📷 📷

---

*The author, Paul Bellan, is Professor of Applied Physics at Caltech.*

There is more on Professor Noel Corngold at [www.aph.caltech.edu/people](http://www.aph.caltech.edu/people)



## Control and Dynamical Systems: From Cellular Systems to Gravitational Systems, and Almost Everything in Between

At its simplest, *control* is achieved when a sensed quantity is used to modify the behavior of a system, as one does in everyday life, such as driving a car and walking. In technology, control is often achieved through computation and actuation, as in automotive controls or controlling a spacecraft. More formally, control makes use of algorithms and feedback in engineered systems, and is a means of ensuring robustness in an uncertain environment. *Dynamical systems* refers to the way systems change over time, such as the movement of your car, the dynamics of walking, or the dynamics of a molecule or of the solar system. More formally, it is the study of processes described by evolutionary equations such as ordinary and partial differential equations. The rigorous bringing together of these ideas and concepts, including their applications as well as the needed mathematics resulted in the birth of the Control and Dynamical Systems Option at Caltech in 1993.

**T**

he original vision was to take advantage of the emerging important areas of nonlinear control systems, dynamical systems, and their essential interactions. This has proven to be extremely viable, and the Option remains at the cutting edge of its domain. It has positioned itself as a key player in the development of the theory, computation, and application of complex systems, dynamical systems, and control, focusing on fundamental theory. One of its unique features is its extensive scientific interaction with many other options at Caltech, such as Applied and Computational Mathematics, Biology, Bioengineering, Computer Science, Computation and Neural Systems, Environmental Science and Engineering, Mechanical Engineering, Electrical Engineering, Aeronautics, Mathematics, Physics, and Chemistry.

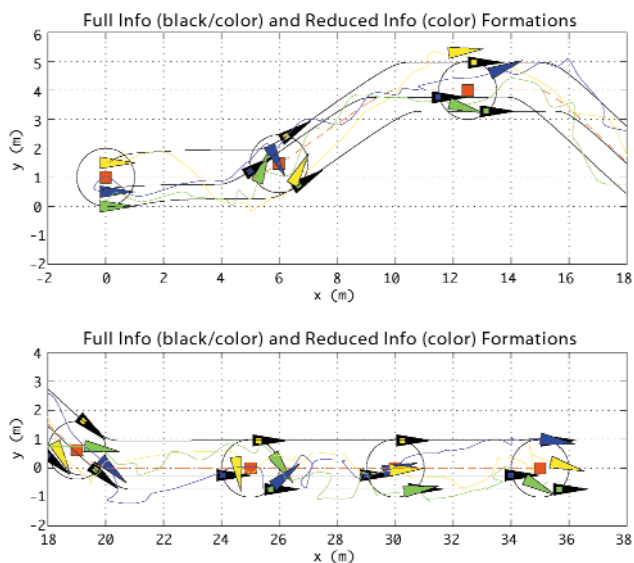
The core faculty members—John Doyle, Hideo Mabuchi, Jerrold Marsden, Richard

Murray—are joined by Senior Research Associate Doug MacMartin to form the CDS Faculty. These are joined by affiliated faculty members Joel Burdick (ME), Fred Culick (GALCIT and ME), Babak Hassibi (EE), Steven Low (CS and EE), Pietro Perona (EE), Thanos Siapas (CNS), Tapio Schneider (ESE), and Michael Dickinson (BE), and by a steady flux of visiting scholars from universities worldwide. Altogether, the group has turned CDS into an extremely sought-after graduate program. In fact, the number of graduate students *accepting* offers of admission, 67%, is one of the highest in the Division.

*The research problems presently occupying the faculty span an enormous intellectual landscape. To wit:*

In the area of biology, a fundamental question that remains to be answered is how do individual molecular mechanisms together with network interconnection create robust behavior from uncertain

components in an uncertain environment? The transition from organisms as genes, to organisms as networks of integrated chemical, electrical, fluid, and structural elements is of course an enormous challenge, but it parallels similar evolution of plans for more integrated engineering networks. Both motivate the development of theories of uncertainty management for complex, interconnected, multiscale systems. The focus of John Doyle, Professor of Control and Dynamical Systems, Electrical Engineering, and Bioengineering, is on complex biological and engineering networks, particularly the interplay between complexity and system fragility/robustness. He has begun to discover “fragility conservation laws” that could eventually be as important in complex networks as mass/energy conservation laws have been to traditional science and engineering. His research shows that biological complexity is dominated by the evolution of mechanisms to more finely tune the tradeoff between robustness and



Interest in stabilizing and maneuvering a formation of multiple vehicles has grown in recent years. Applications include grid search by coordinating robots, surveillance using multiple unmanned air or ground vehicles, and synthetic aperture imaging with clusters of micro-satellites. Murray and his colleagues have come up with new approaches that cast the mathematical problems that must be solved to into *global* optimization problems rather than local optimization problems for each individual vehicle. This leads to improved behavior as shown above. The global model (full info) is represented by the trajectories of the black vehicles. The local model (reduced info) is represented by the trajectories of the colored vehicles. Notice the colored vehicles intersect at times; this corresponds to collision in real implementations.

