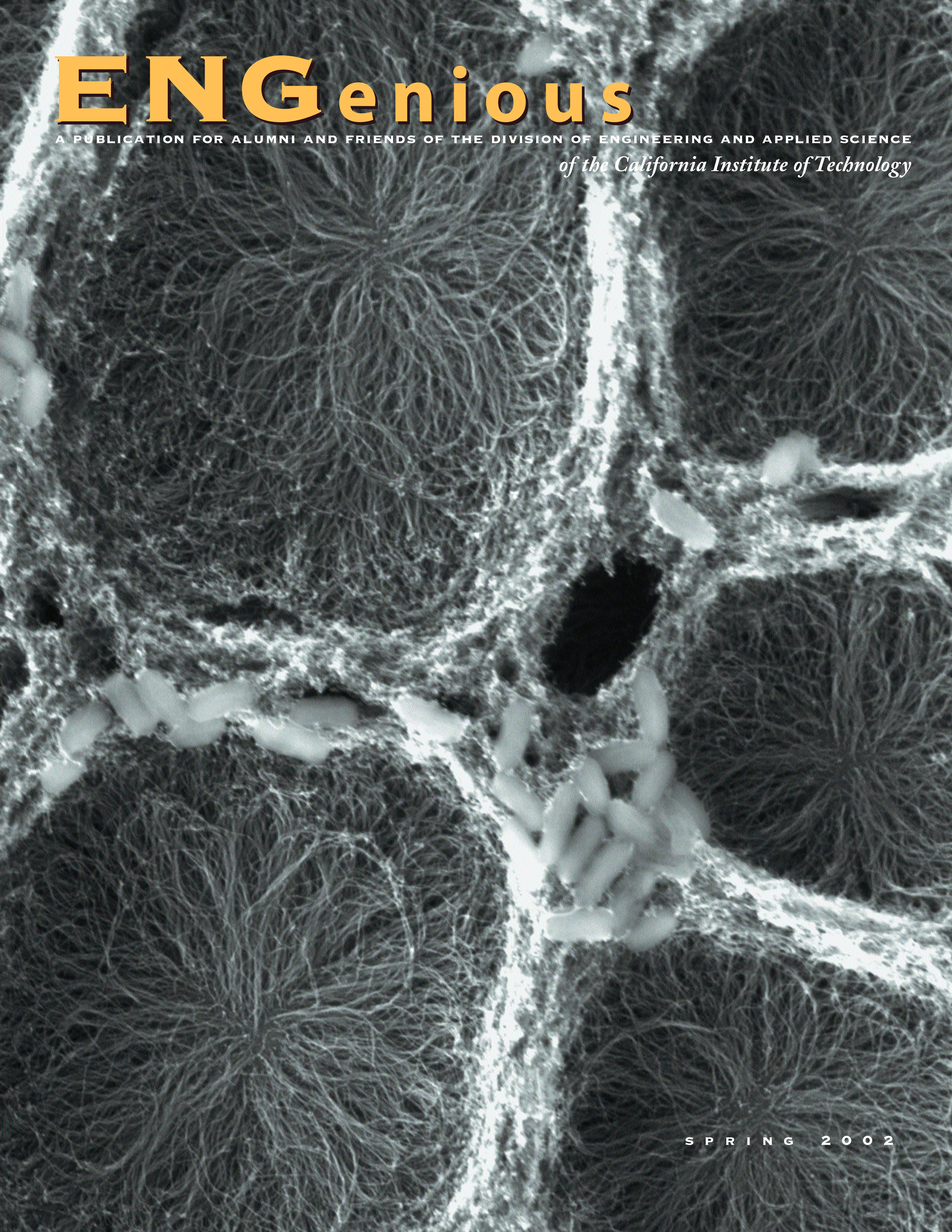
ENGenious

A PUBLICATION FOR ALUMNI AND FRIENDS OF THE DIVISION OF ENGINEERING AND APPLIED SCIENCE

of the California Institute of Technology



SPRING 2002

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SPRING 2002

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.

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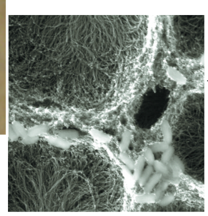
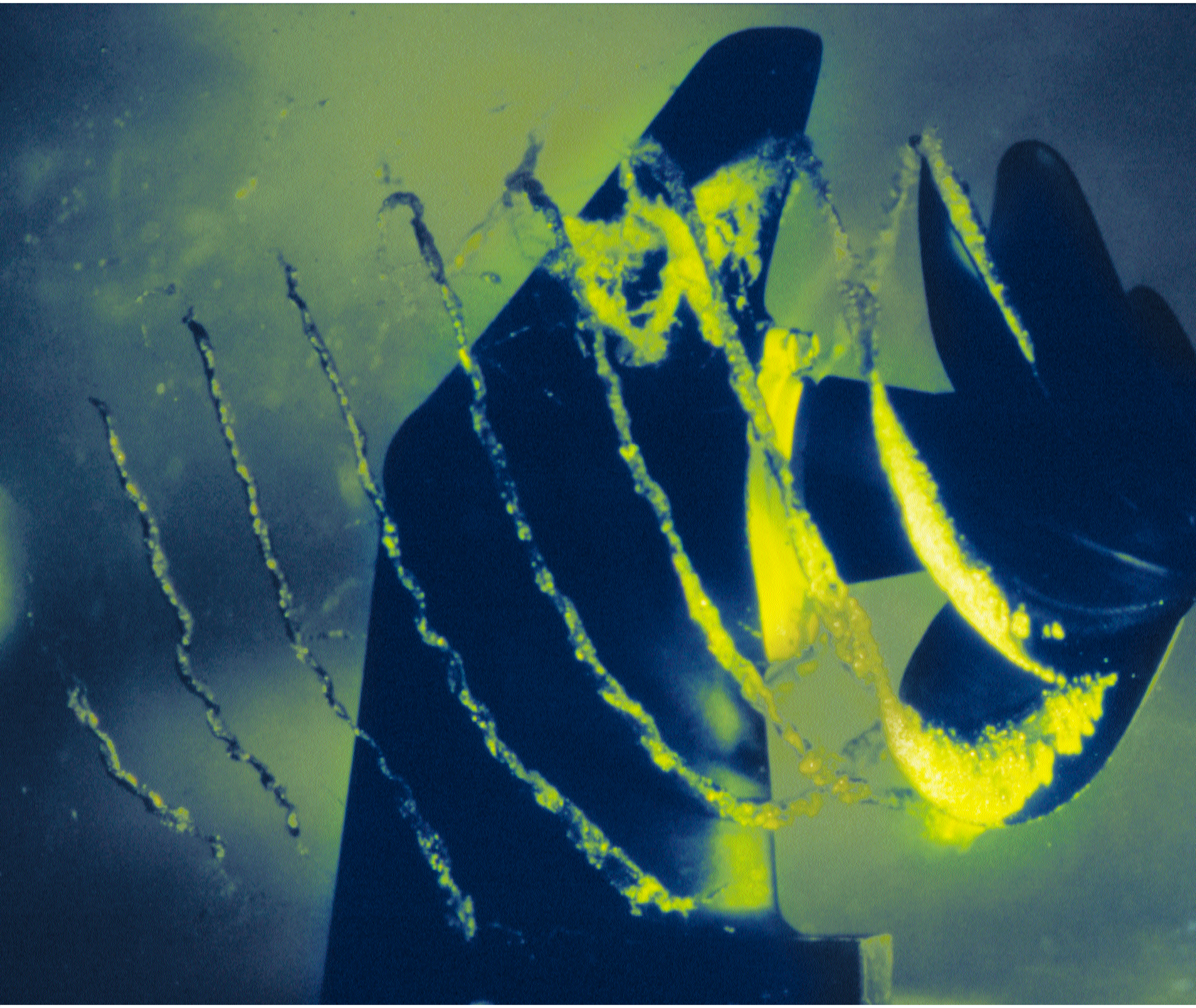


Cover Image Bacteria nests: microscale pattern formation of desiccated carbon nanotube carpets, after immersion in solutions containing bacterial spores (*Bacillus Pumilus*). In this project, carbon nanotubes are used to mimic cilia, which are Nature's ubiquitous micron-sized hair as found in the lung epithelium, for instance. Biomimetics helps us understand how cilia can be used for trapping particulates (spores, bacteria, toxins), for filtering biomolecules (DNA), for transporting fluids (as the mucus in the trachea or uterine cervix), and for sensing fluid flows (as the endolymphatic liquid in the ear cochlea). The master project is a collaborative Caltech/JPL effort on bio-nanofluidics (nanoscale fluid dynamics in biological processes). The principal investigators on this project are JPL's Flavio Noca, PhD '97 Aeronautics, and Mory Gharib (pictured at left), Professor of Aeronautics and Bioengineering, and graduate students Jijie Zhou and Elijah Sansom.

Additional Credits: Microscopy: R. Mielke / JPL ESEM. Spore tests: F. Chen / JPL Planetary Protection Group. Nanotube carpets: JPL Nanotube Group.



Cavitation on a modern ship propeller. This photograph was taken by Mark Duttweiler (PhD '01) in Caltech's Mechanical Engineering, Low Turbulence Water Tunnel. The flow is from right to left.

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

Enter the **second** issue of ENGenious.

Thank you to all the alums who sent comments on the first issue of **ENGenious** *and suggestions for future features, articles, and even design (!). We asked for your feedback and we got it. A full range of opinion arrived in our e-mail boxes expressing what we did right and what we can do better. We've begun incorporating many of your suggestions. Please continue with the feedback, as we hope issue-by-issue to evolve and improve.*

Looking at the larger picture, the Division of Engineering and Applied Science itself is ever evolving—a collection of exceptional people doing exceptional things, and we count our alumni as integral partners in the process. The outstanding efforts of E&AS alumni in academic research, government, and private industry are a large part of the reason we have a level of visibility and impact far exceeding our size. And so beginning with this issue, we'd like to share stories of people out in the field, so to speak, doing wonderful things with their Caltech educations. The profile of alumnus Allen Puckett (PhD '49) starts a new feature we will be continuing in each issue.

This issue spotlights the Division's newest academic option, Bioengineering. We continue with meeting new faculty, getting up-to-date with emeritus faculty and recent events on campus, looking into research by faculty, and re-discovering one of the Division's thirteen options. This issue introduces the Division's newest center, CIMMS (Center for Integrative Multiscale Modeling and Simulation). And we visit a couple of campus resources, the Office of Technology Transfer, and the Sherman Fairchild Library of Engineering and Applied Science.

Finally, before you read on, I would like to take this opportunity to thank, on behalf of the Division, Gordon Moore (PhD '54) and his wife, Betty, for their truly extraordinary donation to Caltech this past fall. It's simply an enormous gesture of confidence in the Institute's past, present, and future. Their gift and that of the Gordon and Betty Moore Foundation, totaling $600 million, will help us do what we do even better.

I hope you enjoy this issue and, as always, let us know how we're doing.

Sincerely,

R I C H A R D M . M U R R A Y

Chair, Division of Engineering and Applied Science

SNAP SHOTS

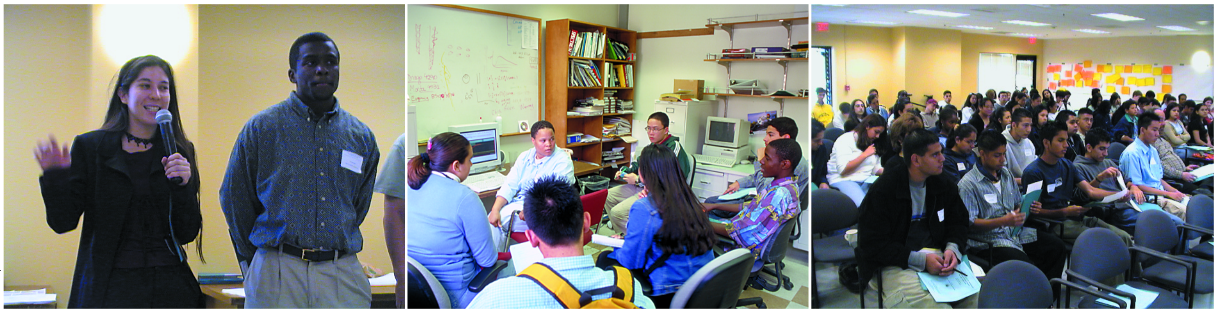
'Round About the Institute

President David Baltimore visits KPCC.

Radio Free Caltech: On Your Radio Dial, FM 89.3, KPCC

PRESIDENT DAVID BALTIMORE sat in as guest host on Southern California Public Radio station KPCC's highly informative and acclaimed show, AirTalk. The radio gig had him taking calls from listeners and interviewing experts in science and the media on AIDS, and discussing the then-upcoming Nobel Centennial celebrations at Caltech and other institutions.

How'd he do, you might ask. So well, in fact, that we're glad that his research and presidency are going so swimmingly at Caltech. He was such a natural that you'd think he had been doing this all his life…and we really like the photograph.



Caltech Minority Student Outreach participants: graduate students Anna Salazar and Terrell Neal (left); Erica Thompson, Caltech Postdoctoral Scholar, leading a group discussion (center); and visiting students (right).

Minority Student Outreach: Will Future Techers Please Raise Your Hands

CALTECH'S 10th ANNUAL OUTREACH PROGRAM for high school youth brought more than 100 students from magnet science and technology schools throughout Los Angeles County to campus in March. The students attended lectures, toured labs, and had one-on-ones with faculty and graduate students. In short, they experienced how research is done at Caltech. Over the two days of interaction, they also learned about opportunities and careers in science and engineering.

The program was sponsored by the Office of Minority Student Affairs, two of Caltech's NSF-funded centers, the Center for the Science and Engineering of Materials and the Center for Neuromorphic Systems Engineering, and the James Irvine Foundation.

To learn more about the program, visit http://www.csem.caltech.edu **and** http://www.cnse.caltech.edu

Ken Burns speaks at Caltech.

Ken Burns: Live in Beckman Auditorium

MASTER FILMMAKER Ken Burns recently delivered a Michelin Distinguished Visitor's Lecture entitled "American Trilogy," covering his Big 3, the award-winning historical documentaries *Baseball*, *The Civil War*, and *Jazz*. Beckman Auditorium was full and the crowd pleased.

Burns is unique in his ability to bring history alive through the artful use of diaries, visual images, and dramatic narration. His work seamlessly explores and conveys the individual and collective American experience of his subjects: "I'm less interested in the dry dates and facts than in the way emotional connections hold the past and it's meaning together and tell a story that we can all share and remember," he stated in an interview.

Look for his most recent project, a documentary on writer and humorist Mark Twain, in a video store or on a PBS station near you.

A Women's Art Exhibit: Go WEST (Women in Engineering, Science, and Technology, that is) Young Woman!

Beverly Karhson, a self-taught painter, is an undergraduate in Mechanical Engineering.

WEST, a campus forum for female faculty, students, and staff, recently sponsored "A Women's Art Exhibit" in Dabney Hall. The painted, drawn, and photographic image was well represented alongside ceramics, prints, and poetry. Absorbing and wide-ranging, the art impressed and spoke to the many visitors.

To encourage and promote discussion about the many issues facing women across the Caltech campus, WEST will sponsor various activities including monthly lunches providing an open forum for discussion and exploration.

Visit the WEST website at http://www.its.caltech.edu/~westclub

2001 ME72 contestants and winners.

ME72 Engineering Design: The 17th Annual Contest

THIRTY CONTESTANTS and an audience of almost 1,000 watched and cheered on the teams as they negotiated the contest's course of steep ramps and slopes. Unlike previous years where ping-pong balls were the objects to collect and manipulate, the 2001 contest required the students to move slippery hockey pucks up a stepped, steep ramp. The tension was high. But the robot that could really "get a grip" carried the day. The winners were Alastair Kusack and Marcus Williams.

