ENGenious

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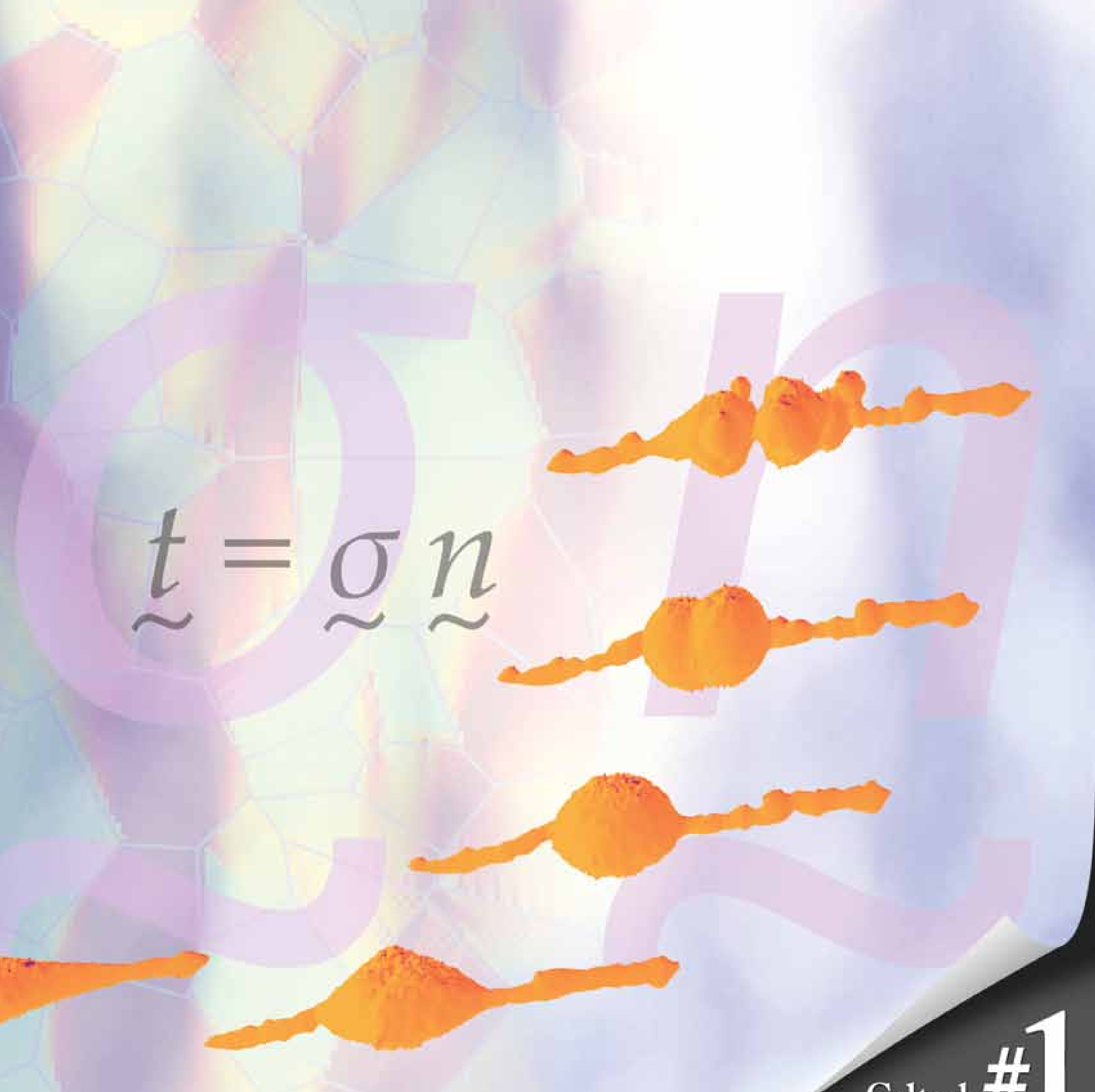

Caltech #1
in Engineering & Technology
Find out more on page 3!

The Caltech Division of Engineering and Applied Science consists of seven departments and is home to more than 75 faculty who are working at the edges of fundamental science to invent the technologies of the future.

We invite you to learn more about the Division through our website, eas.caltech.edu.

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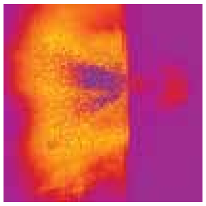

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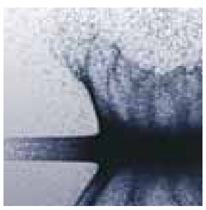

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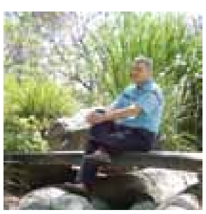

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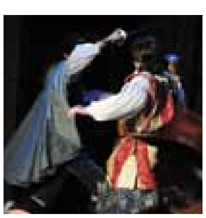

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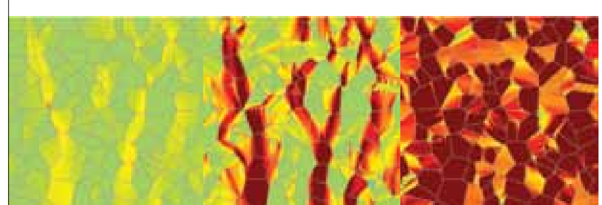
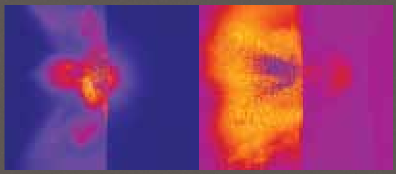
Cultural Ambassador for Science
Brian Brophy, Director of Theater Arts at Caltech