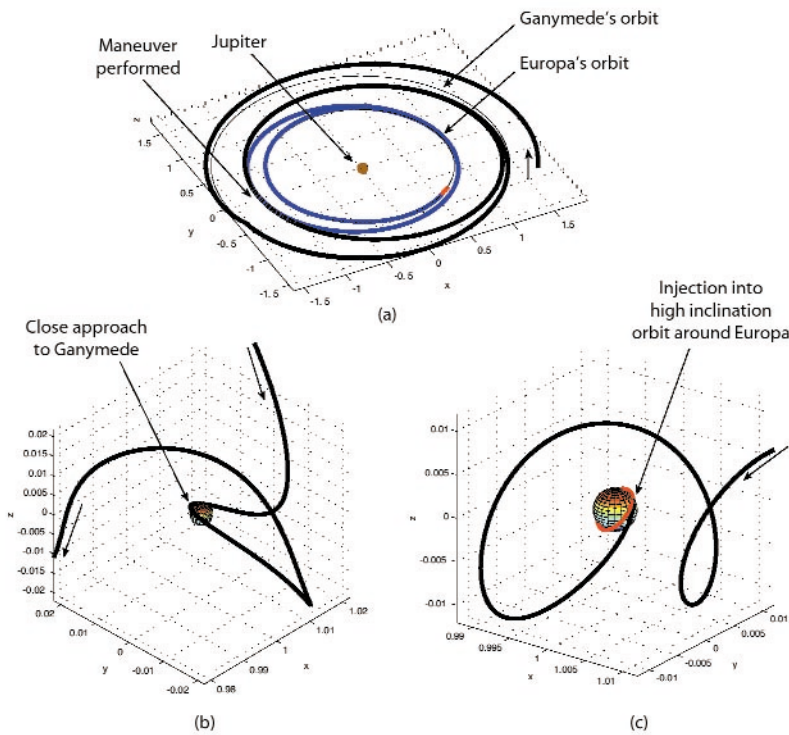
fragility. The systems he studies are often biological: the heat-shock response, metabolic pathways, biological signal transduction, but also include collaborations with Steven Low on internet protocols. The mathematical tools necessary for this work are diverse and include operator theory, real algebraic geometry, computational complexity theory, and semi-definite programming. Long term, this work may have medical implications in many areas, including for example multi-organ failure in intensive care

and antibiotic therapies that could exploit network-level fragilities. It has already contributed to the FAST methods for designing new internet protocols that are currently being tested and deployed (see Research Note, page 10).

Hideo Mabuchi (PhD '98), Associate Professor of Physics and Control and Dynamical Systems, recently joined CDS (his first home is in the Physics department), as it has become clear that in quantum networks and quantum information technology, robustness, quantum

interconnection, and feedback are key issues. Quantum technologies could be powerful, but are profoundly sensitive to errors and noise. It has been in control theory that robustness and related topics have seen the most significant developments, which is why it makes perfect sense for a quantum physicist to join the CDS encampment. He is also working with Doyle on new theoretical methods for treating systems far from thermodynamic equilibrium, particularly when this is regulated and maintained by complex feedback systems.

Another view of many of the same questions centers around problems with many scales. Multi-scale phenomena occur throughout science and technology: from fluid dynamics, where resolving small-scale motions can be a crucial computational bottleneck, to materials science, where small defects or phase changes can affect large scales, to biology, where phenomena on the molecular level and the microsecond time scales affect those on cellular and second scales. To work on these types of problems, Jerrold Marsden, Carl F Braun Professor of Engineering and Control and Dynamical Systems, has recently driven the formation of CIMMS, the Center for Integrative Multiscale Modeling and Simulation. The researchers under the CIMMS umbrella are working on problems that will have application in diverse areas: the Internet, power networks, and acoustic and elastic wave scattering from multiscale heterogeneities. In these and many other areas, a multiresolution infrastruc-



Marsden works with a CDS/JPL team to develop the technique of *low energy inter-moon transfer via resonant gravity assists*. This concept could be exploited for very long, multi-moon exploration missions. Such exploration may allow us to capture enough data to determine if, for instance, life exists in the vast, liquid oceans that are thought to lie under Europa's icy crust. Two other jovian moons, Ganymede and Callisto, are also thought to have liquid water beneath their surfaces.