Find out more about the ME72 Design Contest at http://design.caltech.edu/courses/ME72

Ravichandran in Paris

Guruswami Ravichandran Joins the French Forces at École Polytechnique

ÉCOLE POLYTECHNIQUE (commonly referred to as l'X), founded in 1794 during the French Revolution and currently under the auspices of the Ministry of Defense, is one of the most renowned of a distinctive class of French educational institutions called "les Grandes Écoles." Spread over 440 acres on the Saclay plateau and situated in Palaiseau in the southern suburbs of Paris, it has approximately the same size student body as Caltech—about 900 undergraduates.

In September 2001, Guruswami Ravichandran, Caltech Professor of Aeronautics and Mechanical Engineering, began a one-year residency at the Laboratoire de Mecanique des Solides (LMS) at École Polytechnique as a Directeur de Recherche Associe on invitation from the Centre National de la Recherche Scientifique (CNRS). Ravichandran has traveled to France with his wife and two children.

His principal colleagues at École Polytechnique are Drs. Yves Leroy and Jean Raphanel of the LMS. Dr. Yves Leroy was the first PhD student of Professor Michael Ortiz at Brown University; Ortiz is currently Professor of Aeronautics and Mechanical Engineering at Caltech. LMS has a distinguished history as one of the largest CNRS research laboratories in France; home to over 100 researchers with expertise in theory, modeling, and experiments. Ravichandran is primarily an experimentalist with research interests in mechanics of materials—particularly those pertaining to their dynamic behavior—and heterogeneous and active solids. He is using his time away from Caltech to work on modeling and computational analysis of mechanics problems associated with crystals, defects, and heterogeneous materials, as well as stability of deformation in solids. From his interactions with members of the Mecano-Tectonic group in Paris, he is learning about applications of mechanics to problems in geology.

He is using this opportunity to visit other laboratories and universities in France for updates on the research that is being conducted in mechanics, while still keeping up with his group at Caltech. He is also spending time in the library thinking about new directions for his own research. The outstanding hospitality of the researchers and staff at LMS and the ambiance of École Polytechnique have made his visit a rich and rewarding experience. ENG

"The responsibilities are essentially to conduct research in the field of solid mechanics and interact with scientists within the laboratory (LMS) that I am visiting at the École Polytechnique. The title itself, Directeur de Recherche Associe, means Visiting Senior Scientist."

"My family's most memorable experiences so far, besides the wonderful sights France has to offer (the Chateaux, monuments and museums), are our social interactions with the French families, especially that of Dr. Yves Leroy. We have been welcomed with open arms and included in all their holiday celebrations, thus immersed into French culture. The warm hospitality and friendliness of the people here have impressed us. The city of Paris itself comes across as a living museum and one can experience history at every street corner."

Learn more about Professor Ravichandran at
http://www.solids.caltech.edu/~ravi

Thanos Siapas

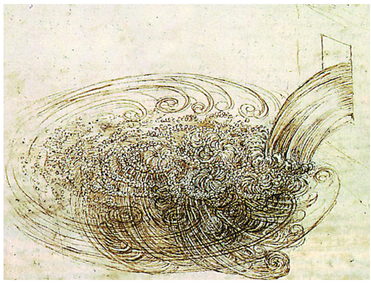
Assistant Professor of Computation and Neural Systems

PROFESSOR THANOS SIAPAS arrived on campus this past January. His research focuses on the study of the principles underlying learning and memory formation across distributed networks of neurons. Using techniques that allow monitoring of simultaneous activity of dozens of single neurons in freely behaving animals, he studies the structure of interactions between the hippocampus and neocortical brain areas and the role of these interactions in learning and memory. He also investigates the cellular and molecular basis of network interactions by analyzing the effects of pharmacological and genetic manipulations on the organization of ensemble neuronal activity. His experimental work is complemented by theoretical studies of network models and the development of tools for the analysis of multi-neuronal data.

Professor Siapas received a BS in Mathematics, a BS in Electrical Science and Engineering, an MS in Electrical Engineering and Computer Science, and a PhD in Electrical Engineering and Computer Science, from the Massachusetts Institute of Technology. Before joining Caltech, he conducted postdoctoral research in behavioral electrophysiology in Matt Wilson's laboratory at MIT.

Professor Siapas has a joint appointment in Caltech's Division of Engineering and Applied Science and Division of Biology. ENG

Learn more about Computation and Neural Systems at
http://www.cns.caltech.edu



CIMMS: The Center for Integrative Multiscale Modeling and Simulation

Because the Real World is Multiscale, Dynamic, and Complex

by Jerrold E. Marsden

Big whorls have little whorls which feed on their velocity, and little whorls have lesser whorls and so on to viscosity.
—*Lewis Richardson* English Mathematician (1881–1953)

TEAM FORMATION

Investigators from many different disciplines have teamed up via the Center for Integrative Multiscale Modeling and Simulation (CIMMS) to model and analyze complex phenomena across multiple time and length scales. The challenge to CIMMS investigators is to help lay the foundation and further specific application areas of multiscale systems. Representative goals are to accurately model, simulate, and control multiscale systems in the presence of uncertainty or errors that might occur across scales. This work will be enabled by the interaction between research groups in multiscale modeling and those in multiscale geometric algorithms. Advances in these two areas are significant but isolated, and CIMMS members intend to systematically bridge the gaps between these two communities. CIMMS will become an intellectual hub for Caltech graduate students, postdocs, and faculty in research areas such as Control & Dynamical Systems, Mechanical Engineering, Computer Science, Electrical Engineering, Applied & Computational Mathematics, and Bioengineering. The Center will also function as a crossroads for industry researchers working on similar multiscale modeling and simulation problems. Researchers will collaborate through workshops, individual interactions, seminars, student internships, and industrial exchanges. A center with national visibility, CIMMS will allow Caltech to lead an intensive, focused effort to create an application-oriented and systematic multiscale approach to a wide range of scientific and engineering challenges.

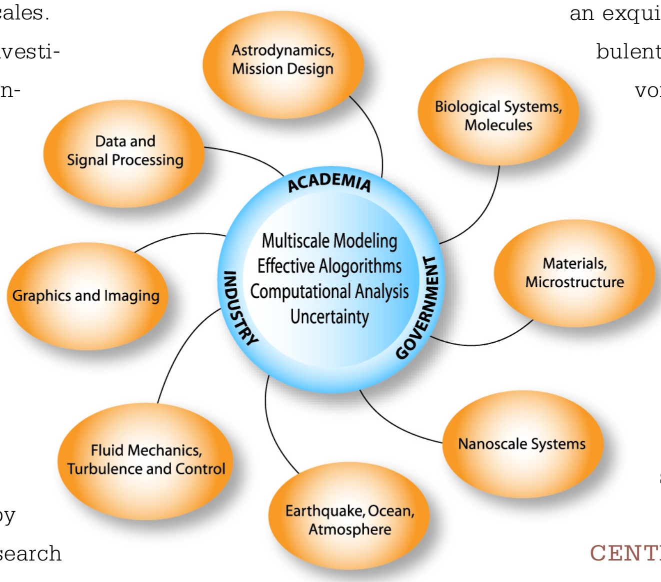
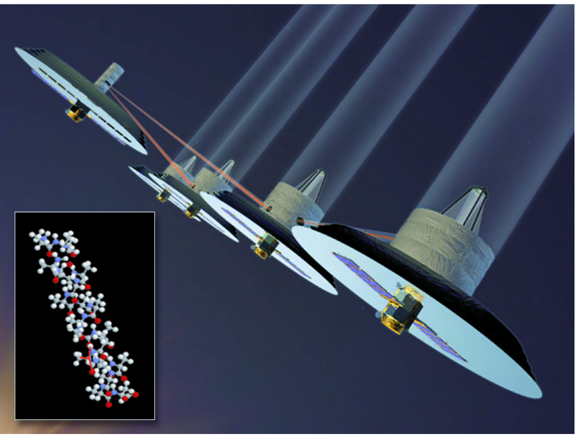


Diagram of the areas of application of the science and technology discovered, tested, and applied by groups within the CIMMS organization.

To represent this multi-task and multi-goal center, investigators selected a drawing by Leonardo da Vinci (above right). This image is an exquisite delineation of the turbulent flow of fluid as it involves vortices within vortices over an ever-decreasing scale. Da Vinci's study of the complexity of a "relatively" simple phenomena, water flowing and mixing, illuminates the essence of the levels of multiscale modeling and simulation.

CENTER MISSION

Despite their ubiquity, multiscale systems are rather poorly understood from a fundamental perspective. CIMMS's mission includes two over-arching themes. The first is to develop a basic "core" infrastructure for the study of multiscale systems (see diagram this page). A prototypical challenge is to reliably compute larger, resolvable coarse scales while accurately modeling the net effect of smaller, or subgrid, scales in both materials



The dynamics of molecular dissociation and satellite dynamics have similar behavior, but on vastly different scales. (Spacecraft figure of TPF, the terrestrial planet finder, courtesy of NASA.)

and fluids. There have been some successes, but there is a need for enhanced cooperation across disciplines to make significant progress. The second theme is to demonstrate the effectiveness of tools developed in the "core" on a variety of interesting application areas.

EXPLORATION & EXAMPLES

Study areas such as atmosphere and ocean dynamics, material microstructures, and biomolecular dynamics remain enormous challenges to computational modeling. More CPU cycles are good but will go only so far.

A profound understanding of mathematical modeling coupled with efficient, accurate algorithms in an integrative environment will allow researchers to better understand how water flows in the open ocean and how, for example, it mixes with pollutants. What happens before, during, and after an earthquake fault ruptures? How can we minimize risk of engine failure in any flying condition for the next generation of jet engines? These, and others, are the kinds of problems CIMMS researchers will study, model, simulate, and control.

Strain on an earthquake fault can take many years to build, but release occurs in seconds. Seismic waves can travel across continents, but local effects (in the Los Angeles basin, for example) may be of utmost concern. The difference in both temporal and spatial scales for these phenomena is enormous.

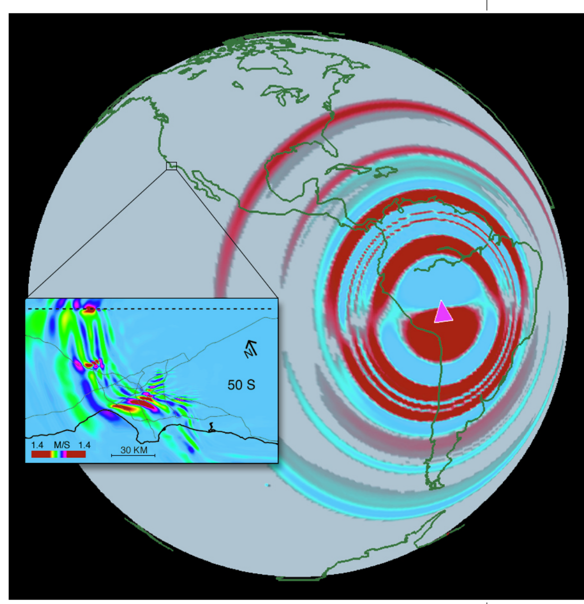
A jet engine involves the complex interaction of fluids, combustion, fan blades, and other engine parts that operate on many different scales. One needs to operate and control such complex processes, often close to stability margins, for greater efficiency. A representative CIMMS task is the creation of tools and techniques to enable virtual jet engines to reliably simulate flight events, material properties, and dynamical phenomena.

Perhaps the greatest multiscale system is our own solar system, contained within our Milky Way galaxy. One can observe the planets moving on a grand scale while simultaneously witnessing the delicate intricacies of Saturn's rings and the turbulent red spot on Jupiter, with its own "whorls within whorls."

Without the crucial element that CIMMS hopes to provide, monoscale approaches—even supersized—will remain insufficient to fully model, analyze, and control complex phenomena. ENG

CIMMS Director Jerrold E. Marsden is Professor of Control & Dynamical Systems. CIMMS Associate Director Tom Hou is Professor of Applied & Computational Mathematics.

For more on multiscale modeling see Rob Phillips's Progress Report on page 12.



Seismic waves from macroscale (tectonic) to microscale (as in the Los Angeles basin) will be studied by CIMMS researchers. (Figure courtesy of Caltech's Jeroen Tromp and UC Santa Barbara's Kim Olson.)

To find out more about CIMMS visit
http://www.cimms.caltech.edu

Modeling in Engineering—The Challenge of Multiple Scales

by Rob Phillips

Whether we consider the design of a new generation of airliners such as the Boeing 777 or the development of the latest microprocessors, engineering relies increasingly on the use of mathematical models to characterize these technologies. In the case of the 777, sophisticated models of the fluid mechanics of air flow over the wings were an integral part of the design process, just as structural mechanics models ensured that flight in turbulence leads to nothing more grave than passenger discomfort.

Models of complex materials that make up our modern technologies also pose a wide range of scientific challenges. Indeed, many of the most important recent advances in the study of materials resulting in entirely new classes of materials such as the famed oxide high-temperature superconductors or fullerenes, and their structural partners known as carbon nanotubes, have engendered a flurry of modeling efforts.

Important problems that such modeling must confront are those of an intrinsically multiscale nature. What this means is that analysis of a given problem requires simultaneous consideration of several spatial or temporal scales. This idea is well represented in drawings made more than 500 years ago by Leonardo da Vinci, in which the turbulent flow of a fluid is seen to involve vortices within vortices over a range of scales. This sketch (see Fig. 1) serves as the icon for the new Caltech center known as the Center for Integrative Multiscale Modeling and Simulation (CIMMS) [see article on page 10]. CIMMS brings together faculty members from several different Options and Divisions including Professors K. Bhattacharya (Mechanical Engineering), E. Candes (Applied & Computational Mathematics), J. Doyle (Control & Dynamical Systems, Electrical Engineering, and Bioengineering), M. Gharib (Aeronautics and Bioengineering), T. Hou (Applied & Computational Mathematics), H. Mabuchi (Physics and Control & Dynamical Systems), J. Marsden (Control & Dynamical Systems), R. Murray (Control & Dynamical Systems and Mechanical Engineering), M. Ortiz (Aeronautics and Mechanical Engineering), N. Pierce (Applied & Computational Mathematics), R. Phillips (Mechanical Engineering and Applied Physics) and P. Schröder (Computer Science and Applied & Computational Mathematics). The aim of multiscale modeling is to construct models of relevance to macroscopic scales usually observed in experiment and tailored in the engineering process without losing sight of the microscopic processes which may dictate processes at the macroscale. Although the relation between force and extension can be observed macroscopically, it is often complex *microscopic* processes that give rise to the macroscopic force-extension curves. Examples include the breaking of hydrogen bonds during protein deformation, and the motion of defects in the deformation of crystalline solids.

A key outcome of the use of computers in science and engineering has been the ability to solve problems of ever-increasing complexity. Whereas the tools of nineteenth-century mathematical physics emphasized geometries of high symmetry (such as spheres and cylinders, each of which is aligned with a set of special functions such as the Legendre polynomials or Bessel functions), current modeling is aimed at considering problems in their full three-dimensional complexity. The key advance enabling such calculations is high-speed computation. As a representative case study of the high level to which such models have been taken, Fig. 2 shows the computational grid (finite-element mesh) used to model a human kidney when subjected to ultrasonic shock waves. The aim is to degrade kidney stones (shock-wave lithotripsy). As noted above, no assumptions are required concerning the symmetry of the body. The level of spatial resolution needed to construct models of systems of interest may vary from one position in the system to another. Indeed, the finite-element method serves as a powerful tool in the multiscale modeling arsenal. Efforts in the Phillips group and that of Michael Ortiz are aimed at bringing these methods to bear on problems ranging from the deformation of dense metals such as tungsten to the fragmentation of human bone to the deformation of individual proteins.