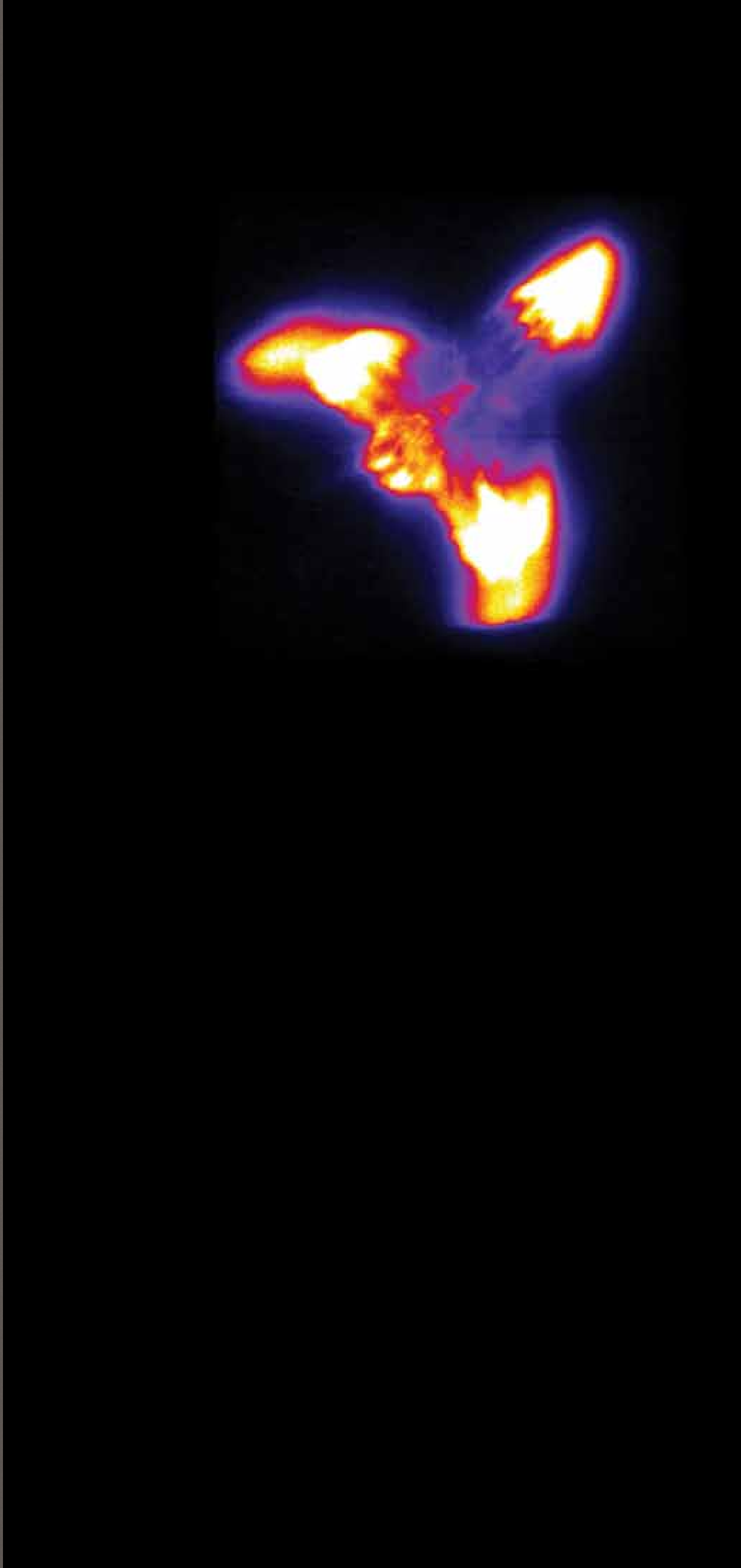
Cover images:

Cell division is a ubiquitous process in biology. A dividing cell undergoes drastic three-dimensional conformational changes, starting from a spread football shape, then turning into a sphere, and finally splitting apart into two daughter cells. During this process, the cell remains connected to its surroundings through the slender extensions at either tip. The forces applied by the cell to its surroundings can be computed through the Cauchy relation ($\underline{t} = \underline{\sigma}\,\underline{n}$), where t *is the traction force,* σ *is a measure of the stress within the material, and* n *describes the shape of the cell.* [Image credit: Jacob Notbohm, Ayelet Lesman]



The image above shows details of the deformation of a polycrystalline shape-memory alloy at the microscale. Shape-memory materials are active or smart materials that have an ability to "remember" a given shape. The process of deformation in these materials is extremely complex, with different features emerging at different length-scales. The image shows the pattern at a micron scale and represents three different levels of load. [Image credit: Andrew Richards]





Above: *High-speed infrared (IR) images of a 1.5-mm-thick 6061-T6 aluminum target at zero-degree obliquity impacted with a 1.75-mm nylon projectile (frontal view) moving from left to right at 5.5 km/s and 6.1 km/s, respectively. The field of view of each image is approximately 25 cm wide by 20 cm high. The IR camera was exposed from 11 µs to 13 µs after impact for the first image (left) and from 13 µs to 15 µs after impact for the second image (right).* **Right:** *Optical high-speed camera image of a nylon cylinder impacting an aluminum plate at a speed of 5.5 km/s that was taken ~4 microseconds after the nylon impactor first contacted the plate. Colors in the image represent the intensity of the light being emitted from each area of the image. Purple is the lowest level of emission, and white areas are the brightest. The images were taken in the GALCIT/JPL hypervelocity impact facility. Experiments were conducted as part of the Department of Energy Predictive Science Academic Alliance Program (DOE-PSAAP) Center in Engineering and Applied Science.*