This figure illustrates some of the maneuvers for a Petit Grand Tour of the jovian moons, a precursor to a Multi-Moon Orbiter. (a) The spacecraft comes into the Jupiter system and transfers from Ganymede to Europa using a single impulsive maneuver, shown in a Jupiter-centered inertial frame. (b) The spacecraft performs one loop around Ganymede, using no propulsion at all, as shown here in the Jupiter-Ganymede rotating frame. (c) The spacecraft arrives in Europa's vicinity at the end of its journey and performs a final propulsion maneuver to get into a high inclination circular orbit around Europa, as shown here in the Jupiter-Europa rotating frame.

ture is called for—involving ideas from mathematics, mechanics, and computer science—to resolve length and time scales in a systematic, hierarchical way. For example, in the modeling of certain physical systems, it is a challenge to compute the larger, resolvable coarse scales reliably, while accurately modeling the net effect of the smaller, or subgrid scales. Recent developments in modeling and algorithms, for example those based on variational and quasicontinuum methods, demonstrate a new era in our ability to accurately simulate turbulent flows, as well as the complex behavior of nonlinear materials. Marsden is currently the director of CIMMS.

Marsden is a unique figure as his work has significantly influenced the three distinctly separate communities of mathematicians, physicists, and engineers. For these contributions, he was honored by the Fields Institute in Canada on the occasion of his 60th birthday in August 2002, with a international workshop organized along the seven main themes of his work: geometric mechanics, fluid mechanics, elasticity and analysis, numerical algorithms, relativity and quantum mechanics, geometric control theory, and dynamical systems.

His current specific research projects involve faculty both at Caltech and other universities and many affiliated students and post-docs. With Tudor Ratiu from Lausanne and other workers in geometric mechanics worldwide, he continues basic investigations into the mathematics that is key to the foundations of mechanics. With Professor Michael Ortiz in GAL-



CIT and Mechanical Engineering, he is studying structured integration algorithms for solid and fluid mechanical systems. And with Naomi Leonard at Princeton, work is being done on the AOSN-II project (Autonomous Ocean Sampling Network), which is a unique mix of control of underwater vehicles, their own dynamics as well as the dynamics of the ocean. He is working on the dynamics of the solar system and space mission design and control, as well as on phase space structure and transport in dynamical systems, including applications to solar system dynamics and biomolecular systems (with Wang Sang Koon of Caltech, Martin Lo [BS '75] of JPL, Michael Dellnitz from Paderborn, Germany and Igor Mezic [PhD '94] from UC Santa Barbara). He is also working on averaging and other multiscale methods in systems, such as fluid mechanics, with Yannis Kevrekidis of Princeton, Darryl Holm of Los Alamos, and Kamran Mohseni (PhD '00) from Boulder.


Richard Murray (BS '85), Professor of Mechanical Engineering, was instrumental in founding the CDS Option, and continues his research broadly in the area of nonlinear dynamics and control of mechanical, fluid, and materials systems, with applications to aerospace vehicles, robotics, turbomachinery, and thin-film processing. Murray has been serving as the Chair of the Division of Engineering and Applied Science since July 2000, but manages a full research schedule as well. He is the Project Director for Team Caltech (see the Snap Shots section on page 4 about Caltech's DARPA Grand

Challenge entry). Working with Dr. Doug MacMartin and Professor Tim Colonius (in Mechanical Engineering), Murray developed and demonstrated approaches to active feedback control of turbomachinery (gas turbines and inlet/compression systems). He is also working on distributed control systems that can be dynamically reconfigured; such systems would, for instance, have application in multi-vehicle motion control systems. Imagine the precision and agility of a flock of birds; now imagine a group of unmanned reconnaissance planes flying in DoD missions.

Several of Murray projects are implemented on the Caltech Multi-Vehicle Wireless Testbed (MVWT), which consists of eight mobile vehicles with embedded computing and communications capability for testing new approaches for command and control across dynamic networks. The system allows testing of a variety of communications-related technologies, including distributed command and control algorithms, dynamically reconfigurable network topologies, source coding for real-time transmission of data in lossy environments, and multi-network communications. A unique feature of the testbed is the use of vehicles that have second-order dynamics, requiring real-time feedback algorithms to stabilize the system while performing cooperative tasks. The MVWT is part of the Caltech Vehicles Laboratory. The testbed is populated with individual vehicles with PC-based computation and controls, and multiple communications devices (wireless ethernet and Bluetooth). The vehicles are freely

moving wheeled platforms propelled by high-performance ducted fans. The laboratory contains access points for wireless communications, overhead visual sensing to allow emulation of GPS signal processing, a centralized computer for emulating certain distributed computations, and network gateways to control and manipulate communications traffic.