One of the precepts which presides over the field of computational science and engineering is Moore's law, which calls for a doubling in the number of transistors per integrated circuit every 18 months. For those of us who exploit computers to solve complex problems, this enables ever-increasing computational resources. From many perspectives, Moore's law should be seen as an expression of unbridled optimism which has set the agenda respected in the semiconductor technology roadmap (*http://public.itrs.net*). It serves as a guide to understanding the way in which the resources of computational scientists have increased since the first models were solved on primitive vacuum-tube computers.

On the other hand, for those interested in brute-force atomic-level calculation of the properties of materials (or any of a wide range of other problems occurring in fluid mechanics, meteorology, computational biology, etc.), Moore's law paints an altogether more gloomy picture. To see this, we need only remark that the number of atoms in a cubic micron of material is roughly 10^{10} since about 3,000 atoms will fit onto each edge of such a cube. Calculations of this size are at least three orders of magnitude larger than the 10 million atoms reached on today's best supercomputers in the case of the simplest materials. Worse yet, this is but one facet of the problem. Just as the maximum size accessible by direct numerical

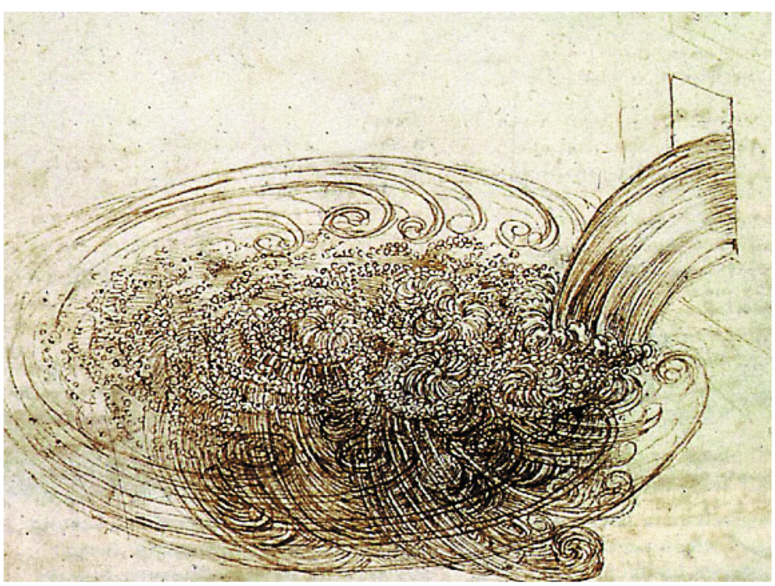


Figure 1. Sketch by Leonardo da Vinci illustrates the sense in which turbulent flow of a fluid is a multiscale phenomenon. Parcels of fluid in a turbulent flow with a net rotation, vortices, are organized hierarchically in such a way that there are vortices within vortices.

calculation is too small, so too are the intervals of time being simulated, with the current standard being that a nanosecond worth of simulation time (10^{-9} seconds) represents *long* simulation time. To drive home this point, we note that if our interest is in the simulation of semiconductor processing, we will need to simulate micron size regions for times much in excess of the nanosecond simulation times described above. Similarly, should our interest be in simulating the properties of the basic building blocks of life, what Francis Crick referred to as the “two great polymer languages,” nucleic acids and proteins, there too we are faced with the simulation of scales in both space and time that will continue to defy our current brute-force computational schemes.

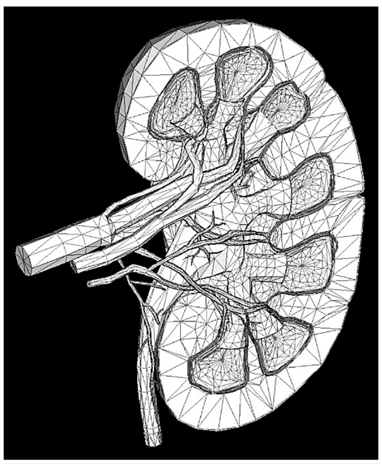


Figure 2. Computational mesh used to evaluate the mechanical response of a kidney to ultrasonic shock waves (courtesy of Kerstin Weinberg and Michael Ortiz).

As an antidote to this scourge on the face of computational science, workers from a host of different fields ranging from applied mathematics to meteorology to computational biology are engaged in work that has been dubbed “multiscale modeling.” From a computational perspective, the premise of multiscale modeling is that new methods must be developed in which alternatives to the full brute-force ideas described above are examined. Though this vibrant field has been hyped by giving it a special name, I suggest that multiscale modeling is really as old as science itself and was being practiced by Newton when he treated the Earth as a point mass, by Hooke when he treated a spring as an elastic continuum, by Bernoulli in the development of the kinetic theory of gases, by Lorentz in his early and primitive models of the absorption of light in crystalline solids, and by Einstein in his treatment of both Brownian motion in liquids and specific heats of crystalline solids. What all of these modeling efforts have in common is the idea of starting with a picture of the material of interest which is oppressively complex and finding a way to replace that complexity with a “coarse grained” model. Said differently, such models can be thought of as viewing the problem of interest with lower resolution. An example from everyday experience is gained by looking out the window of an airplane when flying at 30,000 feet. At this resolution, forests are smeared out and the various topographical features with a scale less than several meters are no longer observable. Nevertheless, from the perspective of understanding the overall forestation and topography of a given region, understanding at this level of resolution is likely *more* useful than a more accurate rendering with resolution at the meter scale.

History is replete with beautiful examples in which multiscale modeling ideas have been used to characterize a range of problems. One such example is related to the following question: given that a gas is a collection of atoms, is it possible to replace models of the gas which acknowledge the underlying graininess of matter by those in which the atomic degrees of freedom are smeared out into continuous fields such as density, temperature, and pressure? Of course, it is well known that the answer to this query can be posited in the affirmative. Further, it is through the multiscale vehicle of the kinetic theory of gases that this transformation in perspective is made.

As illustrated in Fig. 3, a gas may be thought of as a collection of molecules, each engaged in its own jiggling dance until, by chance, one molecule collides either with another molecule or the surrounding walls. The realization of the early thermodynamicists was that the accumulation of all such collisions per unit time corresponds to our macroscopic impression of the pressure exerted on the walls by all of the gas molecules. Through a well-defined statistical formalism, statistical mechanics and the kinetic theory of gases instruct us

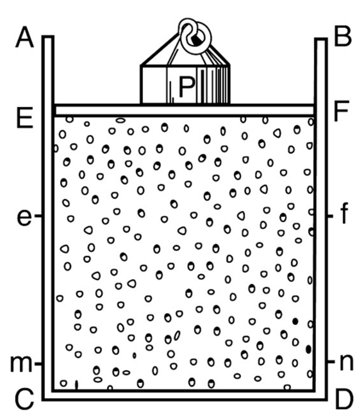


Figure 3. Illustration of the relation between molecular and continuum descriptions of the internal state of a gas. This figure comes from the original paper of Daniel Bernoulli, one of the developers of the multiscale modeling paradigm known as the kinetic theory of gases.

how to compute the macroscopic average quantities measured in the lab as a function of the underlying molecular coordinates. For the present argument, the key point is that by evaluating the molecular mechanics of the various collisions between molecules, it is possible to compute parameters such as viscosity, which show up in higher level continuum descriptions of the fluid. The existence of simple parameters (such as viscosity) capture the details of the underlying microscopic collisions and allow us to replace these microscopic details with continuum notions, an example of multiscale modeling at its best.

Work in the same vein as the kinetic theory of gases has continued unabated and now represents a cornerstone of the modern approach to understanding materials ranging from steel to proteins. In the remainder of this article, we examine one corner of this vast field which has understanding as its first objective and, later, designing and controlling the response of materials when they are subjected to an applied force.

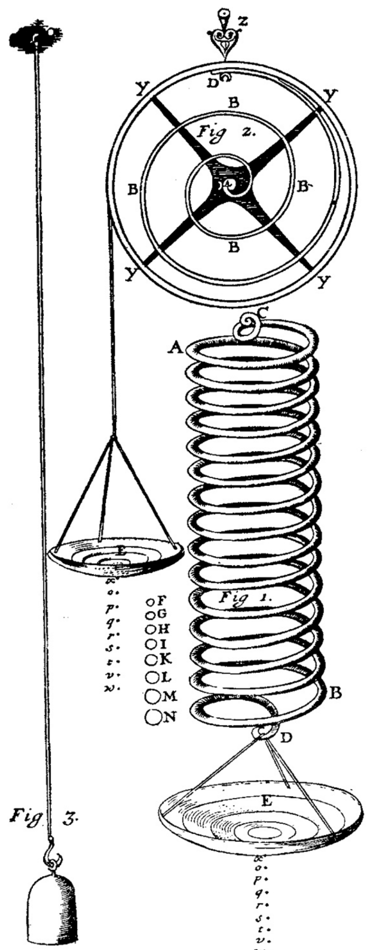


Figure 4. Experimental apparatus used by Robert Hooke in his elucidation of the laws of elasticity.

One of the key ways to understand different materials is to subject them to different external stimuli and watch their attendant responses. One classic example of this strategy is embodied in the formulation of the laws of elasticity. Using experimental apparatus like that shown in Fig. 4, Robert Hooke measured the extension of material bodies as a function of the imposed load and thereby formulated his justly famous law which he expressed as an anagram *CEIIINOSSITTUV*, which when unscrambled reads *Ut tensio, sic vis*—"As the extension, so is the force." In modern parlance, this is written $\sigma = E\varepsilon$: stress is proportional to strain with the constant of proportionality given by the Young's modulus, E. This basic idea jibes with our intuition: the harder you pull on something, the more it stretches. Similar proportionalities have been formulated for material response in other settings such as the relation between current and voltage (Ohm's law) and that between diffusion and the chemical gradient (Fick's law). In each of these cases, the basic idea can be couched in the following terms:

response = material parameter x *stimulus*

However, as one might guess, once the driving force (i.e., the stimulus) becomes too large, the simple linear relation between force and response breaks down and calls for more sophisticated analysis. A particularly compelling example of these ideas is presented in the emerging field of single-molecule biomechanics in which the force-extension curves for individual molecules such as the protein titin found in muscle are measured using the atomic-force microscope. An example of such a curve is shown in Fig. 5. The vertical axis in this curve shows the applied force (measured in piconewtons) while the horizontal axis shows the extension of the molecule (measured in nanometers). What is remarkable is that the molecule goes through a series of processes in which the load increases (corresponding to the elastic stretching of the various domains) followed by a precipitous drop in the load (corresponding to the breaking of collections of hydrogen bonds in one of the globular domains of the protein).

A second example of this same type of massively nonlinear deformation is revealed by the process used to create the tungsten filaments that light our homes every evening. In this case, a cylindrical specimen of tungsten, roughly a

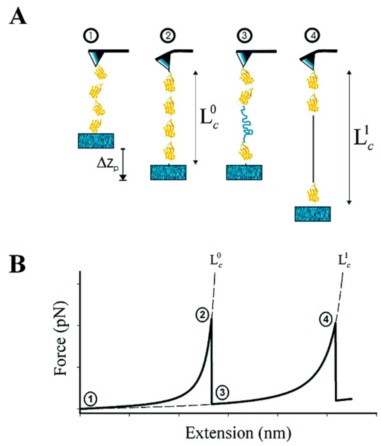


Figure 5. Schematic of the force-extension curve measurement procedure and the force-extension curve for the muscle protein titin. As shown in (A), the molecule is stretched using the atomic-force microscope and leads to (B), a force-extension spectrum which is a mechanical fingerprint for the molecule of interest (courtesy of Julio Fernandez).

meter long and several centimeters in diameter, is put through a series of deformation steps in which the tungsten is progressively elongated. By the end of this process, the tungsten rod of original length on the order of a meter has now been stretched to a length of *hundreds* of kilometers. This process takes place without changing the overall volume of the rod. We leave it to the reader to work out what this implies about the final diameter of the tungsten filament.

The nonlinear deformation of either proteins or tungsten (and most everything in between) is an intrinsically multiscale problem because in each case the macroscopic force response is engendered by microscopic processes. In the case of the deformation of a protein like that shown in Fig. 5, it is the breaking of particular sets of hydrogen bonds that give rise to steep drops in the force-extension curve, bonds which are characterized by a length scale of 10^{-10} m and not the 10^{-8} m typical of the measured force-extension curves. Similarly, in the deformation of tungsten, it is the motion of atomic-scale defects known as dislocations that give rise to the overall plastic deformation. As a result, in both of these cases a bridge is required which allows for a modeling connection to be made between the "microscopic" processes such as bond breaking and the macroscopic observables such as the force-extension curve. Efforts in the Phillips group and that of Michael Ortiz have been aimed at constructing multiscale models which are sufficiently general to be able to treat the force-extension curves in materials ranging from proteins to tungsten.

An intriguing alternative to the atom-by-atom simulation of force-extension curves like those discussed above has been the development of new techniques in which high resolution is kept only in those parts of the material where it is really needed. We close this essay with a brief exposition of the use of these methods to examine the way in which defects give rise to plastic deformation in strained materials, and how by virtue of entanglements of these defects, such materials are hardened. Without entering into a detailed exposition of the character of defects that populate materials, we note again that the plastic deformation of materials is often mediated by defects known as dislocations. Roughly speaking, dislocations are the crystal analog of the trick one might use to slide an enormous carpet. If we imagine such a carpet and we wish to slide it a foot in some direction, one way to do so is by injecting a bulge from one side as shown schematically in Fig. 6. Hence, rather than having to slide the whole carpet homogeneously, we are faced instead with only having to slide a little piece with a width equal to that of the bulge. Nevertheless, the net result of this action is overall translation of the carpet. This same basic idea is invoked in the setting of stressed crystals where the sliding of one crystal plane with respect to another is mediated by a line object (like the bulge described above) on which atomic bonds are being rearranged.

One of the key features of deformed crystals is the fact that the defects described above can encounter other such defects which exist on different crystal planes. The net result is the formation of a local entanglement known as a dislocation junction. The formation of such entanglements has the observable consequence that the crystal is harder—the critical stress needed to permanently

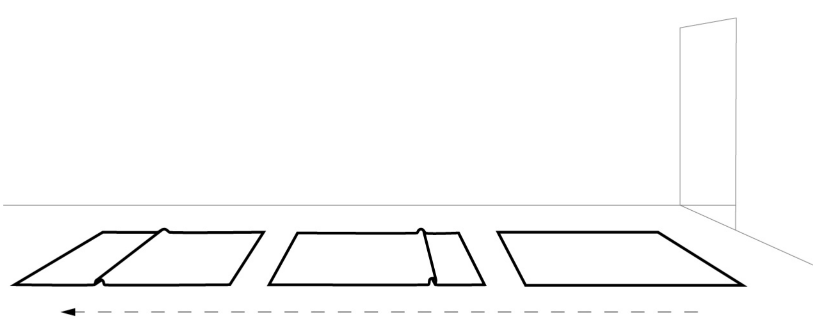


Figure 6. The sliding of a carpet by injecting a bulge is analogous to deformation of crystals by injecting dislocations.

deform the material (i.e., the plastic threshold) is raised by the presence of junctions. Although this entanglement is ultimately and intrinsically a particular configuration of the various atoms that make up a material, by exploiting ideas from elasticity theory it is possible to represent all of this atomic-level complexity in terms of two interacting lines. For present purposes, the replacement of the all-atom perspective by an elastic theoretical surrogate is exactly the type of multiscale analysis argued for earlier in this essay.