This issue of *ENGenious* features a number of our faculty, alumni, and students who are working at the edges of fundamental science to invent the technologies of the future and to tackle the biggest problems facing humanity. As you read, I encourage you to think about the Engineering and Applied Science (EAS) Division and Caltech's greatest achievement—**the creation of new schools of thought**. These schools of thought reflect our combined achievements and excellence in both research and education. It starts with the faculty's dedication and commitment to training students in their area of expertise or singularities of excellence, which is supported by mastery of the fundamentals. Then these students become the next generation of academics, researchers, technologists, and leaders who in turn train their own students and associates, and in the process they influence industry, the economy, and even government policy and societal perceptions. They are the inheritors and carriers of both our educational and our research philosophies.

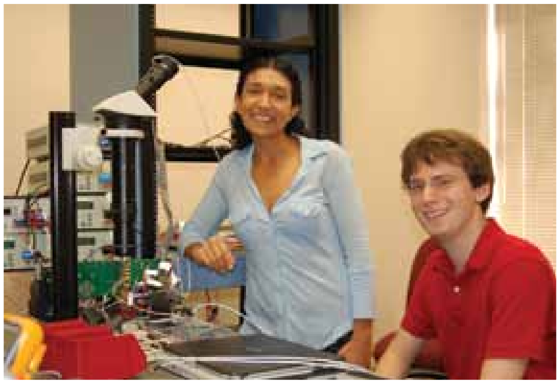
One may ask how the small number of faculty in the EAS Division can have so great an impact that Caltech can maintain the top position in the *Times Higher Education* world university rankings in the area of engineering and technology for multiple years. First, by design, we don't cover all areas in engineering and applied science. We dynamically choose only the ones that we consider the most important, and we are ready to retire the ones that are not intellectually stimulating. Our faculty do not represent a continuum of research interests and specialties. We are, in the words of my old Caltech mentors, Professors Jim Knowles and Eli Sternberg, **a collection of isolated singularities**. However, in order for these isolated areas of excellence to be effective, the second principle has to be introduced. This principle dictates that the barriers between disciplines, departments, and even divisions remain very low so that both faculty and students can cross them, if they wish, without spending unnecessary energy. This is a principle that is also shared throughout the Institute and necessitates the existence of a truly interdisciplinary culture in which turf and labels become secondary to intellectual exchange. Other major engineering schools speak of the value of interdisciplinary research; our difference is that we have practiced it since our founding over 100 years ago. It was simply critical to our survival.

In this analogy, the isolated singularities of excellence represent our chosen disciplinary strengths in research and teaching, while our interdisciplinary research groups and centers can be viewed as sparks created between the disciplines. These energetic sparks of interdisciplinary brilliance may or may not be short-lived, but they are triggered by our desire to tackle society's big problems and are facilitated by low barriers to enter new fields. New challenges, such as renewable energy, and new ideas, such as bioinspired engineering, create new and sometimes unexpected sparks. Long-standing problems, such as terrestrial hazards involving both the fluid and the solid earth, represent longer-lasting sparks. Indeed, engineers do best when they tackle and mitigate humanity's biggest calamities and problems.

A.J. Rosakis

Ares J. Rosakis
Theodore von Kármán Professor of Aeronautics
and Professor of Mechanical Engineering;
Chair, Division of Engineering and Applied Science

'Round About the Institute



Azita Emami-Neyestanak and undergraduate Jeff Sherman

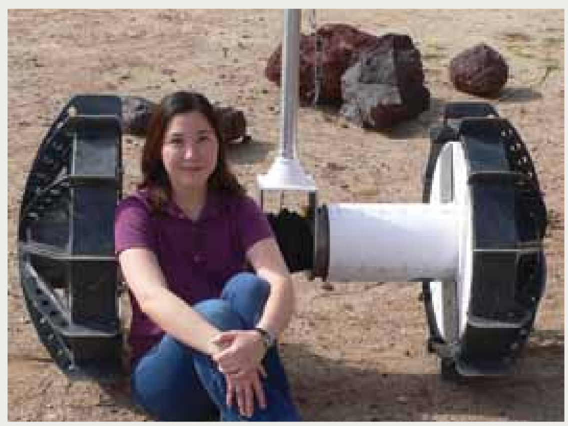
Protecting the Brain with Infrared Light

Undergraduate student Jeff Sherman spent the summer working with Electrical Engineering Professor Azita Emami-Neyestanak on a novel, noninvasive early treatment for traumatic brain injury. Sherman was a Summer Undergraduate Research Fellowship (SURF) student and winner of the 2012 Arthur Rock SURF Fellowship. They worked on an approach that uses minimally invasive infrared (IR) light and intravenous medications to diagnose and treat patients during the "golden hour" right after the brain injury occurs. The aim is to prevent the long-lasting sequel of secondary brain injury by locally delivering drugs to the injured area. In concussions and other types of traumatic brain injury, the blood-brain barrier is transiently disrupted in the region of the injury; the team takes advantage of this by targeting delivery of therapeutic agents to the site of injury. The long-term goal of the electrical engineers on the team is to develop a wearable and portable device with optimum arrays of IR transmitters and backscatter detectors. Such a device can be carried by emergency and combat medics and can be used in hospitals and sports stadiums.