Murray is also active in the Control and Dynamical Systems Alliance (CDSA), which is developing a shared curriculum at leading research and educational institutions in the United States and Brazil. Graduate and undergraduate students are encouraged to study and undertake research projects at Alliance universities here and in Brazil. A central focus of the CDSA is to develop new approaches to education and outreach for the dissemination of basic ideas in control and dynamical systems to non-traditional audiences. These ideas are implemented in a new course at Caltech, CDS 101, Principles of Feedback and Control. It is co-taught by Murray, Mabuchi, MacMartin, Michael Dickinson (Bioengineering), and Steven Low (Computer Science and Electrical Engineering).

The evolution of the Option has been remarkable for such a short time span; with bridges across campus and across continents, CDS continues to thrive. 

---

Visit the Control and Dynamical Systems website at [www.cds.caltech.edu](http://www.cds.caltech.edu)

## More Than Getting Your Feet Wet: SURF, the Summer Undergraduate

Research Fellowship Program

by Carolyn Ash

**T**his summer Caltech's SURF program celebrated its 25th birthday! Even the original founders of the Summer Undergraduate Research Fellowships had no idea of the phenomenal success the program was going to enjoy. Founded in 1979 by then-professor of chem-

soned mentors. Students experience the process of research as a creative intellectual activity and gain a more realistic view of the opportunities and demands of a professional research career. After collaboration with potential mentors, students write research proposals. A faculty committee reviews the proposals

the unparalleled opportunity to probe nature's secrets or to create new devices or processes. Participants begin to learn the language and concepts of their disciplines. Their research roots develop in the environment of inquiry, analysis, and scientific ethics. The joys and struggles of solving new



ical engineering Fred Shair, with 18 students and 17 faculty, SURF has served over 3,440 students and has become a model for similar programs at universities throughout this country and abroad. This summer 440 students, including 192 from other institutions, participated in SURF. Today, 48% of all living Caltech alumni who received their bachelor's degree from the Institute since 1980 have done SURF projects. Close to 20% of SURF students become co-authors of peer-reviewed articles, present at conferences, or contribute to significant technical reports.

Modeled on the grant-seeking process, the SURF program introduces undergraduate students to research under the guidance of sea-

and awards are made on the basis of reviewer recommendation.

Students awarded SURFs carry out their projects during ten weeks in the summer. At the conclusion of the summer, participants submit technical papers and give oral presentations at SURF Seminar Day, a symposium patterned after professional technical meetings. As with any fellowship, students receive a stipend; the stipend in 2003 was \$5,000 for the ten-week period.

President Baltimore writes, "I am proud of this program, which is one of the jewels in Caltech's crown. SURF helps to make Caltech a world leader in research and education." Through SURF, students join the community of researchers and scholars. They have

problems deepen their understanding of the process of science and engineering. Through their presentations on SURF Seminar Day, students are introduced to the importance and value of communicating their work.

SURF founder Fred Shair says, "SURF allows students to grow personally as well as professionally. An important aspect of SURF is the encouragement of each student to believe that she or he can accomplish tasks that others have not. SURF has strengthened the Caltech and JPL learning community, which is centered around bright and enthusiastic students being coached by mentors, graduate students and postdoctoral scholars, and alumni."

It has been noted that science and engineering not communicated are essentially science and engineering not done. The SURF communication requirements help students develop their oral and written presentation skills. Two donors to the SURF program endowed prizes to provide an incentive for students to prepare outstanding research reports. Ten years ago, Robert C. Perpall (BS '52 ME, MS '56 ME), endowed a prize in memory of his late wife, Doris S. Perpall, as an incentive for Caltech SURF students to give excellent oral presentations. Cash prizes of \$500, first place; \$300, second place; and

workshops addresses issues related to career options and preparation for graduate school. These workshops aim to help students develop their short-term career decisions in the context of long-term life and career goals. Weekly suppers at local restaurants allow faculty and students to interact informally. Each summer, students can attend the “behind the scenes” tour at the Huntington Library, Art Collections, and Botanical Gardens.

The essence of SURF is the mentor-protégé interaction. Serving as a mentor to a young scientist is an important role.

process. Students can bring a fresh perspective to the work because they have not developed biases about what should or should not happen, and they might ask the simple questions that are often overlooked when one has been immersed in the research for a long time.