Figure 7 shows the structure of such a dislocation junction as computed not by considering the atoms that make up the material, but rather as a collection of interacting lines. Just as the various molecules that make up a gas can be eliminated from consideration by invoking an equation of state and exploiting hydrodynamics, so too in the context of modeling the deformation of materials may we replace defects that are intrinsically atomistic by elastic surrogates which allow us to answer the multiscale challenge of material response. As a result of exploiting the correspondence between the atomic-level and elastic description of junctions, we have been able to evaluate the critical stress needed to disentangle the two dislocations that make up a given dislocation junction. One example presented here (that of interactions between dislocations), ferrets out the nature of the conspiracy between the various defects such as dislocations, grain boundaries, and cracks that make up materials and that are responsible for observed macroscopic material response. Some of the other problems we have examined using multiscale models are the nucleation of dislocations at crack tips, the interactions of dislocations with grain boundaries, and the response of proteins to external forcing (Fig. 5).

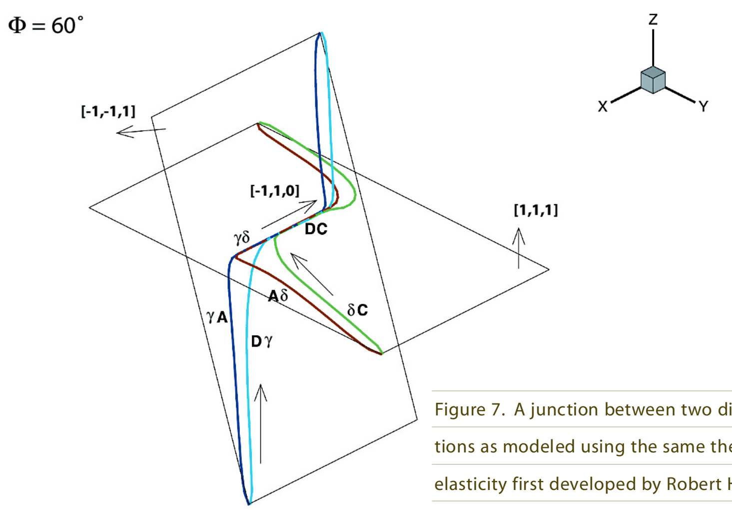


Figure 7. A junction between two dislocations as modeled using the same theory of elasticity first developed by Robert Hooke and derived using the experimental apparatus of Fig. 4.

This essay has attempted to convey some of the excitement that has arisen because of the advent of the ability to build models of systems of interest to scientists and engineers that intrinsically involve multiple scales in either space or time or both. Though we have argued that multiscale modeling has always been a part of the theoretical arsenal used to investigate problems ranging from turbulent flow to the magnetic properties of materials, high-speed computation has led to a resurgence of interest in the construction of coarse-grained models. This represents an amusing twist of fate since naively one might have expected that such computational resources would allow for the “first principles” simulation of processes without the need for theoretical surrogates. On the other hand, I have argued that as it has always been, the development of compelling models of the world around us must be based upon the realization of a tasteful distinction between those features of a system which are really necessary and those that are not. This idea served as a cornerstone in many of the great historical examples of multiscale modeling and serves as an embodiment of Einstein’s dictum that “Things should be made as simple as possible—but not simpler.” ENG

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Visit Professor Rob Phillips’s web pages via
http://www.me.caltech.edu/faculty

Mechanical Engineering: Future Forward

by Erik K. Antonsson

Mechanical engineering is the branch of engineering that is generally concerned with understanding forces and motion and their application to solving problems of interest to society. The field traditionally includes aspects of thermodynamics, fluid and solid mechanics, mechanisms, materials, and energy conversion and transfer, and involves the application of physics, mathematics, chemistry and, increasingly, biology and computer science. Importantly, the field also emphasizes the process of formulation, design, optimization, manufacture, and control of new systems and devices.

For most of the 20th century, mechanical engineering meant fluid and solid mechanics, thermodynamics and design. However, technical developments in the last decade have established the importance of interdisciplinary engineering and science, presaging the emergence of new technical disciplines within mechanical engineering. These new areas build on an understanding of the fundamental behavior of physical systems; moreover, the focus of this work is at the interface between traditional disciplines. Examples of the new disciplines include several overlapping mechanical engineering areas: micro/nano electro-mechanical systems (MEMS/NEMS); simulation and synthesis; integrated complex, distributed systems; and biological engineering. These new disciplines represent the crucial directions for Mechanical Engineering (ME) at Caltech.

Micro/nano systems have enormous promise to introduce sensing, actuation, controls, and computation into a wide range of situations. Everything from control of flow and combustion in gas turbines, local climate control in buildings, to advanced surveillance systems is being contemplated.

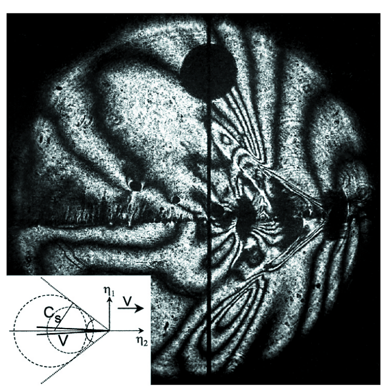
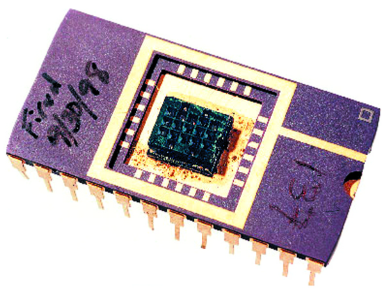


Image of an intersonic shear crack moving at a speed higher than the speed of shear waves and creating a shear sonic boom. From the research of Ares J. Rosakis, Professor of Aeronautics and Mechanical Engineering.

The road to realization of this promise will be long and challenging and requires the application of all of the traditional mechanical engineering disciplines to this new field. Many research efforts are underway at Caltech, from developing novel micro-thrusters and sensors for micro-spacecraft, developing novel active materials for micro-actuators, to constructing advanced modeling methodologies that bridge the length-scales from atomistic to continuum.

Simulation and synthesis of novel engineering designs is an exciting area of research at Caltech. In the early 1960s, engineering design methodology underwent a renaissance. Methods began to be developed to guide engineers through a process to produce high-quality designs. In the mid-1980s, these methods began to evolve from their informal (guide-



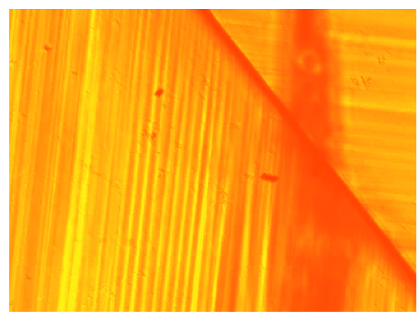
The digital propulsion "rocket chip" was developed at Caltech in collaboration with TRW and the Aerospace Corporation as enabling technology for micro-spacecraft. The microthruster array consists of a three-layer sandwich of silicon and glass, and is shown here mounted in a standard 24-pin ceramic dual-inline electronics package. This prototype contains 15 individual thrusters in the central 3 by 5 array. The visible bond wires are connected to resistors in each thruster that initiate combustion of the lead styphnate fuel. Each thruster cell produces 0.1 milli-newton-seconds of impulse, and about 100 watts of mechanical power. A successful suborbital test flight of these MEMS devices has been conducted.

line-like) origins to more formal, i.e., computable, methods. Recently, the foundations of methods to automatically synthesize new designs have begun to be developed. Synthesis is a difficult task; the creation of new designs is often thought of as a fundamentally human act. Emerging research has demonstrated that aspects of synthesis can be formalized and the foundations now exist to actively pursue highly automated synthesis techniques.

Integrated, complex distributed systems are all around us. Almost no engineered devices exist and operate in isolation. Automobiles and aircraft are part of a larger transportation system; manufacturing equipment is part of a larger production system; medical sensors are part of a larger health-care system. The modeling, simulation, and design of engineered devices must be done in the context of the increasingly highly interconnected distributed systems of which they are a part.

The recent explosion in the field of biology makes clear the urgent need for the development of the discipline of biological engineering to leverage the scientific advances for the benefit of society. Accordingly, Caltech's Bioengineering Option has strong participation from Mechanical Engin-eering. Our view is that just as chemical engineering has built on the scientific advances in chemistry to develop useful products and systems, bioengineering will build on the advances in molecular and neural biology. These new directions will take us far into the future—and the ME faculty are poised to help lead the way. A full strategic plan is available on the ME website.

In recognition of increasing student interest, the faculty has instituted an *undergraduate option* in Mechanical Engineering to begin in the 2002/03 academic year. The aim is to prepare students for research and professional practice in this era of rapidly advancing interdisciplinary technology. The program builds on the core curriculum to combine individual depth of experience and competence in a particu-



Microscopic patterns of the ferroelectric material barium titanate. This photograph was taken by Eric Burcsu, a Caltech graduate student jointly supervised by K. Bhattacharya, Professor of Applied Mechanics and Mechanical Engineering, and G. Ravichandran, Professor of Aeronautics and Mechanical Engineering. This material and related ferroelectric materials have an interesting property known as electrostriction: they change shape when an electric voltage is applied to them. Therefore, they are used as actuators that drive various micro-devices. Bhattacharya and colleagues predicted and demonstrated a new mode of electrostriction based on manipulating these patterns; the resulting electrostriction is at least 10 times larger that what was previously known.

History of the ME Option at Caltech

Mechanical Engineering has a long history at Caltech, and indeed the origins of the Option predate the formation of Caltech itself. The May, 1907 Throop Polytechnic Institute *Bulletin* indicated that "Although courses in Mechanical, Civil and Mining Engineering are not outlined below, considerable work is given in these branches of engineering and their collateral subjects. It is also the purpose of the Institute to extend the work along these lines as demand for it arises."

Apparently there was vigorous demand. Only a month later, in the June, 1907 *Bulletin*, a four-year program of subjects required for graduation in mechanical engineering "looking toward the degree of B.S." were published. These courses included Chemistry, Physics, and Calculus, as well as Shop Work, Machine Details, Prime Movers, Surveying, and Commercial Law.

A year later, in the May, 1908 *Bulletin*, it was noted that a Mechanical Laboratory had been established, and was "equipped with apparatus for the investigation of the strength of materials, to which will be added immediately, the apparatus needed to fully equip in other lines of mechanical experimentation."

The importance of engineering to the developing Throop Polytechnic Institute was made clear in the April, 1910 *Bulletin*: "The Institute confines its degrees to Electrical, Mechanical, and Civil Engineering." By January, 1917, Chemical Engineering, Chemistry, Engineering, and Economics, and General Courses had been added to the list of Bachelor of Science degrees offered by the Institute. The December, 1928 *Annual Catalog* of the (now) California Institute of Technology included a page showing the numbers of students in each area. Seventy-nine seniors were listed in Engineering (21 of whom were in Mechanical Engineering), out of a total Senior Class of 110 students. These numbers grew steadily to slightly over 40 seniors in ME until World War II. At the end of the war, the pent up demand for Mechanical Engineering was evident, with nearly 70 seniors, and 91 juniors in the program. A graduate program was added in 1933.

The Mechanical Engineering program continued through the 1959–1960 academic year, along the way adding a fifth year to the undergraduate program for students interested in a more specialized education. In 1960, however, the Institute chose to consolidate its undergraduate engineering offerings into a single program. The September, 1960 *Catalog* indicates "The California Institute of Technology has adopted a single engineering curriculum strong in the sciences and humanities with great flexibility of choice among the engineering sciences." Thus began the E&AS undergraduate program that currently graduates nearly 100 students each year.

In 1997, in recognition of student and faculty interest in a program more focused on Mechanical Engineering, a "Concentration" in Mechanical Engineering was introduced. The *Catalog* listed a set of required courses for students interested in ME. Students satisfying those requirements would earn an E&AS degree from Caltech, but with a notation on their official transcript, that they had "Concentrated in Mechanical Engineering." The number of students choosing to concentrate in ME has steadily grown, reflecting a continuing strong interest in the discipline.

With the reintroduction of the undergraduate Option in 2002/03, the Mechanical Engineering program at Caltech has come full circle.

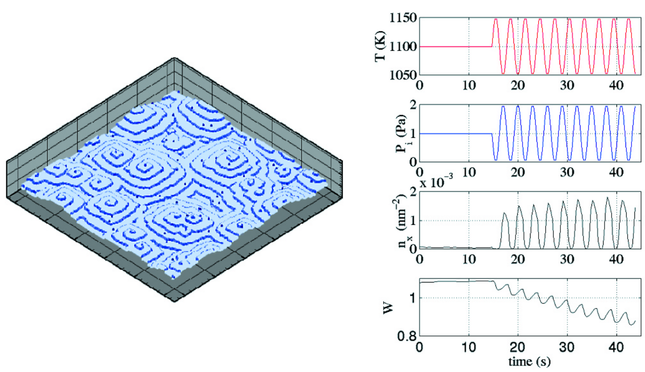
lar chosen mechanical engineering specialty, with a strong background in the basic and engineering sciences. It maintains a balance between lectures, laboratory, and design experience, and will emphasize the problem-formulation and solving skills that are essential to any engineering discipline. The program will also strive to develop in students self-reliance, creativity, leadership, professional ethics, and the capacity for continuing professional and intellectual growth.

Mechanical engineers are found in a wide range of application areas including automotive, aerospace, materials processing and development; power production, consumer products, robotics and automation; semiconductor processing; and instrumentation. Mechanical Engineering can be the starting point for careers in bioengineering, environmental engineering, finance, and business management.

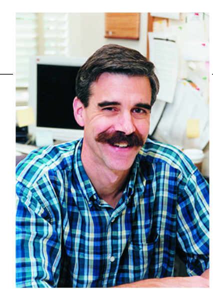
ME CENTENNIAL

The year 2002 marks the 95th anniversary of the establishment of Mechanical Engineering at Caltech and 2007 will mark the Centennial of the Mechanical Engineering program at Caltech. We are now initiating plans for this important event. Historical vignettes, photographs, and publications will be enthusiastically welcomed to help illuminate the distinguished history and contributions of the program.

To learn more about the ME Option and the anniversary celebrations visit
http://www.me.caltech.edu



A dynamic thin-film deposition. Use of time-varying process conditions may enable deposition of films with novel properties or lead to lower-cost processes. From research on engineering microstructural complexity in ferroelectric devices by David G. Goodwin, Professor of Mechanical Engineering and Applied Physics.



Erik K. Antonsson, Professor of Mechanical Engineering, is the Executive Officer of the ME Option. His research interests include formal methods for engineering design, formal design synthesis, representing and manipulating imprecision in preliminary engineering design, rapid assessment of early designs (RAED), structured design synthesis of micro-electro-mechanical systems (MEMS), and digital micropropulsion microthrusters. His research work is supported by the NSF, DARPA, and industry. He has published over 100 scholarly papers in the engineering design research literature and holds four U.S. Patents. He is a Fellow of the American Association of Mechanical Engineers (ASME), a co-winner of the 2001 TRW Distinguished Patent Award, the recipient of the 1995 Feynman Prize and a 1986 NSF Presidential Young Investigator Award. He served as an editor for the ASME Journal of Mechanical Design *and is currently on the editorial board of two international journals:* Fuzzy Sets and Systems *and* Research in Engineering Design.