To learn more about Professor Emami-Neyestanak's research, visit www.mics.caltech.edu, and to learn more about SURF, visit surf.caltech.edu.

Testing an Extreme-Terrain Rover

Melissa Tanner (SURF '08), a mechanical engineering graduate student and student lead for the Keck Institute for Space Studies (KISS) mini-program Tools and Algorithms for Sampling in Extreme Terrain, mentored five 2012 Summer Undergraduate Research Fellowship (SURF) students who developed instruments and tested various aspects of scoop sampling on the extreme-terrain rover called Axel. The rover could one day be used to explore the moon, Mars, or an asteroid. The Caltech faculty mentor to the project is Joel W. Burdick, Richard L. and Dorothy M. Hayman Professor of Mechanical Engineering and Bioengineering, who is also part of the Caltech and Jet Propulsion Laboratory team developing Axel.



Melissa Tanner with an extreme-terrain rover

To learn more about the project, visit robotics.caltech.edu/~pablo/axel/home.html, and to learn more about KISS, visit kiss.caltech.edu.

Reinventing the Toilet

Michael Hoffmann, the James Irvine Professor of Environmental Science, and his research team were awarded a $100,000 prize by Bill Gates for their first-place finish in the Reinventing the Toilet Challenge research initiative sponsored by the Bill and Melinda Gates Foundation. Their winning prototype and concept employs a toilet system that uses the power of the sun to drive an electrochemical waste treatment reactor. The reactor breaks down water and human waste into fertilizer and hydrogen, which can be utilized in hydrogen fuel cells to produce electricity. The treated water is then recycled in a closed-loop system to flush the toilet in preparation for future use.

To learn about their self-contained photovoltaic-powered domestic toilet, visit eas.caltech.edu/news/489.

The Hoffmann group solar toilet research and development team on the roof of the Linde-Robinson Laboratory

Redefining the Limits of Photovoltaic Efficiency

Harry Atwater and Eli Yablonovitch, co-founders of Alta Devices, hold the world-record–breaking solar cell.

Since 2009, the Light-Material Interactions in Energy Conversion Energy Frontier Research Center (LMI-EFRC) has established itself as a national resource for fundamental optical principles and photonic design for solar energy conversion. The center, directed by Professor Harry Atwater, is creating new optical materials for high-efficiency photovoltaics and has fostered a world-leading capability for fabrication of complex 3-D photonic nanostructures and light absorbers. The LMI-EFRC team consists of expert researchers including faculty, postdoctoral scholars, and students from Caltech, Lawrence Berkeley National Laboratory, and the University of Illinois at Urbana-Champaign. Their discoveries include demonstrating the first optoelectronically active 3-D photonic crystal; utilizing the entire solar spectrum in photovoltaics via up-conversion, down-conversion, down-shifting, and spectrum splitting; designing architected silicon microwire arrays for enhanced solar absorption; and emphasizing the importance of light emission in photovoltaics, which led to Alta Devices' world-record–breaking solar cell.

To learn more about innovative research at the LMI-EFRC, visit lmi.caltech.edu.

Transforming Our Knowledge of the Quantum World

The Institute for Quantum Information and Matter (IQIM) at Caltech is the newest of the National Science Foundation's 11 Physics Frontiers Centers. It is charged with the responsibility to develop and sustain outreach efforts to the scientific community and the public. Have you ever wondered what makes a theoretical physicist tick? Does looking at the quantum world change how you see other things? Through the blog *Quantum Frontiers*, IQIM scientists, grad students, and participants in the summer research program share varied perspectives (not limited to science). IQIM is also supporting two conferences in January 2013, one for undergraduate women in physics and the second for youth in connection with TEDxCaltech: The Brain.

To learn more, visit iqim.caltech.edu.

Top to bottom:
Venkat Chandrasekaran; Andrei Faraon; Scott Diddams; Peter Schmid

New Faculty

Venkat Chandrasekaran
Assistant Professor of Computing and Mathematical Sciences

Venkat Chandrasekaran's research interests lie in mathematical optimization and its application to problems in the information sciences. His recent contributions include computationally efficient methods for learning latent variables in statistical models and techniques for solving a broad range of inverse problems that arise in scientific disciplines. A central theme in these approaches is the prominent role played by convex geometry in high dimensions. Current efforts are focused on developing algorithms for processing massive amounts of data, with the upshot being that larger datasets are more efficient to process than smaller ones.

Chandrasekaran received his PhD in electrical engineering and computer science from the Massachusetts Institute of Technology (MIT) in 2011 and his undergraduate degrees in mathematics and in electrical and computer engineering from Rice University in 2005. He has been a postdoctoral fellow at the University of California, Berkeley, where he worked on statistical inference problems involving massive datasets. He has also been a visiting researcher at the Los Alamos National Laboratory, where he was part of the Center for Nonlinear Studies in the Theoretical Division, working on problems at the intersection of statistical physics and machine learning. He received the 2012 Jin-Au Kong Outstanding Doctoral Thesis Prize in electrical engineering at MIT for his dissertation.

Andrei Faraon
Assistant Professor of Applied Physics and Materials Science

Andrei Faraon is interested in developing nanophotonic quantum technologies for devices that operate close to the fundamental limit of light-matter interaction. Applications include on-chip optical signal processing at ultra-low power levels, energy-efficient sensors, biophotonics, and quantum information processing. The development of nanophotonic quantum devices in the Faraon lab involves a design phase based on nanoscale classical and quantum optics, nanofabrication that pushes the limits of state-of-the-art cleanroom equipment, and optical characterization at the single photon level.