Caltech alumni play many important roles in helping SURF to thrive. Aside from making donations large and small, alumni attend SURF Seminar Day (the third Saturday in October), and some even serve as session chairs for SURF Seminar Day. Alumni may attend informal suppers with SURF




## Students experience the process of research as a creative intellectual activity and gain a more realistic view of the opportunities and demands of a professional research career.

\$200, third place are awarded following a three-round event. Marcella Bonsall endowed the Marcella and Joel Bonsall prize for technical writing to encourage students to develop strong writing skills. Each year up to eight awards are made following a rigorous faculty review of SURF final reports nominated for the prize by SURF mentors. Students are giving much stronger presentations as a result of the competition established by these prizes.

To enhance the research experience, SURF students have the opportunity to attend many educational, professional, and social and cultural events. Weekly seminars given by Caltech faculty and JPL technical staff provide SURF students with an overview of research pursued on campus and at JPL. A series of professional development

Students are welcomed into the community of researchers and scholars as colleagues. Mentors pass on the nature and culture of science to the next generation and play a significant role in providing intellectual stimulation for their students. Mentors provide advice, make observations, and give feedback, often helping students to develop a career focus. Sometimes the relationships formed through scholarly collaboration last long after the student completes his or her degree and ultimately develop into strong professional interactions.

Mentors also benefit. They gain personal satisfaction from working with students. They often enjoy training the next generation, watching students mature intellectually, and knowing that they played an integral part in that

students arranged by the Alumni Association during the summer. They participate on the SURF Board and SURF Administrative Committee, and some make presentations at SURF’s professional development workshops. Alumni help judge student oral presentations. We welcome alumni participation in all forms, and encourage you to contact us if you’d like to get involved.   

---

*The author, Carolyn Ash, is the Director of Student-Faculty Programs, which includes the SURF and MURF programs.*

For more information visit these websites:

[www.surf.caltech.edu](http://www.surf.caltech.edu)

[www.murf.caltech.edu](http://www.murf.caltech.edu)

[www.sfp.caltech.edu](http://www.sfp.caltech.edu)



## An E&S Who's Who: Recipients of the Caltech Distinguished Alumni Award

We realized a while back that nowhere has the Engineering and Applied Science Division collected and published the names of all of its Distinguished Alumni. The Distinguished Alumni Award is the highest honor the Institute bestows upon an alumnus/a. It is in recognition of extraordinary achievement in business, community, and professional life, and may be acknowledging a particular achievement of noteworthy value, a series of such achievements, or a career of noteworthy accomplishment.

The award was initiated as part of Caltech's 75th Anniversary celebration in 1966. Nominations are made by a joint faculty-alumni committee and confirmed by the Board of Trustees; the awards are presented at a ceremony during Caltech's annual Alumni Seminar Day.

So, here they are. We salute each and every one. Their contributions reflect well on Caltech and the Division, and they deserve wide recognition among their fellow alumni and the larger community. Kudos!

A note on the listing: The E&S recipients are listed alphabetically by decade of first Caltech degree. The year in parentheses just after the name is the year the Distinguished Alumni Award was received. The title below the name reflects the position the person held *at the time the award was given*. (d) indicates the person has passed away.

### 1920s

**James Boyd** (d) (1966)  
President, Cooper Range Company  
BS 1927 Eec

**Richard G. Folsom** (d) (1966)  
President, Rensselaer Polytechnic  
Institute  
BS 1928 ME, MS 1929 ME, PhD  
1932 ME

**W. Morton Jacobs** (1971)  
President and Executive Officer,  
Southern California Gas Company  
BS 1928 ME

**Mark Serrurier** (d) (1981)  
Retired. Worked on the design of  
the 200 inch telescope at Mt.  
Palomar; assisted with continuing  
development and modernization of  
the "Moviola" used for film editing,  
received an "Oscar" for this work.  
BS 1926 CE

### 1930s

**Horace Babcock** (1994)  
Director Emeritus, Observatories of  
the Carnegie Institute of  
Washington  
BS 1934 CE

**Francis H. Clauser** (1966)  
Academic Vice Chancellor,  
University of California, Santa Cruz  
BS 1934 Ph, MS 1935 ME,  
PhD 1937 Ae

**Trenton R. Dames** (d) (1993)  
Co-founder, Dames and Moore  
BS 1933 CE, MS 1934 CE

**Frank W. Davis** (1968)  
President, Fort Worth Division,  
General Dynamics Corporation  
BS 1936 ME

**Louis G. Dunn** (d) (1974)  
Retired  
BS 1936 Ae, MS 1937 ME, MS 1938  
Ae, PhD 1940 Ae

**Warren E. Fenzi** (1977)  
President, Phelps Dodge  
Corporation  
BS 1937 CE

**Arthur T. Ippen** (d) (1970)  
Ford Professor of Engineering,  
Massachusetts Institute of  
Technology  
MS 1935 CE, PhD 1936 CE