Assembly and Creativity: An Interview with Three Founders of Caltech's Newest Option

NATURE HATH NO GOAL THOUGH SHE HATH LAW—or so observed the seventeenth-century poet John Donne. While we can only speculate about the former, we are certain about the latter, and researchers in the new Caltech interdisciplinary Option of Bioengineering aim to analyze, understand, and adopt the laws governing Nature's handiwork for the extreme benefit of multiple areas of science and engineering. Centered in the Division of Engineering and Applied Science, the graduate Bioengineering Option will be a full collaboration with the Division of Biology and the Division of Chemistry and Chemical Engineering.

At a variety of levels of order—from the molecular to the cellular to the organismal—biology is becoming more accessible to approaches that are commonly used in engineering, such as mathematical modeling, systems theory, computation, and abstract approaches to synthesis. Conversely, the accelerating pace of discovery in biological sciences is suggesting new design principles that may have important practical applications in man-made system design. Thus, the research synergism created at the interface of the enhanced understanding of complex biological systems and the design and synthesis of complex biological systems offers unprecedented opportunities to meet challenges in both biology and engineering.

The educational mission of the Option is to create a new generation of bioengineers superbly trained in both engineering and biological science, ready to realize the possibilities of reverse engineering of biological systems and produce biological structures from man-made materials. The faculty and students are drawn from diverse disciplines such as biology, computational and neural systems, mechanical engineering, electrical engineering, computer science, aeronautics, chemistry, and chemical engineering.

Some of the questions driving the research of this approach-integrating group include how can we engineer robust and controllable components (at levels of molecules, gene networks, and organelles) that can be inserted into organisms for clinical and research use; how can emerging engineering technologies, such as robotics, MEMS, and nano-scale systems technology, be used to improve our ability to carry out biological research, as well as enhance medical clinical practice; and how can biological discoveries be used to guide the development of new engineering components and systems?

Caltech has the distinct opportunity to redefine traditional "bioengineering," which typically concentrates on biomechanics, to include new areas of molecular biophysics and neurobiology, both of which are ripe for the application of engineering tools to analyze and synthesize biologically based and inspired systems. To learn more about the new Option, ENGenious interviewed Mory Gharib, Professor of Aeronautics and Bioengineering, Steven Quake, Associate Professor of Applied Physics, and Paul Sternberg, Professor of Biology.


Professor Steven Quake


Professor Mory Gharib


Professor Paul Sternberg

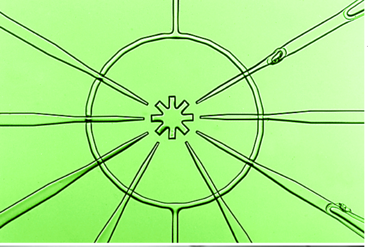



bioengineering interview

ENGENIOUS: What's the Bioengineering Option all about?

GHARIB: I think one can claim the Caltech version has converged with something that we think will address very certain principles of bioengineering, biosynthesis and biomimetics, and learn from nature's design, to come up with physics, analysis, and better devices. But you know, we can't just jump into it. You cannot just mimic nature. You have to first understand it. You have to mimic both function and, for example, geometry, in terms of reality. So, that's why we put together this program. It's not 100% complete, but there are different aspects that require a strong synergy between biology, engineering, chemistry, chemical engineering, and physics. Paul and Steve can add to this from their perspectives…

STERNBERG: As an experimental biologist, I'm trying to reverse engineer nature, to look at these organisms, to figure out how they do the wonderful things they do. And at some point, you say, we think we understand how it works. But, the proof of that



A microfabricated rotary pump device. Such a device consists of two layers: fluid channels on the bottom and pneumatic actuation channels on top. Fluid channels are 100 µm wide and 10 µm high. Two applications based on this rotary pump have been demonstrated: efficient on-chip fixed-volume and continuous flow mixing of two streams; and accelerated sensitivity in a surface binding assay.

A 1.5 mm long zebrafish (*Danio rerio*) embryo 48 hours post fertilization. Analysis of intracardiac fluid dynamics of the early embryonic heart may represent a useful approach to understand the interplay between physical forces, developmental gene expression, and cardiac pathogenesis.

understanding is turning it into engineering. And really, that's part of the excitement here—to demonstrate that for certain systems, whether they be molecular systems or gadgets, we can make something that's new.

QUAKE: Bioengineering at Caltech is M.S.G.: molecules, systems, and gadgets. Those are the three broad categories that capture what the central people in our Option are doing. In the area of molecules, we have some really clever and sharp faculty who are interested in this problem of molecular design, particularly for biological molecules. So Nature, the tinkerer and the designer, she's handed us 200,000 proteins to play with, but people at Caltech aren't satisfied with that. They're trying to come up with very clever ways to make new molecules. We have a very strong group in this respect. It's cool because they have a nice interplay between biology and engineering. For example, one of the ways Frances Arnold [Dickinson Professor of Chemical Engineering and Biochemistry] tries to design is to design by using evolution, which is not something that's in a normal engineering tool kit. But she's taking the principles of biological evolution and applying them to protein design.

Guys like Steve Mayo [Associate Professor of Biology and Chemistry; Associate Investigator, Howard Hughes Medical Institute] are trying to use very sophisticated computational methods to do evolutionary design. Systems engineers are good at making systems and have worked out a number of principles for doing that. Nature has done it, too, but historically biologists just haven't really appreciated that part of nature's designs. This has become a very interesting area to look at: to try to understand how biological systems function as a whole. Many people think that maybe nature uses similar design principles that engineers have worked out and they're trying to push that analogy and see how far it will take them.

GHARIB: These collaborations between biologists and engineers are not new. They work together on devices and approaches to systems. All the devices that helped the genomic revolution were designed by engineers and biologists working together. But, now that we have sequenced DNA, we ask ourselves how to put it back together in order to reconstruct big molecules, and eventually organs and systems.

QUAKE: The third area is gadgets. That's what engineers do—they make gadgets. And again we have a very strong group at Caltech. Guys like Mory are trying to take lessons from nature and look at the fundamental physics of how nature makes devices. How a growing heart develops, and how a heart pumps.

GHARIB: How does nature pump in general?

QUAKE: So he's trying to look at nature, understand what nature does and then try to engineer man-made gadgets that use those principles. Because in many cases, they're actually quite transposable and useful.

ENGENIOUS: So it's a very different viewpoint from a strict engineering perspective.

GHARIB: That's right. And also different from other bioengineering or biomedical programs because most of them try to build the pump that works inside someone's body. They build micro-fluidic devices without looking at the concept in nature. They have good solutions, but that's different from what we're trying to do.

ENGENIOUS: Look at nature and work backwards? So you're taking a much more biologically focused approach?

STERNBERG: Philosophically biological in approach, yes, but the outcomes might be different. You don't actually have to make it look like something in nature. You could use the principle, a design principle, and then come up with something new.

QUAKE: There's a very famous example of that which was done here at Caltech in the '80s. Done by the CNS group [Computation & Neural Systems], right? The general idea was trying to understand how the brain computes. The mathematical, physical models—neural networks—were sort of discovered and explored, and the pioneers were here. At the end of the day, I think they weren't that useful for understanding biology, but the principles that came out of them have found a number of applications in the engineering world. And so you'll find neural nets all over the place now as a computational tool. It's something that was inspired by biology, but it's got applications in engineering.

STERNBERG: But again, the interface is pretty interesting. Here's a little historical project that led to gadgets: Shuki Bruck [Gordon and Betty Moore Professor of Computation and Neural Systems and Electrical Engineering], some students, and I were trying to model certain aspects of development and function of a worm we were working on. We realized immediately that we were not collecting data fast enough. To get a good model you need a great deal of data. And the biologists, you know, are used to painstakingly doing it by themselves without any gadgets.

So we started to design something that could look at the worm to see how it wiggles, and where it moves in a sine-like wave. We developed a system that's proven to be very useful to quantitatively obtain information about what the worm looks like as a function of time. We could see how it wiggles and you can basically use that information to do the genetics of a sine-like wave, and try to model it.

QUAKE: Science always advances on gadgets. There's a long history of this. You can look in physics how it's happened. Physics in the 20th century has been driven by essentially two big projects from World War II. One is the radar lab at MIT. The development of microwave radar led to the development of the maser, development of the laser, atomic clocks, the precision frequency standards, high precision tests of QED [quantum electrodynamics]. You can trace it all very clearly back to the development of laser technology. And likewise Los Alamos had a huge influence on the development of particle physics.

GHARIB: Every time you have a new device, it leads to new understanding and, boom, new information comes.

STERNBERG: Much of this is on the analytical side and that's very useful. And then as you start to build things, you can say, all right, we have this device which has part of a living organism. Now we can start engineering. We can use things that we know that we've done in the laboratory to make this organism do something to our specifications. It's a very different kind of approach and there are some simple things you may find out that you never even asked about before—low hanging fruit.

ENGENIOUS: For example?

STERNBERG: Well, let's just say a lot of research in biology has been on merely finding the new components. Finding new parts and not saying how they work together: to really think about how it's working as a system, to understand in detail. Okay, you're limited by imagination, but when you start applying it, you immediately say, wait a second. If we want to get more sensitive, what's the tradeoff? And then we go do measurements. We would never have thought about those sorts of engineering issues before.

GHARIB: Let me give you a couple of examples of how we learn from nature. In the macroscopic realm, let's look at the heart. Let's say it, a mature heart, has four valves, a complicated thing. But if you look at the embryonic stages, the heart works without valves. How do you make it pump and pump without rest? For example, in a collaboration with Scott Fraser [Director, Biological Imaging Center Anna L. Rosen and Professor of Biology], we study the embryonic heart of the zebra fish. We've learned how to actually build valveless pumps. Then you try to use that new pumping technology in other applications. We try to put back into nature what we learn from it—to help people who have problems with their hearts.

Another example has to do with photosynthesis. We'd like to see how we can build VLSI circuits on lettuce leaves. Chlorophyll can be used as a capacitor, the power supply, and wire. So if the program is right, you can probably build a real circuit. This sounds like science fiction. But there are people at JPL who have already started to model this.

STERNBERG: Yeah, that's the spirit of the bioengineering field. Open it up. Go back to the science fiction. You know, let's mix up dif-

Medical robot prototype. The goal of this device is to access, in a minimally invasive fashion, the portions of the small intestine that cannot be accessed by conventional endoscopes.

ferent talents, different perspectives, see what happens.

ENGENIOUS: How is all this being communicated to students? What kinds of courses are being taught? They must be radically different from other courses.

QUAKE: It's a big challenge because we're bringing together two communities that historically had very little in common. And so, when we recruit graduate students we try to get them to come here from different backgrounds, from both engineering and the biology communities. So how can you make a curriculum that will address their needs, fill in the gaps, and take them to places we want them to go?

The way we've chosen to address that is to think about tailoring each student's curriculum to his or her background. The engineers take biology courses. The biologists take engineering courses. The centerpiece of the curriculum is our core course, Bioengineering 200, which they take together as a lecture and a lab component, that will help synthesize the two fields for them and lay the foundation for what we think are the important issues to look at in bioengineering.

ENGENIOUS: How long does it take before they get to the core course?

GHARIB: Well, we start them with this one year course in bioengineering—covering the principles of bioengineering. This first year is taught by three different instructors and each one brings a different aspect into the picture. [For a list of course descriptions visit the BE website at *http://www.be.caltech.edu*.] In the meantime they also take a vigorous program in mathematics, mechanics, chemistry, and biochemistry. It's a real challenge.

STERNBERG: But they're going to have to take risks to get the rewards.

QUAKE: This term [in BE 200] they're doing an extended experiment where we teach them how to program computers, if they haven't done that already. We're also going to have them do a very simple bioinfomatic analysis of a bacterium. This bacterium has the smallest known genome, 500 base pairs. So it's something that they can manage to analyze on a small PC. We're going to have them write, what I call, a toy version of algorithms that will find genes and find relationships between genes. We want them to kind of have the thrill of playing with the entire genome of an organism and try to do some computations on them.

The second month we're going to have them play with a real genetic circuit. We're going to take one of the existing genetic circuits that a group, just a couple of years ago, had managed to engineer a toggle switch in *E. coli* by using principles of visual design. We're going to have them make measurements on this bacterium and characterize this toggle switch, explore the boundaries of its performance, and do some basic molecular biology on it. We'll use it as a vehicle to teach elementary microbiology skill to the group. I think the biologists will have no problem with it but the engineers may have to explore new territory.

ENGENIOUS: Do we have any joint programs with any medical school?

GHARIB: Yes. UCLA and USC. So Bioengineering is part of the consortium of the MD/PhD programs that Caltech has with UCLA and USC.

STERNBERG: There are approximately two students a year from the UCLA and USC programs.

GHARIB: Students who were accepted this year into our program all had admission to at least one of the top five bioengineering departments in the country. They chose to come here because of the quality of the faculty.

ENGENIOUS: What really distinguishes the Caltech program from all the other distinct programs? How is Caltech unique?

GHARIB: I think it's the philosophy that's different. We try to teach them to learn about life's devices. There are other programs that study tissues left and right, top and bottom. But we're trying to understand how the tissues are being made.

STERNBERG: We have no boundaries. We're going to take a very broad look at things. We have three divisions coming together out of necessity, and we're going to get access to every possible great idea, and many great minds.

GHARIB: Each faculty member here acts like a biological system. If you look at a biosystem like a muscle, it doesn't do just one thing. It's capable of performing different functions. Caltech faculty immerse themselves in different fields. You may think I work on heart valves, but the next day you'll see me working on laser devices. It's very important that each one of us has interests, professional interests, in different fields of science and engineering. That's why I think we're different. Each student receives lots of exposure from our experience.

STERNBERG: That's what makes it different. Of course it's just starting. We'll see. But we're excited about the timing.

ENGENIOUS: How did you become involved in this and become an active participant, get the Option going?

QUAKE: Well, you know, my own career has been sort of on the boundary of physics and biology. As a one-person show, you can only go so far. To have a whole option set up where everyone is trying to do the same thing, incorporate different areas and philosophies, is tremendously attractive to me. Paul had also spontaneously started trying to incorporate ideas from engineering into his research. Mory was the one who got us all organized.

GHARIB: I think the idea of having bioengineering here at Caltech is not new. If you look at the top programs in this country, three of them were started by Caltech graduates: Georgia Tech, UC San Diego, and UC Berkeley. I think what's new here is that a new generation came in at about the time of the new revolution in biology. Suddenly we realized that it's more exciting than ever. We looked at the levels the students were looking at, cell sequences and cell sorters. Those are things that, ten years ago, it was hard to even imagine. Now we can tackle the problem, learn about it, and work with people like Paul and come up with better ideas.

QUAKE: Yeah, it's sort of a grass roots effort. Mory just pointed out, hey, everyone's doing all this great stuff. Let's build a real quality program around it and create an infrastructure that educates students in an organized way, rather than piecemeal.

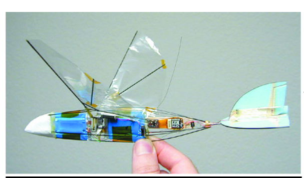
STERNBERG: I think part of it is giving support to students. I have several areas of research: bioinformatics, databases, generating devices in modeling, and computational biology that I can offer support in. You know, it's always a struggle when students are torn because they don't have the peer support when it comes to what to do, how to go about things. So this program is a potential source for that support network. The other thing is it's just so exciting.

ENGENIOUS: What kinds of devices or what kinds of fundamental results might we expect in the next 5 to 10 years?