Faraon received his BS in physics from Caltech in 2004. He then moved to Stanford for a PhD in applied physics and an MS in electrical engineering, both of which he received in 2009. His PhD research focused on developing integrated photonic crystal devices with coupled quantum dots for classical and quantum information processing. Following his PhD, he became a postdoctoral fellow in the Intelligent Infrastructure Lab at Hewlett-Packard (HP) Laboratories in Palo Alto, California. At HP, he developed photonic quantum technologies based on nitrogen vacancies in diamond and built optical interconnect devices in silicon. Faraon received the Ross Tucker Award in 2008 for advancement of the technology of materials used in semiconductor electronics. He has published over 25 journal articles and coauthored three book chapters.

Moore Scholars

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

Scott Diddams

Physicist and Project Leader, National Institute of Standards and Technology

Scott Diddams is an experimental physicist working in the fields of precision spectroscopy and metrology, nonlinear optics, and ultrafast lasers. Since 2000, Diddams has been a staff member and project leader at the National Institute of Standards and Technology (NIST). His work focuses on the development of optical frequency combs, and he has pioneered their use in optical clocks, tests of fundamental physics, novel spectroscopy in the visible and mid-infrared, precision metrology, and ultralow noise frequency synthesis. Diddams received his PhD from the University of New Mexico in 1996. From 1996 through 2000, he did postdoctoral work at JILA, a joint institute of the University of Colorado at Boulder and NIST. In 1998, Diddams was awarded a National Research Council fellowship to work at JILA with Dr. John Lewis Hall on the development and use of optical frequency combs. With JILA colleagues, he built the first self-referenced, octave-spanning optical frequency comb and used it to demonstrate carrier-envelope phase stabilized pulses, as well as carry out direct optical-to-microwave measurements. Diddams is also a recipient of the Department of Commerce gold and silver medals for "revolutionizing the way frequency is measured" as well as the Presidential Early Career Award in Science and Engineering (PECASE) for his work on optical frequency combs. He is a Fellow of the Optical Society of America and the American Physical Society.

Peter Schmid

Research Director, French National Research Agency; Professor of Mechanics, École Polytechnique

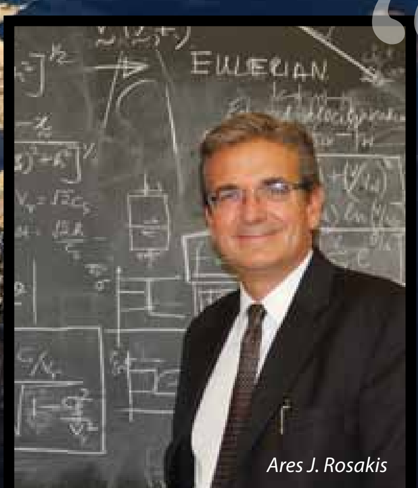
Peter Schmid's research interests lie in computational fluid dynamics, in particular in hydrodynamic stability theory and flow control. His current efforts focus on the description and targeted manipulation of flow behavior in complex geometries. Applications range from control of instabilities to suppression of noise amplification, from techniques for mixing enhancement to designs with reduced flow sensitivities. The tools to accomplish these objectives originate from control theory, model reduction algorithms, system identification techniques, iterative linear algebra, and optimization. In addition, he is interested in quantitative flow analysis and the extraction of coherent flow structures from experimental or numerical data sequences, including their use in low-order representations for control purposes.

Schmid is currently a research director with the French National Research Agency (CNRS) and Professor of Mechanics at the École Polytechnique in Paris. Previously, he held a faculty position in applied mathematics at the University of Washington in Seattle. He is a Fellow of the American Physical Society, an Overseas Fellow of Churchill College (Cambridge University), and the recipient of the French "Chaire d'excellence" award and the Alexander von Humboldt Research Fellowship. He received his PhD in mathematics from MIT and his engineer's degree in aeronautics and astronautics from the Technical University Munich.

Medicine, Energy, Defense, Space, and Earthquakes

The Far-Reaching Arm of Solid Mechanics Research at Caltech

To better understand the field of solid mechanics as studied at Caltech, *ENGenious* approached 11 members of the faculty from a variety of disciplines, including aerospace engineering, materials science, mechanical engineering, and geophysics.



Ares J. Rosakis

“We have been able to do research that other solid mechanics groups have not been able to do because of the combination of very high investment in new experimental techniques and an unusually strong theoretical understanding.”

Ares J. Rosakis
Theodore von Kármán Professor of Aeronautics and Professor of Mechanical Engineering; Chair, Division of Engineering and Applied Science

"Solid mechanicians act as a bridge between fundamental science and industry. We at Caltech take a broad view: in a sense, we take the baton all the way to the finish line."