**John G. McLean** (d) (1970)  
President, Continental Oil  
Company  
BS 1938 APh

**John R. McMillan** (d) (1980)  
Chairman of the Board, Reserve  
Oil and Gas Company, Los  
Angeles, California  
BS 1931 ME

**William W. Moore** (1993)  
Co-founder, Dames and Moore  
BS 1933 CE, MS 1934 CE

**Walter H. Munk** (1966)  
Associate Director, Institute of  
Geophysics and Planetary Physics,  
University of California, San Deigo  
BS 1939 APh, MS 1940 Ge

**Bernard M. Oliver** (d) (1972)  
Vice President, Hewlett-Packard  
MS 1936 EE, PhD 1940 EE

**John R. Pierce** (1966)  
Executive Director, Research  
Communications Sciences Division,  
Bell Telephone Laboratories  
BS 1933 EE, MS 1934 EE,  
PhD 1936 EE

**Louis T. Rader** (1966)  
Vice President, General Manager,  
Information Systems Division,  
General Electric Company  
MS 1935 EE, PhD 1938 EE

**L. James Rainwater** (d) (1976)  
Professor of Physics, Columbia  
University  
BS 1939 APh

**L. Eugene Root** (d) (1966)  
President, Lockheed Missiles and  
Space Company  
MS 1933 ME, MS 1934 Ae

**William R. Sears** (1988)  
Professor, Aerospace and  
Mechanical Engineering, University  
of Arizona  
PhD 1938 Ae



James J. Duderstadt



James E. Hall



Max V. Mathews



Arati Prabhakar



Charles R. Trimble



Benoit B. Mandelbrot



Robert L. Noland



Allen E. Puckett



Vernon L. Smith



**Hsue-Shen Tsien** (1979)

Chairman, Institute of Mechanics, National Academy of Science, Beijing, China  
PhD 1939 Ae

**Victor V. Veysey** (1976)

Assistant Secretary for Civil Works, U.S. Department of the Army  
BS 1936 CE

## 1940s

**Mihran S. Agbabian** (2000)

Fred Champion Professor Emeritus of Civil Engineering, University of Southern California  
MS 1948 CE

**William F. Ballhaus** (1978)

President, Beckman Instruments, Inc.  
PhD 1947 Ae

**Arthur E. Bryson, Jr.** (1991)

Pigott Professor of Engineering, Department of Aeronautics and Astronautics, Stanford University  
MS 1949 Ae, PhD 1951 Ae

**William J. Carroll** (1996)

Vice Chairman, Board of Directors, Montgomery Watson, Consulting Engineers, Inc., Pasadena, CA  
BS 1948 CE, MS 1949 CE

**Joseph V. Charyk** (1966)

President, Communications Satellite Corporation  
MS 1943 Ae, PhD 1946 Ae

**Earnest H. Clark, Jr.** (1981)

President/Chief Executive Officer, Baker Oil Tools, Inc., Baker International Corporation  
BS 1946 ME, MS 1947 ME

**Julian D. Cole** (d) (1971)

Professor and Chairman, Department of Mechanics, University of California, Los Angeles  
MS 1946 Ae, Eng 1946 Ae, PhD 1949 Ae

**Satish Dhawan** (1969)

Director, Indian Institute of Science  
Eng 1949 Ae, PhD 1951 Ae

**Yuan-Cheng B. Fung** (1994)

Professor of Bioengineering and Applied Mechanics, Emeritus, University of California, San Diego  
PhD 1948 Ae

**Thomas Hudspeth** (1993)

Chief Scientist, Space and Communications Group, Hughes Aircraft Company  
BS 1941 EE

**Hassan M. Ismail** (d) (1972)

President, Cairo University  
PhD 1949 CE

**Chia-Chiao Lin** (1992)

Institute Professor, Emeritus, Massachusetts Institute of Technology  
PhD 1944 Ae

**Paul B. MacCreedy, Jr.** (1978)

President, AeroVironment, Inc.  
MS 1948 Ph, PhD 1952 Ae

**Richard H. MacNeal** (1998)

Chairman and Chief Executive Officer, The MacNeal-Schwendler Corporation  
MS 1947 EE, PhD 1949 EE

**Benoit B. Mandelbrot** (1988)

IBM Fellow, T. J. Watson Research Center, Abraham Robinson Professor of Mathematical Sciences, Yale University  
MS 1948 Ae, Eng 1949 Ae