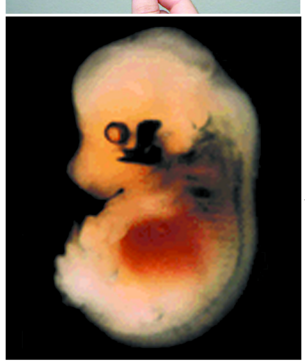
QUAKE: We're pursuing a program to attempt to make very highly integrated chip-based devices to do biology, lab on a chip as it were. There's a huge number of very basic scientific problems that one can address with new gadgets. We have already made the world's smallest valves and pumps and we recently figured out ways to integrate them so you can have thousands of these valves on a chip and do very complex plumbing. A fundamental problem we're particularly interested in is microbial diversity. Look around the world, pick any environmental sample, whether it's sea water, soil, something from your gut, or a termite gut. You'll find that there is an incredibly diverse ecosystem of bacteria living in there. And in large measure, these ecosystems are completely uncharacterized. How do you characterize bacteria? Well, you've got to grow them in a culture. And when you start growing…

STERNBERG: And many of these things can't be cultured because they need 15 different friends.

QUAKE: That's right. Many of these things can't be cultured



The Microbat—a flapping wing microelectromechanical (MEMS) device may one day go where man would rather not.



The mouse embryo is studied to understand the regulation and execution of developmental decisions that lead from multipotential,undifferentiated precursor cells to their specialized differential products.

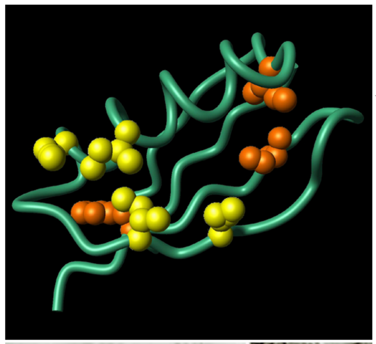
because they need friends. Or what happens is that when you try to culture, the fastest growing ones completely overwhelm the population. So instead of having this incredibly diverse population, you have a fairly simple one. The conventional tools in biology left that aside. We think our microfluidic chips are going to allow us to take a peek at this microbial diversity because we developed the tools to manipulate and analyze single cells. What we'd like to do is take a population, divide it up, and then analyze each cell independently. This is something that has more value than basic science. There's a large number of diseases that are associated with bacterial populations, either from getting a bacteria or getting an imbalance in the community. And actually it's suspected that many current diseases that aren't associated with bacteria just might be of bacterial origin. So there's a whole field of emerging infectious diseases and the next easiest tool is to try to track them down and nail the associations.

GHARIB: There are many new fields like nanotechnology that we'll be using. JPL has many programs in this area and gives another flavor to our program. That's the space side of bioengineering. For example, we get many good students here because they associate Caltech with JPL and GALCIT. And they'll grab benefits from having access to all. Maybe one day we can come up with a true implantable heart system, a cardiovascular system that can be implanted that's self-sufficient, takes energy from the body, and is efficient enough that it works like a real heart. But it will take five, ten or more years. And many technological revolutions have to occur before we can offer such things.

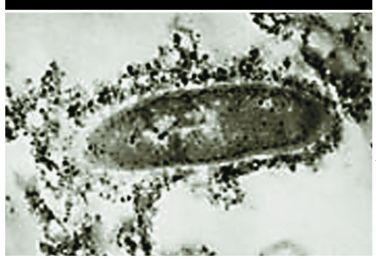
ENGENIOUS: And Paul, what kinds of things, in the next five to ten years, are you looking forward to?

STERNBERG: I think building circuits within cells and building gadgets within cells that communicate with each other and do other things. That's where we come to the self-assembled device, one of the mysteries of life.

STERNBERG: Generally we just talk. Once you're in the program, you're excited about it and you talk it up. I was on jury duty and I was sitting there waiting to get called, and the guy sitting next to me was excited about applying to the program. He was a former Caltech student, out for ten years. But that's where he got the idea.



In the ever expanding knowledge of the chemistry of life, Caltech researchers are exploring the intimate details of protein structure and stability and using this knowledge to design, build, and test proteins with novel biochemical properties.



The continued study of bacteria may reveal how they transfer electrons to insoluble minerals via organic compounds.

ENGENIOUS: How are you recruiting the best students?

QUAKE: By doing the best science.

GHARIB: Steve is right, indirectly. The faculty is the best asset of the program. And the reputation of our program is helping with recruitment.

This year, we started registering the program with different organizations, to try to bring our strengths to the attention of the best students in different departments, and encourage them to apply. We write and ask them to come here for an interview. We are very selective. Last year out of the 45 who applied, we picked six.

ENGENIOUS: Any wrap-up thoughts that you want to communicate particularly to an alum audience?

GHARIB: The message is that this is a new, exciting option with lots of promise. It's got some of the best faculty that we can put together here at Caltech. They're all eager and energetic to bring their talents and energies here. So as a result it's very fun to work with this group. Lots of good ideas, lots of challenging ideas. It makes it more challenging for us to accommodate other faculty because the expectations are very high for the Option. ENG

Caltech's Bioengineering webpage is at
http://www.be.caltech.edu

Anna Iwaniec: Bioengineering Graduate Student Working Close to the Heart

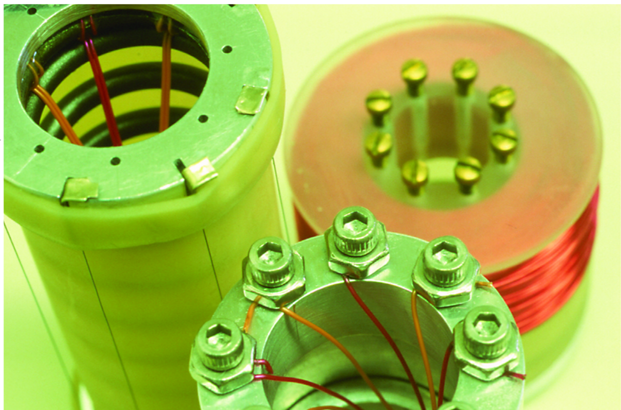
THE GRADUATE STUDENTS WORKING ON THEIR PhDs IN BIOENGINEERING come to Caltech from a variety of disciplines and institutions. Anna Iwaniec, however, is homegrown. After completing her BS in Engineering and Applied Science (with honors), with a concentration in Mechanical Engineering, she tinkered around for a year in various engineering-type things. In contact with Professor Mory Gharib, she returned to Caltech as an engineer in his cardiovascular fluids dynamics laboratory. Her interest and ability in mechanical design lent itself perfectly to the design and testing of a few of Gharib's heart pump ideas.

Working closely with the pumps simultaneously expanded and concentrated her thinking about her future directions. What the world needs now, she thought, were new paradigms in medical device and product design. *"Oftentimes, medical devices are designed by doctors. I think that I can offer new ideas to the industry by applying my engineering skills. It is the combination of backgrounds that will allow for the development of innovative designs."* Gharib suggested that she apply to the new Option in Bioengineering. World-class biological sciences research was happening a couple of buildings away on campus and, if she could integrate the two broad areas, maybe she could approach these same engineering problems in radical ways and truly advance the work she was doing.

That was the upside. The flipside was that a mechanical engineer now had to take biology classes (a couple of buildings away) from Caltech's superstars of anatomy, physiology, molecular biophysics, neurobiology, and the like. Ouch. This was going to be hard and, not surprisingly, it is. *"I was really nervous jumping into classes without all the background that most of the students had, though I knew that the courses would give me knowledge important for gaining a broader perspective of my research."* But Caltech seems to attract people who rise to the challenge and make things their own.

How's she doing? Nearly nine months into the program, Anna's excited. The course work thus far is as interesting and fulfilling as it is challenging, and there are great people all around. *"No matter how abstract the work at Caltech gets, you know that you can always rely on fellow students and faculty to lead you in the right direction to help you accomplish your goals."* We'll get back to you in a few years to let you know where it's all leading... ENG

Visit Anna's personal page to learn more.
http://www.iwaniec.org



Prototype designs demonstrating how helical bands can be used to create a squeezing action were originally conceived to create valveless pumps. Such design principles may lead to important biomedical fluid displacement devices.

The Caltech Office of Technology Transfer: Making Friends and Start-Ups

by Fred Farina

Ten thirty on a sunny Tuesday morning. A handful of yellow leaves on Holliston Avenue. The first signs of a timid Southern California autumn. The San Gabriel Mountains decide to join us today. The haze temporarily lifts. It's a good day. Professor Smith and one of his doctoral students, Sarah, pass by Human Resources walking decisively. They can see the mountains in front of them. Their destination: the Office of Technology Transfer (OTT). Their mission: a start-up. Their secret dream: the next Microsoft. Their reality check: Larry Gilbert. Their best ally: OTT Director Larry Gilbert.

Larry's assistant, Penny, announces the visitors. Larry gets off the phone. He was talking to a VC. He greets Professor Smith and Sarah with a nonchalant, "What have you got?" Smith replies, "a funded company." The news arrived this morning, his start-up has received funding to the tune of $5 million. This day is getting even better.

Because Caltech only took a small equity position in the company, the founders, Professor Smith and Sarah, were able to retain substantial ownership. Together with the management team they have put in place with the help of OTT, they will embark on the development of a competitive product while valiantly leading the company to a possible IPO or maybe an acquisition. Smith and Sarah are glad they have been disclosing their inventions to OTT over the years. They are happy OTT aggressively filed patent applications to protect their inventions, provided advice and guidance through the start-up process, gave them a fair licensing deal for the patent rights owned by Caltech, introduced them to top venture capitalists, and referred competent professionals such as lawyers and accountants so critical in the early stage of a start-up. In fact, they are really glad they came to OTT, and today they are here to share their success.

Nice story. Very nice story. And not that uncommon. Every year, five to ten start-ups get off the ground hoping to successfully commercialize Caltech/JPL technology. OTT's involvement includes negotiating a licensing deal, as well as fully assisting the young company in all aspects of the start-up process.

Beyond start-ups, OTT is involved in a multitude of activities revolving around the transfer of technology developed at Caltech and JPL to the commercial sector. Despite OTT's young age (it was founded in 1995), Caltech has become a nationwide leader in the transfer of university-based technology, ranking near the top in the number of technologies disclosed and licenses executed every year. OTT consists of nine members known as the "Otters," including five licensing professionals and four administrative staff. The activities of the office can be divided into four main categories:

- Identifying promising technologies and evaluating their commercial viability.
- Selecting inventions which warrant patent protection and managing the patent portfolio (this responsibility is shared with the Office of Intellectual Property Counsel).
- Negotiating and drafting license agreements with commercial companies.
- Fostering start-ups and assisting Caltech entrepreneurs.

These activities embody the four main facets of the Institute's philosophy on technology transfer.

The first aspect of this philosophy relates to building and maintaining relationships with faculty and other inventors in order to maximize the influx of invention disclosures. The office takes particular care to create a friendly and non-bureaucratic environment in which inventors feel comfortable about reporting new inventions and regard the process as painless, almost fun. To this end, Otters routinely meet with faculty and other technologists, discuss their research, and solicit their input. Aside from making the work more interesting for the Otters as they actively interact with our distinguished faculty, this strategy has resulted in a dramatic increase in the number of inventions disclosed to the Institute. In 1995, less than 80 inventions were disclosed; in 2001 the office received more than

Members of the Office of Technology Transfer (left to right): Penny Wolfe, Traci Arnold, Melinda Bakarbessy, Bob Gallagher, Larry Gilbert, Scott Carter, Rich Wolf, Liz Olson, Fred Farina.

160 invention disclosures.

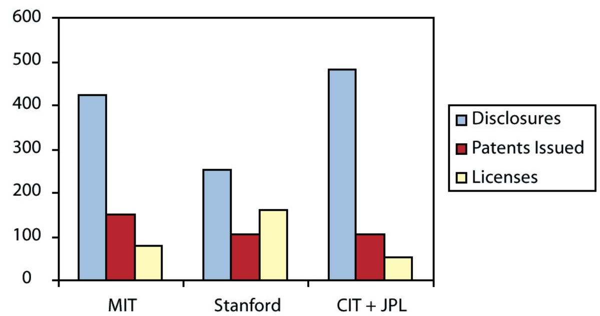
Protecting the Institute's intellectual property is a central OTT responsibility. The general approach is one whereby inventions are evaluated for their commercial viability, and patent applications are filed for those which are deemed to have the potential to be successful in the marketplace. In particular, market trends are identified, areas of technology in high demand are determined, and invention disclosures which relate to these technologies are aggressively protected using the patent system. In order to efficiently implement this strategy, the Otters stay abreast of the trends by monitoring areas of high market demand and constantly researching promising areas of technology. Strategically limiting the number of patent applications filed to those inventions that have the potential to generate royalties greatly reduces the high cost of developing and maintaining a strong patent portfolio.

Then there is licensing strategy. Here, the difficulty is to determine whether the technology at hand would have the best chance to quickly and profitably reach the marketplace if licensed to a larger company, a medium size corporation, or a start-up. To accommodate differences between this wide range of licensees, license agreements are tailored to the needs of the licensee and may include royalties only, equity only, or a combination of both, in exchange for the transfer of intellectual property.

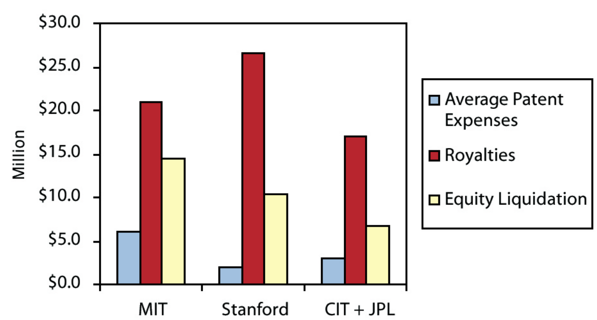
By investigating which technologies are being pursued by major corporations, it is possible to identify the inventions that are best suited for a strict royalty licensing deal with a large company. Using as an example a single patent covering a therapeutic, it would be costly and inefficient to base a start-up entirely on this invention, while a large pharmaceutical company will have the resources and expertise to develop a drug, bring it to market, and generate revenues. On the other hand, a group of patents covering a certain area of technology, such as optical switching, may best be licensed to a start-up. Indeed, a substantial patent portfolio will attract investors, and the start-up will devote all of its resources to the development of a competitive product. At a large company, technology development opportunities often abound, and certain technologies may be left on the shelf in favor of more profitable pursuits. Additionally, historical data from Caltech and other leading universities also show that revenues generated from equity deals with small businesses are second only to a few large royalty deals with major corporations. Unless a technology is clearly best suited for a "strict royalty/large company" licensing deal, OTT will first consider equity opportunities with start-ups, and then explore licensing opportunities with established companies if the elements of a start-up are not present.

Caltech has become a nationwide leader in the transfer of university-based technology, ranking near the top in the number of technologies disclosed and licenses executed every year.

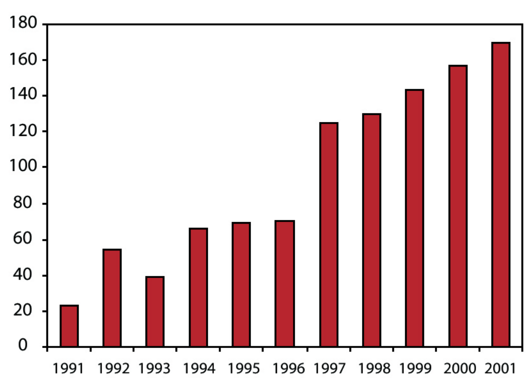
All things considered, the "two bites of the apple" approach informs everything OTT does. By fostering entrepreneurial activities of the inventors, creating a friendly environment for entrepreneurs, providing support, contacts, and valuable services to start-ups, and allowing entrepreneurs to hold large equity positions in companies, OTT is earning the trust and support of Caltech innovators. In addition to the direct impact on the Institute's community, the region benefits from the high-tech industry growth generated by Caltech's entrepreneurial activities. This reflects well on the Institute, and also produces prosperous entrepreneurs who will remember the role Caltech played in their success and will likely give back to the Institute. This concept is what is referred to as "two bites of the apple," the first bite being the equity consideration in the company for the license, and the second being the charitable donation. Caltech has already been the beneficiary of charitable gifts of stock from Umachines and Codegrok, largely because of OTT's role in their early development.