Michael Ortiz, *Dotty and Dick Hayman Professor of Aeronautics and Mechanical Engineering*

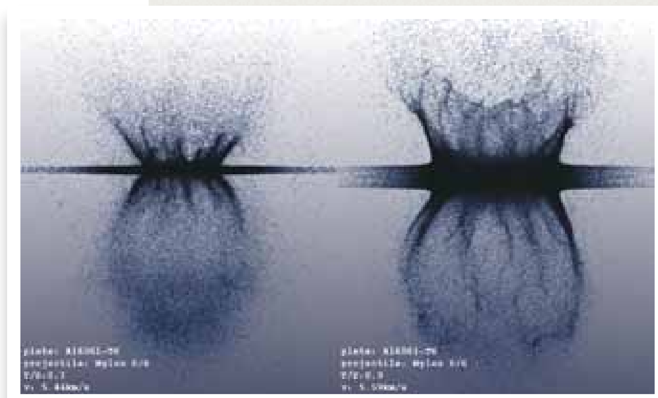
Michael Ortiz

Solid mechanicians focus on the deformation and failure of materials with a defined rest shape—for example, the solid parts of Earth, the human-built environment, and biological matter such as the human body. An overarching theme is to study the physics of a solid body's reaction to diverse influences—stress, deformation, temperature changes, electromagnetic fields, fluid flow—and how it fails. This is addressed on a range of length scales, from a cluster of atoms to tectonic plates, using experimental, theoretical, and computational methods. It also involves behaviors happening at highly diverse timescales, from picoseconds all the way to geologic timescales.

Professor Michael Ortiz, who is the first recipient of the prestigious Rodney Hill Prize in Solid Mechanics, describes the Caltech solid mechanics group as covering the "entire waterfront of solid mechanics." He explains, "Solid mechanicians act as a bridge between fundamental science and industry. We at Caltech take a broad view: in a sense, we take the baton all the way to the finish line. We are involved in real-world applications, engineering, and testing. We are needed, and that's why we're still in business."

Ortiz's colleagues describe his seminal contributions to the field as a combination of cutting-edge mechanics and mathematics. He sees himself as primarily an engineer. "Others come to the field from physics or applied math and may have a different emphasis," he explains. "As an engineer, I envision the end application. We start with an application and do whatever we need to solve the problem or make progress in an area—we may use applied mathematics, computational mechanics, or another approach, but our research and our papers are always applications-driven."

Caltech solid mechanics group member Professor Ares J. Rosakis underscores their unique approach. "We have an even balance of theoreticians, experimentalists, and numerical analysts, and we respect this balance, which



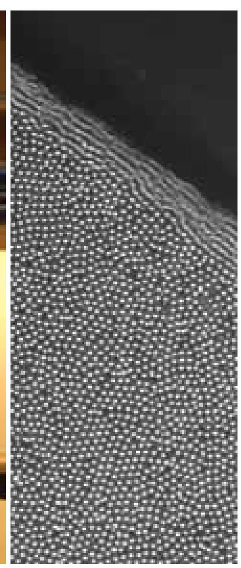
Above: *Example of simulation of two hypervelocity-impact experiments performed under the auspices of Caltech's PSAAP Center. A nylon projectile strikes aluminum plates of two different thicknesses, thereby setting in motion complex physics ranging from an initial impact plasma to fragmentation and debris-cloud formation. The complexity of the material behavior and attendant deformation process render this type of simulation a "predictive challenge" and test the limits of our ability to predict material behavior under extreme conditions. The figures are predicted "shadowgraphs" showing the structure of the debris cloud in a manner that lends itself to direct, full-field three-dimensional comparisons with experimental data.*

> *Landslides, earthquakes, or liquefaction can devastate an entire region, but all of these processes are controlled on a minute or granular scale. It's really about a grain in touch with another grain. If we could understand how these grains interact, then we can understand why landslides occur, or how sand castles hold together.*
>
> José E. Andrade, *Associate Professor of Civil and Mechanical Engineering*

does not necessarily exist at other universities," he says. "We are very interactive—we mix it up. We do not believe that only theory, only numerics, or only experiments do justice to our field. Of course, we have excellent people and excellent students—but this strong commitment to continuous interaction among group members is what really gives us the edge." In the context of his research, Professor Rosakis adds, "We have been able to do research that other solid mechanics groups have not been able to do because of the combination of very high investment in new experimental techniques and an unusually strong theoretical understanding. That combination and our strength in experimental mechanics have allowed us to move into the area of earthquake source dynamics. We are simultaneously applying an arsenal of diagnostics and theoretical knowledge in dynamic failure of engineering solids to attack the problem of earthquakes." What's next? "I want to pursue 'laboratory earthquakes' and create my dream: a seismology facility analogous to the Caltech wind tunnel—the seismological wind tunnel!" says Rosakis. "With my academic roots in aerospace engineering, I would use a fluid mechanics approach, in which models are tested in highly instrumented environments with multiple and synchronous diagnostics. A sophisticated seismic testing facility will enable us to observe and measure simulated earthquake events that are difficult, if not impossible, to measure *in situ*."

Computational solid mechanician and Professor of Mechanical Engineering and Geophysics Nadia Lapusta uses the experiments of Professor Rosakis to inform her earthquake modeling. "My colleagues and I are conducting lab experiments and developing theories to understand the mechanical properties of the earth, which helps us build sophisticated numerical models to explain the observed phenomena," she says. "The next question is whether we can produce a physics-based model that allows us to predict a range of earthquake fault behaviors. We won't predict a specific earthquake event, but we can use our results to offer a range of plausible future events. As we continuously enhance our models based on observations, experiments, and theories, we will eventually succeed in doing this." Professor Lapusta works with other solid mechanicians and geoscientists to understand fault interactions that include the full spectrum of scales—from the macroscopic scale of Earth's crust to the microscopic scale of granular materials (such as soil, decomposed granite, or sand). Micromechanical modeling is essential to her quest to discover the physical law governing earthquakes. "The rapid motion that generates

Left: *José E. Andrade*
Right: *High-resolution picture of a granular avalanche at the Geomechanics Lab at Caltech*



earthquakes occurs in the highly pulverized core of fault zones, within millimeter-wide layers which are composed of nano- to micrometer-sized particles," she says. "If the laws we use are based on a first-principles theory of how these granular materials interact, and that is verified by experiments, then we will have more confidence in applying our models to regimes where experiments cannot be done."