**Duane T. McRuer** (1983)

President and Technical Director, Systems Technology, Inc., Hawthorne, California  
BS 1945 ME, MS 1948 ME

**Ruben F. Mettler** (1966)

President, TRW, Inc.  
BS 1944 EE, MS 1947 EE, PhD 1949 EE

**John W. Miles** (1997)

Professor of Applied Mechanics and Geophysics, University of California, San Diego  
BS 1942 Eng, MS 1943 Ae, MS 1943 EE, AeE 1944 Ae, PhD 1944 Ae

**Robert L. Noland** (1989)

President and CEO, Ketema, Inc., Odenton, MD  
BS 1941 ME

**Stanley C. Pace** (1987)

Chairman and Chief Executive Officer, General Dynamics Corporation  
MS 1949 Ae

**Robert J. Parks** (1992)

Deputy Director, Retired, Jet Propulsion Laboratory  
BS 1944 EE

**Allen E. Puckett** (1970)

Executive Vice President and Assistant General Manager Hughes Aircraft Company  
PhD 1949 Ae

**Eberhardt Rehtin** (1984)

President, Aerospace Corporation  
BS 1946 EE, PhD 1950 EE

**Harold A. Rosen** (1976)

Vice President for Engineering, Space and Communications Group, Hughes Aircraft Company  
MS 1948 EE, PhD 1951 EE

**Glenn A. Schurman** (1994)

Corporate Vice President of Oil Field Development and Production Operations, Chevron Corporation  
MS 1946 ME

**Vernon L. Smith** (1996)

Regents' Professor of Economics, Department of Economics, University of Arizona  
BS 1949 EE

**Douglas C. Strain** (1986)

Vice Chairman, Board of Directors, Electro Scientific Industries  
BS 1948 EE

**Kiyo Tomiyasu** (2002)  
Consulting Engineer, Lockheed  
Martin Corporation  
BS 1940 EE

**Max L. Williams, Jr.** (1995)  
Dean, Emeritus, School of  
Engineering, University of  
Pittsburgh  
MS 1947 Ae, Eng 1948 Ae,  
PhD 1950 Ae

**Thornton A. Wilson** (d) (1968)  
Executive Vice President, Boeing  
Company  
MS 1948 Ae

**Abe M. Zarem** (1969)  
Retired, Electro-Optical Systems  
MS 1940 EE, PhD 1944 EE

## 1950s

**Moshe Arens** (1980)  
President, Cybernetics, Inc.  
Savyon, Israel  
MS 1953 ME

**Frank Borman** (1966)  
Colonel, United States Air Force  
MS 1957 Ae

**Richard D. DeLauer** (d) (1985)  
President, Orion Group Ltd.  
Eng 1950 Ae, PhD 1953 Ae

**James E. Hall** (2001)  
President, Chaparral Cars  
Incorporated  
MS 1957 ME

**Steingrimur Hermannsson**  
(1986)  
Prime Minister, Iceland  
MS 1952 EE

**Anthony J. Iorillo** (1990)  
President, Space and  
Communications Group, Hughes  
Aircraft Company  
BS 1959 ME, MS 1960 Ae

**Jack L. Kerrebrock** (1997)  
Richard Cockburn Maclaurin  
Professor of Aeronautics and  
Astronautics, Massachusetts  
Institute of Technology  
PhD 1956 ME

**Max V. Mathews** (1989)  
Professor of Music (Research),  
Stanford University  
BS 1950 EE, BS 1950 ME

**H. Edwin Reinecke** (1969)  
Lieutenant Governor, California  
BS 1950 ME

**George E. Solomon** (1983)  
Vice President and General  
Manager, Electronics and Defense,  
TRW, Inc.  
MS 1950 Ae, PhD 1953 Ae

**Alvin W. Trivelpiece** (1987)  
Director of Office of Energy  
Research, U.S. Department of  
Energy  
MS 1955 EE, PhD 1958 EE

**Donald L. Turcotte** (1999)  
Professor of Geological Sciences,  
Cornell University  
BS 1954 ME, PhD 1958 Ae

## 1960s

**Robert W. Bower** (2001)  
Professor, University of California,  
Davis  
MS 1963 EE, PhD 1973 APH

**Milton M. Chang** (2002)  
Chairman of the Board, New  
Focus, Inc., Santa Clara, CA  
MS 1965 EE, PhD 1969 Eng

**Robert W. Conn** (1998)  
Dean, School of Engineering and  
Walter J. Zable Professor of  
Engineering, University of  
California, San Diego  
MS 1965 ME, PhD 1968 ES