Plot 1 illustrates the number of invention disclosures received, patents issued, and licenses completed at Caltech, Stanford, and MIT over fiscal year 2000.



Plot 2 illustrates the patent expenditures relative to revenues at Caltech, Stanford, and MIT over fiscal year 2000.



Plot 3 illustrates the number of campus invention disclosures received (JPL not included).

In the future, OTT hopes to increase the number of start-ups created every year while securing a number of high-revenue royalty deals. This can be realized only with the help of Caltech/JPL inventors and entrepreneurs. Otters always welcome inquiries and are happy to assist with issues relating to the patent and licensing process, start-up information, business contacts and referrals to professionals, or any other technology-transfer related questions.

It's spring and two winters have passed since Professor Smith and his student received their first round of funding. Much has happened. Positive things for the most part. Several Caltech students joined the company after graduation and the company's Pasadena offices have expanded. A second round of funding came in last year and a product has been developed. Today is a defining day for the company. Smith and Sarah have asked Larry to meet them at the Ath for dinner. Champagne is on the table. "What have you got this time?" asks Larry. Hardly containing her excitement, Sarah jumps in: "Today we signed on our first customer, and the order is big big big ..." ENG

Fred Farina, MSEE '92, is a Licensing Associate in the Office of Technology Transfer.

For additional information, including a comprehensive list of start-ups, please see http://www.caltech.edu/ott

Sherman Fairchild Library: Technical Reports in the New World

by Kimberly Douglas

In 1997, Caltech opened the Sherman Fairchild Library of Engineering and Applied Science, the result of a generous gift from the Sherman Fairchild Foundation. This new library provided not only an aesthetic environment for study and reading but also a state-of-the-art computer-systems infrastructure. The fast network, new servers, and high-end workstations formed the core of expanded networking services of the future. Recently this technology was upgraded with wireless access by a gift from the Lee Center for Advanced Computing. One of the most far-reaching of the Library's new initiatives is the commitment to the creation and maintenance of digital technical reports and other documents—part of a revolution in academic publishing that is now taking place across the globe.

It is generally accepted and understood that the research community, along with everyone else, is shifting from a printing-press culture to one dominated by the global computer internet. Faculty members in every discipline hail the convenience of real-time desktop access to whole collections of journal articles over the internet. It was the creation of the world wide web that made this ubiquitous electronic alternative to the print journal possible, though subscription barriers remain the same and research libraries continue to struggle with escalating journal prices.

As society moves into the electronic environment, the Copyright Law and its attendant doctrines and interpretations* have been alternately challenged or championed depending on one's perspective of how the internet optimizes sharing of information. If the scientific ethos, as Robert K. Merton observed in 1942, is to continue to embrace common ownership of research findings, then society or, at the very least, the research community, must establish a new model for its written work that balances the existing law with the needs and behaviors of that group.

The research community has been dependent on publishers for peer-review and distribution of work for community acknowledgement. Naturally, the publishers, societies, as well as commercial entities develop and adhere to a business plan to survive. For the most part, these have evolved into a "reader pays" access model that creates ever-higher financial barriers for the prospective audience. At the Conference on Scholarly Communication hosted at Caltech in March 1997 (see *http://library.caltech.edu/publications/ScholarsForum/proceedings.htm*), the attendees, university librarians and provosts from across the United States, concluded that distribution of scholarly works could be decoupled from the peer-review process. This would make the former less dependent on the publishers' business plan and thus free it from the high cost barrier necessitated by publisher involvement.

Similar to the culture of preprint distribution in the physics community, engineering departments have a long and successful history of producing valued technical reports documenting the research of their respective faculty. These reports have functioned not only as communications to funding agencies but also as a mechanism for exchanging research results with targeted groups at other universities and institutes around the world. Such exchanges continue to be a necessary part of the informal human network so essential for sharing research results—a sharing that is a prerequisite for research progress.

The intent/purpose of this genre, that of reporting back to funding agencies and disseminating research results, is aided by current technologies allowing technical reports to be digitally mounted on a network for all to easily discover and access. Computer science technical reports are an established example. For decades, even as far back as the 1950s, computer science departments around the world published technical reports documenting the research of faculty and students. Through a Defense Advanced Research

* *Doctrine of First Sale (Section 109 of the Copyright Act, 17 U.S.C. 109) allows the owner of a copy of a legally acquired book or recording to sell or otherwise dispose of possession without the authority of the copyright owner. The principle of fair use (Section 107 of the Copyright Act, 17 U.S.C. 107) continues to be subject to varying interpretations despite the factors laid down in the law.*

Projects Agency (DARPA) grant in 1994, this effort was migrated to a digital federated library environment called NCSTRL, the Networked Computer Science Technical Reference Library, *http://www.ncstrl.org*. Over the years and through the success of the program, the list of participating organizations has now grown to over 200, including Caltech. The project's impact curtailed the need for print copies of the reports to be produced and distributed. Moreover, as long as each site keeps its digital collection current and its repository server up, everyone on the internet has immediate 24/7 access to the worldwide collection.

Many engineering groups at Caltech generate technical report series, including Earthquake Engineering Research Laboratory Reports, the GALCIT Reports in Aeronautics, and the aforementioned Computer Science Technical Reports. Unhindered by licensing and cost barriers, interested persons anywhere and at anytime can access these collections over the internet.

In 1999, the Caltech Library System conducted a self-publishing survey at Caltech and found that, as was hypothesized, the Engineering and Applied Science Division predominated on the Caltech web. This observation formed the basis for moving aggressively to mount the Division's reports to the internet, thus forming the nucleus of a digital library. Subject specialist librarians from the Sherman Fairchild Library work with the Division's faculty to review the collection, assure quality control, and mount the reports in the digital repository. The Library converts any print-only reports to pdf files, adds the metadata (descriptive and identifying elements of the document) for searching, and submits them electronically into the local digital repository, *http://library.caltech.edu/digital* for archiving in perpetuity. This approach has made over 260 Computer Science reports back to the 1980s now available. Another 193 reports from the Earthquake Engineering Research Laboratory were added this past year. In addition to converting retrospective collections, the library oversees the addition of new reports authored by current faculty and students, such as the Computer Science Technical Reports, to active repositories.

Most recently, in late June 2001, the success and interest in the Library's work opened another trial for digital scholarly publishing to the internet. Professor of Mechanical Engineering Chris Brennan, organizer of the Fourth International Symposium on Cavitation, approached the Caltech Library System to publish the conference's papers on the web. Submissions began in May 2001 and the site was ready for use by early June. Even with a few papers still lacking, the proceedings of nearly 100 papers were available for viewing well before the conference began. No time was lost for collating, printing, and mailing. The papers continue to be available to all and the proceedings are documented via the national library catalog, Worldcat, with a link to the persistent URL, *http://cav2001.caltech.edu*.

The Library's commitment to the maintenance and world-wide discovery of the digital library entails adhering to current and evolving national standards for protocols, file formats, and markup. To that end, the Caltech Library System joined the Coalition of Networked Information, *http://www.cni.org*, and is an active participant in NCSTRL, NDLTD, and other organizations implementing the Open Archives Initiative (OAI) *http://www.openarchives.org* protocols for metadata harvesting.

A year ago at Caltech, Professor Kenneth Pickar commented that the internet is the "mother of all disruptive technologies." Through the gift of the Sherman Fairchild Foundation, the Caltech Library System embraces the capability and potential of the internet to offer the research community opportunities to make the most of this most excellent disruption. ENG

Kimberly Douglas is the Director of the Sherman Fairchild Library of Engineering and Applied Science and Technical Information Services.

Caltech Alumni Association members have access to many of the Library's services including on-site use of the on-line services and databases.

More about the Sherman Fairchild Library at
http://library.caltech.edu/sherman

Paul C. Jennings, PhD '63: Profile of an Everywhere Man

by George W. Housner

PAUL JENNINGS RAN THE GAMUT AT CALTECH from student to Professor, Chairman, Provost, acting Vice President for Business and Finance and, this year, Professor Emeritus. He says that he enjoyed his career as Professor most and is now looking forward to an academic career with no duties and no commitments during which he can do all those jobs that he has in his mind and did not have time to do.

Paul was born in 1936 in Brigham City, Utah and grew up in Paonia and Grand Junction, Colorado where he began his love affair with trout fishing in mountain streams. He always liked the outdoor life. In high school he thought of becoming a Forest Ranger and even got a summer job in Alaska, which cured him of this idea. He obtained a BS degree in civil engineering from Colorado State University and then came to Caltech for graduate studies, obtaining his PhD degree in 1963. At that time, the draft was still in effect, but an ROTC student could get deferment to do graduate studies and then owe the military three years of duty. In the spring of 1963, Archie Higdon, author of several pre-war engineering mechanics books, visited Caltech and told me that he was responsible for the teaching of mechanics at the newly organized Air Force Academy. He would identify the bright young men who were getting their PhDs

and owed the three years and would then have them assigned to the Air Force Academy. He said that he intended to have Paul Jennings and Wilfred D. Iwan [BS '57, MS '58, PhD '61, Director, Earthquake Engineering Research Laboratory] come to the Academy to teach mechanics and, in fact, that was arranged.

In 1964 there came the great Alaska earthquake, Richter magnitude 8.4. I, as well as Donald Hudson and Ronald Scott were drawn into the activities, in particular, preparing the engineering report on the Alaska earthquake for the National Academy of Sciences. As Paul's PhD research had been on destructive earthquakes, he seemed a logical person to help in this effort. A request was made to the Air Force, and Paul was assigned to Caltech for over a year.

Paul was appointed a Member of the Engineering Panel of the National Academy of Sciences Committee on the Alaska earthquake and made several trips to Alaska to view the damage and to collect data. The Caltech efforts resulted in a massive report containing 31 papers, several of which include his name as author. He was released from the Air Force in December of 1966, six months early in an economy move that occurred just as the Vietnam War effort was building. Paul was appointed Assistant Professor on January 1, 1966, at a salary of $10,500 and embarked on his academic career.

For the next 20 years, Paul had an active academic life: teaching, supervising PhD students, doing research and publishing 48 technical papers. He was widely recognized as one of the leaders in the field of earthquake engineering. He also was engaged in many extracurricular pro bono activities, including serving as president of the Earthquake Engineering Research Institute and president of the Seismological Society of America. He also served on numerous national committees, including the National Research Council Committee on Seismology and the National Research Council Committee on Natural Disasters, which he chaired. He was also a member and later chairman of the Charles Stark Draper Prize Committee of the National Academy of Engineering. During these years he served as consultant on the seismic design of most of the Exxon Hondo deep-water oil drilling platforms in the Santa Barbara channel and also the fifty-two story Atlantic Richfield Tower buildings in Los Angeles, as well as others.

During his career, he received numerous honors and awards: Election to the National Academy of Engineering, the Walter Huber Research Prize from the American Society of Civil Engineers, the Newmark Medal from the American Society of Civil Engineers, and was elected Fellow of the American Academy of Arts and Sciences and of the American Association for the Advancement of Science.

In 1985 Paul was appointed Chairman of the Engineering Division which began his administrative career. After four years, he was appointed Vice President and Provost and worked with President Thomas Everhart. When his term as Provost ended, the position of Vice President for Business and Finance was vacant because David Morrisroe unexpectedly had to retire for health reasons. Paul was asked to serve in this position until a permanent appointment could be made. He served for one year and then returned to being a professor, only to come back and serve again in 1998–1999 as Acting Vice President for Business and Finance, during the interim between John Curry and William Jenkins. In the fall of 1999 he again returned to the faculty. In that year he also received the Best Paper of the Year Award from *Spectra*, the journal of the Earthquake Engineering Research Institute. He again resumed a slate of professional activities. For the past three years he has served as the chair of the California Council on Science and Technology. He is presently the chair of an administrative committee charged with proposing a new campus center building at Caltech.

When President Nixon visited Chairman Mao, they agreed that China and the U.S. should cooperate, especially in science. Apparently the only scientific subject that appealed to both sides was earthquakes...

During his professorial career, Paul has traveled to many countries—Spain, Italy, Turkey, Japan, China, India, and others—to investigate or to confer on earthquakes. The trip to China had special significance. When President Nixon visited Chairman Mao, they agreed that China and the U.S. should cooperate, especially in science. Apparently the only scientific subject that appealed to both sides was earthquakes and so some trips were arranged for Chinese teams to come to the U.S. and for U.S. teams to visit China. Paul was a member of the U.S. National Academy of Sciences team that visited China in 1978 and spent three weeks visiting various locations and earthquake laboratories. The main purpose for making this trip was to learn about the Great Tangshan Earthquake of 1976, which devastated the city of Tangshan and the surrounding countryside and killed an estimated 500,000 people. When the team returned to the United States, Paul was editor of the report published by the National Academy of Sciences that described what was learned during the trip.

Although Paul is now Professor Emeritus, he has not yet shaken the administrative dust from his coat. He is still involved in various tasks. He expects that in due course he will be free at last, and he is looking forward to twenty more productive years of academic life. ENG

The author, George W. Housner, is the Carl F Braun Professor of Engineering, Emeritus, and is an MS '34, and PhD '41 graduate of Caltech.

Allen E. Puckett: PhD '49, Aeronautics

by Jill Andrews

Use your imagination! And don't be afraid of taking risks.

How does an unknown, bright young Caltech scholar, during the pre-World War II era, become a leader in the exploding new world of supersonic aerodynamics, airfoil theory, and guided missiles? How does that same expert in fluid mechanics easily switch fields to become an international leader and corporate visionary during the rapid evolution of electronics and global satellite communications? And, after reflecting on a long and successful career, what message does he wish to send to his fellow alumni? For answers, I visited Caltech Distinguished Alumni awardee Allen E. Puckett at his Los Angeles home.

For more than 60 years, Allen Puckett has been at the left, right, and center of a number of important research advances. As an industry captain with strong connections to government and academic research, he played various key roles in the development of supersonic flight, guided missiles, manned space flight, and communication satellites. After launching his career with his seminal thesis, *Supersonic Wave Drag of Thin Airfoils*, an important examination in radical aerodynamics, he went on to collect numerous awards, including the National Medal of Technology for the construction of the first synchronous satellite and the first commercial communications satellite.

INTRODUCTION TO CALTECH — AND THE WAR

Puckett's scientific, engineering, and technological adventures were set in motion during his years at the Guggenheim Aeronautical Laboratory at the California Institute of Technology (GALCIT). He had arrived at Caltech from Harvard in 1941, invited by Theodore von Kármán, who became his mentor and a source of inspiration:

Theodore von Kármán gave me the strongest feelings of curiosity, the urge to explore and discover. He taught the value of the pleasure of exploring new ideas. He was a remarkable man—a wonderful human being. Just to know him was a privilege. He had a way of inspiring and stimulating us to keep probing, working to discover whatever it was we were looking for.