José E. Andrade, Associate Professor of Civil and Mechanical Engineering, further explained the importance of the micromechanical approach. "We're trying to unravel what makes geological materials tick on a large scale. Landslides, earthquakes, or liquefaction can devastate an entire region, but all of these processes are controlled on a minute or granular scale. It's really about a grain in touch with another grain. If we could understand how these grains interact, then we can understand why landslides occur, or how sand castles hold together." Professor Andrade describes his plans to introduce higher standards to his computer models. "We've been forcing our models to adhere to higher standards by comparing them with actual experimental data," he says. "We have developed strong connections with other experimentalists in this area, but I also would like to pursue a suite of boutique-type experiments—that is, conduct clever but uncomplicated experiments that motivate us to pursue a certain line of research, while keeping our models honest." Andrade is also interested in testing his models in space research: "An exciting project we're interested in is using some of our tools for planetary exploration. We'd like to increase our understanding of interactions between spacecraft and regolith (a layer of loose, heterogeneous material covering solid rock on Earth and other celestial bodies) in extraterrestrial conditions."

Many Caltech solid mechanics faculty have strong ties to NASA's Jet Propulsion Laboratory (JPL), the lead U.S. center for robotic exploration of the solar system and the home of major programs in space-based Earth sciences. An especially strong collaboration exists between Caltech and JPL in the form of a dual appointment: Sergio Pellegrino is the Joyce and Kent Kresa Professor of Aeronautics and Professor of Civil Engineering, and Jet Propulsion Laboratory Senior Research Scientist. For Professor Pellegrino, this association has been key. "The pivotal moment was when I decided I would move from Cambridge to Caltech

Left: *The snapshot shows dynamic rupture on the Parkfield segment of the San Andreas Fault spontaneously occurring in a numerical physics-based model that reproduces the inter-, co-, and post-seismic fault slip associated with the 2004 M6 Parkfield earthquake.* **Right:** *Nadia Lapusta is seated in front of CITerra, a high-performance computing cluster at Caltech used for geoscience applications, including advanced earthquake simulations.*

> *"The next question is whether we can produce a physics-based model that allows us to predict a range of earthquake fault behaviors. We won't predict a specific earthquake event, but we can use our results to offer a range of plausible future events."*
>
> Nadia Lapusta, *Professor of Mechanical Engineering and Geophysics*


Chiara Daraio

"*We create materials by selecting simple building blocks that interact in interesting ways, and then we assemble them into more complex structures . . . This is an unconventional approach to the creation of materials that merges the basic principles of solid mechanics with materials science.*"

Chiara Daraio, *Professor of Aeronautics and Applied Physics*

"*Innovation comes about by working at these interfaces—posing a real problem that a designer has, applying the knowledge of the mechanics community, and discovering new solutions.*"

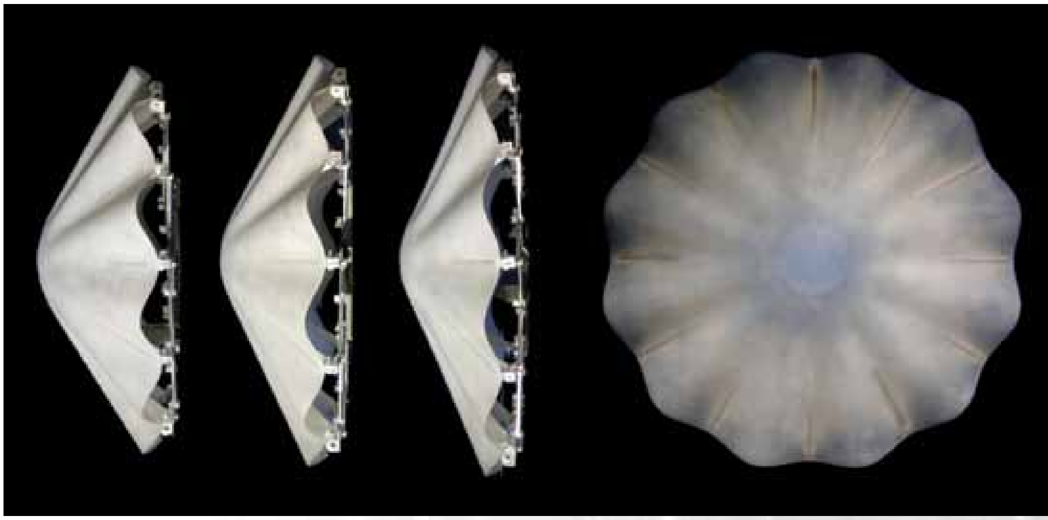
Sergio Pellegrino, *Joyce and Kent Kresa Professor of Aeronautics and Professor of Civil Engineering, and Jet Propulsion Laboratory Senior Research Scientist*