**James J. Duderstadt** (1989)  
President, University of Michigan  
MS 1965 ES, PhD 1968 ES

**Philip Mwangi Githinji** (1993)  
Vice Chancellor, Kenyatta  
University  
MS 1961 ME, Eng 1963 ME

**Robert Merton** (1999)  
John and Natty McArthur  
University Professor  
Graduate School of Business  
Administration, Harvard University  
MS 1967 AMA

**Roddam Narasimha** (1986)  
Director, National Aeronautical  
Laboratory, Indian Institute of  
Science  
PhD 1961 Ae

**Navin C. Nigam** (1991)  
Director (President), Indian  
Institute of Technology, Delhi  
PhD 1967 CE

**Ozires Silva** (1992)  
Minister of Infrastructure, Brazil  
MS 1966 Ae

**Ivan E. Sutherland** (1985)  
Vice President, Sutherland, Sproull,  
and Associates, Inc.  
MS 1960 EE

**Charles R. Trimble** (1995)  
President and CEO, Trimble  
Navigation  
BS 1963 Eng, MS 1964 EE

## 1970s

**Yoshiaki D. Hagiwara** (2000)  
Assistant to General Manager,  
Sony Corporation, Atsugi  
Technology Center  
BS 1971 Eng, MS 1972 EE,  
PhD 1975 EE

**Henry C. Yuen** (1999)  
Chief Executive Officer  
Gemstar Development Corporation  
PhD 1973 AMa

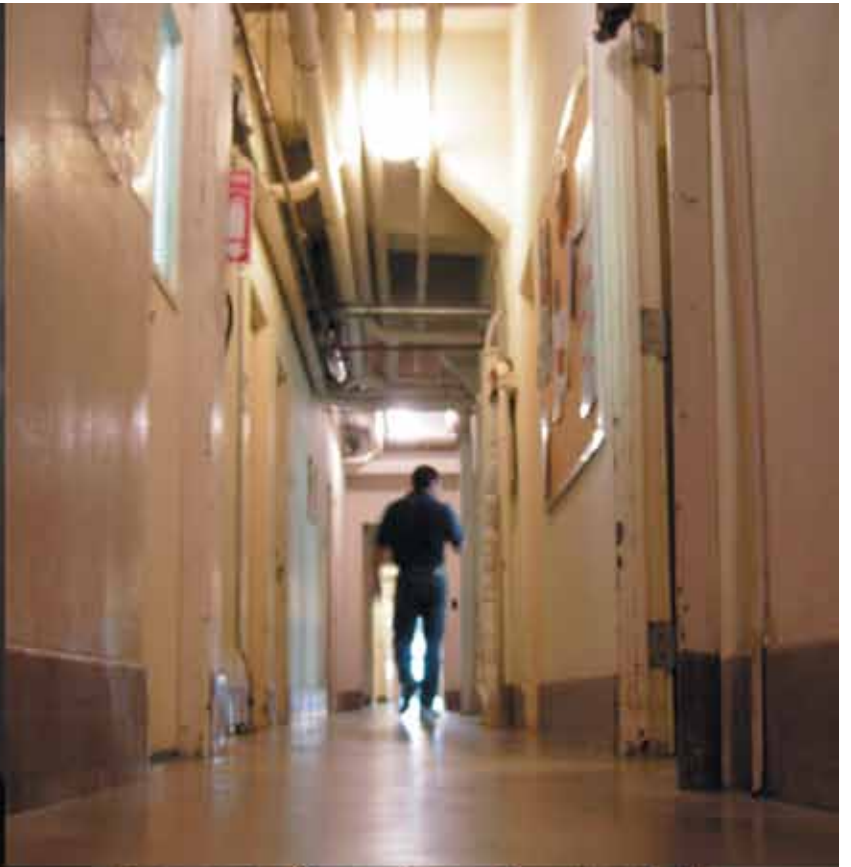
## 1980s

**Arati Prabhakar** (1995)  
Director, U.S. National Institute of  
Standards and Technology  
MS 1980 EE, PhD 1985 APH

---

Visit Caltech's Alumni Association website at  
[www.its.caltech.edu/~alumni](http://www.its.caltech.edu/~alumni)





The mission of the California Institute of Technology is to expand human knowledge and benefit society through research integrated with education. We investigate the most challenging, fundamental problems in science and technology in a singularly collegial, interdisciplinary atmosphere, while educating outstanding students to become creative members of society.



**DIVISION OF ENGINEERING AND APPLIED SCIENCE**

*California Institute of Technology* 1200 E. California Boulevard, Mail Code 104-44, Pasadena, CA 91125

[www.eas.caltech.edu](http://www.eas.caltech.edu)