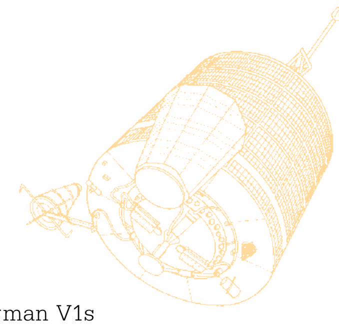
Puckett had barely set foot on campus when the United States entered World War II. The unique combination of the place as it was then, with the people Puckett met there, was at once tumultuous and thrilling—and always filled with discovery. Progress on his PhD was delayed by world events. However, the experience he gained as a consultant to the U.S. Government (1945–1949) added weight to the importance of finding ways to apply research to real-world challenges. Every day he and his fellow scholars learned something new and dedicated themselves to imagining new applications for their research.

THE FLUID MECHANICS YEARS

When I arrived here there were plans to build a 3-inch square test section supersonic wind tunnel. No one had ever built one in this country and that was my project.

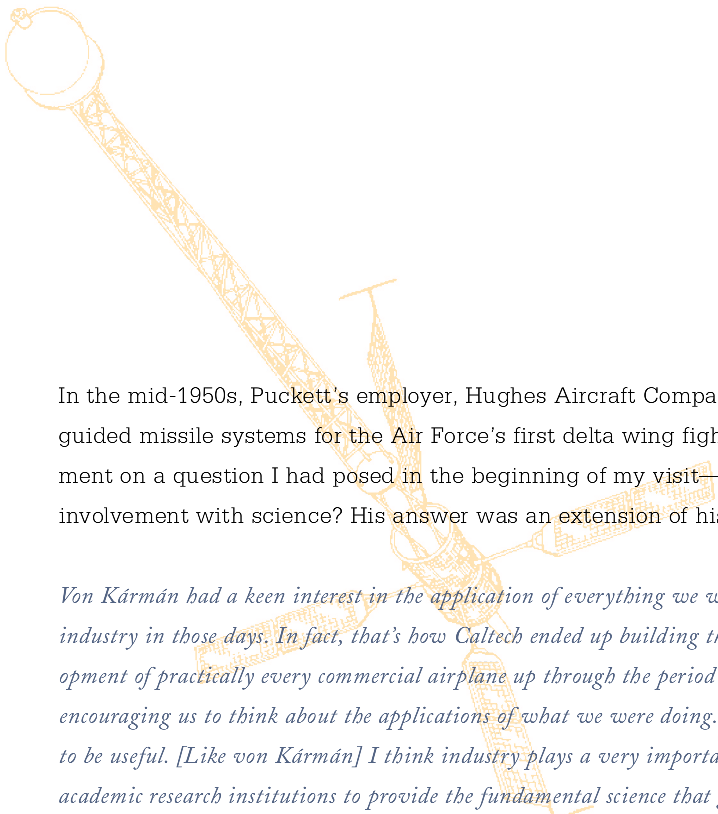
Puckett had moved into a turbo-charged atmosphere, where his own imagination, intelligence and perseverance were both appreciated and strengthened. He first worked on an Army Ordnance Corps-funded project to test various types of artillery shells and projectiles for supersonic flight. Even though artillery projectiles exceeded the sound barrier, conventional wisdom of the day cautioned that airplanes would never fly faster than the speed of sound. But with the appearance of the German V1s and V2s, the U.S. Government's interest increased dramatically in wings, stabilizers, and bodies that might resemble missiles or aircraft at supersonic speeds.

Von Kármán, who had heard about a new German wing design that might possibly overcome the sound barrier, challenged Puckett to calculate the new concept: a "swept" leading edge that might delay the effects of shock waves over the wing, thus "fooling" the wing into "thinking" it was going slower than it actually was. The idea sounded possible to von Kármán. He trusted Puckett's ingenuity, mathematical expertise and, of course, his imagination, to produce a plausible calculation in support of the theory. In less than two years, Puckett produced the calculations that supported the concept. His paper got a lot of attention, and it became the basis for his PhD thesis.



While playing with various calculations, Puckett realized that the equations were "pretty messy," so to illustrate the basic principles involved, he chose a simple shape: the triangle. It was several years later and long after he left Caltech that the delta wing, as he coined it, would be incorporated into aircraft such as the Convair F-102 "Delta Dagger."

I used a triangle because the geometry was simpler—the equations were easier to handle, and it made it easy to develop some principles or concepts about the effect of sweeping back the leading edge—the triangle could be long and skinny, or blunt—and then you had to choose where the maximum thickness would be—farther forward, or aft. Later in my paper and in my thesis I called it a "delta wing." This was the first serious attempt at a delta wing.



In the mid-1950s, Puckett's employer, Hughes Aircraft Company, was chosen to build the radar and fire control and guided missile systems for the Air Force's first delta wing fighter, the F-102. Puckett paused at this point to comment on a question I had posed in the beginning of my visit—what did he think about the importance of industry's involvement with science? His answer was an extension of his Caltech mentor's vision and the ethos of GALCIT:

Von Kármán had a keen interest in the application of everything we were doing. He maintained strong connections with the aircraft industry in those days. In fact, that's how Caltech ended up building the famous 10-foot wind tunnel, which was used in the development of practically every commercial airplane up through the period of the war. He kept his students very much motivated by encouraging us to think about the applications of what we were doing. He wanted to know that the things we worked on were going to be useful. [Like von Kármán] I think industry plays a very important role in modern science, but it still has to depend on the academic research institutions to provide the fundamental science that goes into all aspects of what industry does—solid state physics, for example, or biomedicine. The industries are necessary to develop the applications that make this all pay off in the end—I think the universities more and more are recognizing that the collaboration between industry has been an essential part of the process to provide end results that are useful to you and me—to the people of the world.

FROM SUPERSONICS TO ELECTRONICS

In the days of pre-supersonic flight, GALCIT faculty and students certainly had the right stuff. Anything they published was new, a first. Yet in the years following the War, soon after he joined Hughes, another "revolution" occurred—this time in the electronics field, which promised far-reaching effects on data processing, data storage, and communications. These three areas of electronics application changed the way the world communicated with itself. Puckett again was in the right place at the right time, and he moved easily from the world of theoretical fluid mechanics to the promising new field of electronics.

It was the mathematical underpinnings that allowed me to switch fields. That is a very interesting part of my career—I was just plain lucky to be around as the electronics field was beginning to explode. It matched very well with all the things I had been doing, so how could I not move into this new field? Everything we touched was new and exciting—the field was wide open! If you were reasonably bright and had some imagination—and worked a little bit—you could be the first and a leader in the field.

The introduction of satellite communication had an enormous impact on the world, and researchers at Hughes were among the first to set things in motion. They had proved it could be done by transmitting the 1964 Olympic games from Tokyo to this country via satellite, marking the first time anyone could see an event in real time from the other side of the globe. Yet Puckett and his colleagues did not stop there. Supporting the idea of man in space was next. They took on a government contract to broadcast the first television pictures of the surface of the Moon, a vital preparatory step in the Apollo program, which put the first man on the Moon in 1969.

The Surveyor Project was one of my most memorable and valuable accomplishments. From a communications point of view, distance just disappeared.

FROM ELECTRONICS BACK TO FLUID MECHANICS...SORT OF

During the next two decades, as Hughes' Executive Vice President, then President, and finally Chairman and CEO, Puckett kept pace with emerging technologies. With Hughes, he found ways to create applications for the most sophisticated research results scientists and engineers in academia could offer. No doubt his influence gave rise to Hughes' mission of today: Breaking the Thought Barrier.

In 1987, he once again found himself in the right place at the right time—exploring, full-time, the practical applications of fluid mechanics in the form of sailing yachts. "Retirement" is the grand adventure that allows him, between marinas and large bodies of water, to spend more time with his wife, Marilyn, and his children and grandchildren.

Although his full-time commitment to industry shifted to Chairman Emeritus status in 1987, Puckett's interest in technological advancement has only accelerated since then. In this context, he is extending his business acumen visionary thinking through phila thropic efforts for Caltech faculty and students. He and Marilyn, lo time members of the Caltech Associates, have established the Allen and Marilyn Puckett Professorship and most recently funded the Puckett Laboratory fo Computational Fluid Dynamics.

It is interesting to note that the most dramatic real innovations in technolo have been the result of private enterprise—the original and unconventio thinking of a small number of people an environment that encourages inno tive thinking. In the academic world philanthropic contributions can be a factor in creating the right environm for innovation. It is not possible to p dict the results—that is the essence of innovation—but we can guarantee t there is enormous opportunity for dra matic new ideas. ENG

Jill Andrews works on behalf of Calt educational outreach programs.

Mitigating the Effects of the Ultimate Fracture Mechanics Problem:

John Hall Looks at Earthquakes

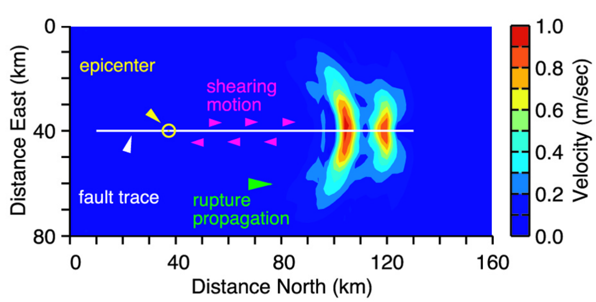
PROFESSOR OF CIVIL ENGINEERING JOHN HALL works with a group of earthquake engineers and scientists at Caltech who aim to understand and mitigate the risks posed by major earthquakes. Hall is intrigued by the interplay between engineering and seismology, the challenge of the technical issues, and the necessary tasks of public education and application of research results. In the earthquake field, success is ultimately measured by achievements in risk reduction.

Over the last decade, Hall has been interested in how to reassess the earthquake safety of tall buildings in light of findings that have been made since many of these structures were built. The biggest high-rises are steel frames with welded connections that, as revealed by the 1994 Northridge earthquake, may exhibit brittle fracture rather than the desired ductile yielding when stressed during strong ground shaking. Recent discoveries of new faults has increased the seismic hazard in many cases, such as the Elysian Park blind thrust fault under Los Angeles which could produce a magnitude 7 event. Furthermore, earthquake faults are now known to focus energy in the direction toward which the rupture is propagating, a kind of seismic Doppler effect, resulting in rapid ground displacement pulses that could be especially damaging to tall buildings. The ongoing research program uses mathematical building models and computer simulation to quantify these effects and provide data on which economic justification of retrofit programs could be based.

Computer simulation is an important tool in Hall's research. He has employed it, for example, in studies of the earthquake response

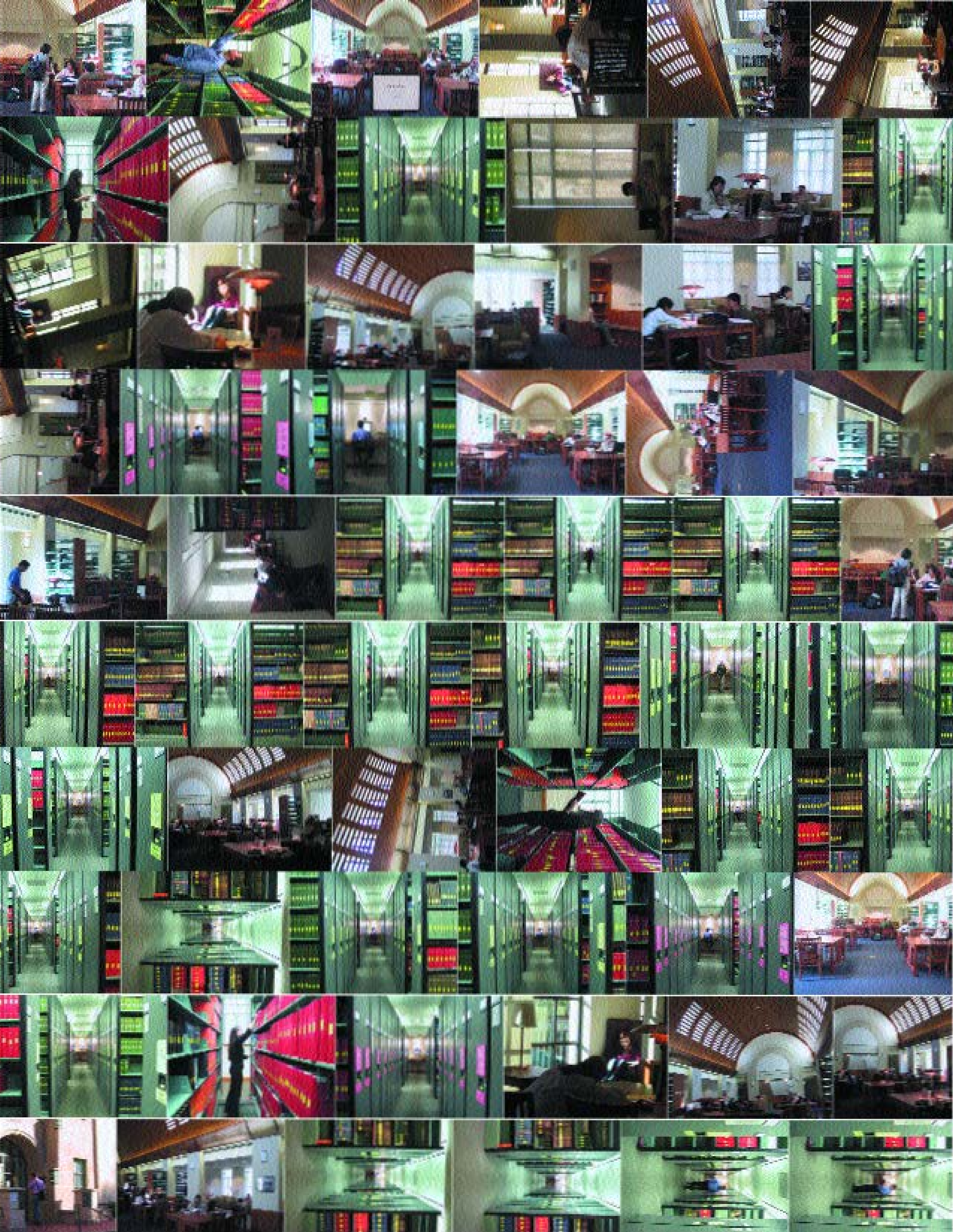
With potential savings in the tens of billions of dollars, it is entirely practical to establish a dedicated laboratory... which would feature a large shaking table on which full-size houses could be erected and tested.

of concrete arch and gravity dams and in demonstrations of the effectiveness of using rubber base isolators and shock absorbers to obtain highly seismic resistant designs for structures such as hospitals which need to be functional after an earthquake. Computer simulation is even being applied to the Earth to model the earthquake itself. A recent investigation has shown how the particular features of the 1999 Chi-Chi earthquake in Taiwan resulted in a relatively benign Doppler effect, which helps to explain the less-than-expected damage from shaking for this magnitude 7.6 event.



The above graphic of a fault line shearing in a computer-simulated earthquake demonstrates that large ground velocities occur in front of the propagating rupture, the seismic Doppler effect.(Credit: B. Aagaard)

In 1998, Hall took on the management of a multi-university research project funded by the Federal Emergency Management Agency (FEMA) to improve the earthquake resistance of wood construction used in housing. Long neglected by the research community, wood buildings suffered about $20 billion in damage from the Northridge earthquake. Since wood construction is surprisingly complicated structurally from a mathematical modeling point of view, much of the effort has been laboratory based in order to investigate basic behavioral modes. So far, limited shake-table testing indicates that structural enhancement of the typical exterior stucco finish and interior gypsum board walls, together with other modest improvements, could tremendously reduce the damage potential of wood houses. With potential savings in the tens of billions of dollars, it is entirely practical to establish a dedicated laboratory for such studies, which would feature a large shaking table on which full-size houses could be erected and tested. As the present FEMA project winds down, Professor Hall takes every opportunity to argue for this exciting new facility for earthquake engineering research. ENG



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