Sergio Pellegrino

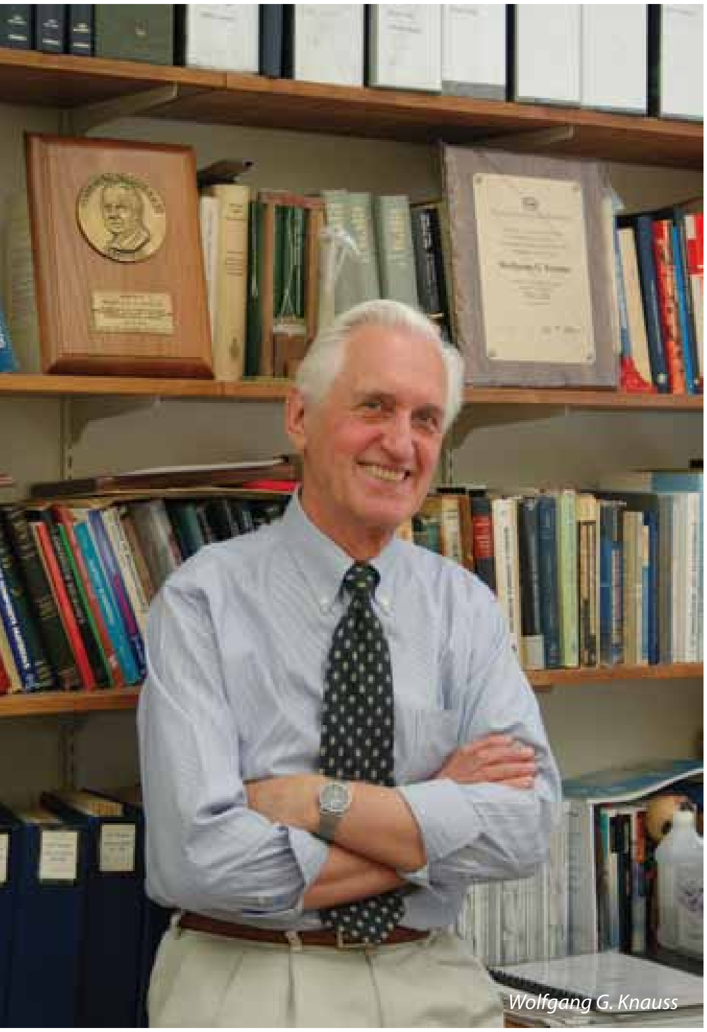
to start my second career," he says. "Caltech is unique. A second career is likely to bring even greater rewards than the first, since one benefits from the experience already gained and one can make better decisions about work going forward: what to do, what not to do. For me, the magical aspect was that GALCIT was reconnecting with space research, and there was and continues to be enormous opportunity to work at the interface between GALCIT and JPL. I have not merely moved to another university and pursued another set of interesting things—I've received strong support and encouragement from the highest administrative levels at both Caltech and JPL."

Professor Pellegrino enjoys working at the intersection of two different fields, which he has done since his student days. "I was interested in working across the gap between engineering and design—especially the analysis of lightweight structures," he says. "I now work across a different kind of gap—between space engineering and solid mechanics. I position myself in the middle and work to either solve an existing problem or to identify problems no one else is thinking about. About ten years ago, for example, I worked on very thin films for structures such as ultralight space-based communication antennas or sunshades to shield telescopes from the sun. When I thought about how curved surfaces in these structures should be designed, I realized that a deeper understanding of the mechanics of wrinkled films was required. A sunshade does not have to be perfectly smooth; if we allow it to become a little bit wrinkled, we can then simplify its design and make it much lighter, but to do this we need a rigorous analysis of how far from perfectly smooth the film will be. This type of analysis had not been done before, as it wasn't recognized to be important. That's an example of how innovation comes about by working at these interfaces—posing a real problem that a designer has, applying the knowledge of the mechanics community, and discovering new solutions."

Innovation and creativity are also at the heart of Professor Chiara Daraio's research. "New materials inspire innovation: When new materials are discovered, new applications, systems, and devices can be invented," she says. "Our group designs materials and devices with new mechanical and acoustic properties. We create materials by selecting simple building blocks that interact in interesting ways, and then we assemble them into more complex structures. The way the building blocks interact with each other determines the overall mechanical properties that characterize the final materials. This is an unconventional approach to the creation of materials that merges the basic principles of solid mechanics with materials science. Working at the interface of such traditionally separate



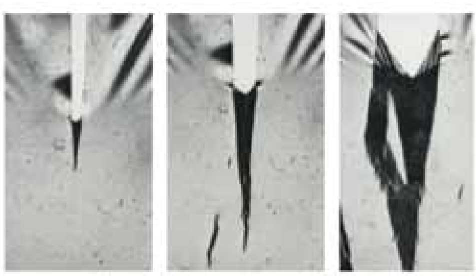
Concept for a variable geometry decelerator. This concept exploits the radial compliance of a corrugated thin shell to vary the diameter and cone angle of the decelerator, in order to control the trajectory of a spacecraft entering a planetary atmosphere. The required actuation is provided by an expandable ring structure attached to the edge of the shell.



Wolfgang G. Knauss

“There are so few experimentalists in the world, in particular in the United States. But Caltech is strong in that regard. Many people essentially wait for experimental results so they can go on with the theory.”

Wolfgang G. Knauss, *Theodore von Kármán Professor of Aeronautics and Applied Mechanics, Emeritus*



A crack propagating in a polymer foil

disciplines is easy in Caltech’s diverse and broad solid mechanics group. Although the day-to-day focus is on fundamental physics and mechanics, Professor Daraio’s experimental work has many applications, including the control of vibrations in space structures, the fabrication of new thermally stable mirrors, and mechanical energy harvesting. But when asked about the future of solid mechanics, she emphasizes biomedical applications. “I believe the design of new materials can have a large impact on biomedical applications. For example, my group uses some of the nonlinear acoustic devices we built to test hard biological systems, such as bones or the stability of implants, through a collaboration with the University of California at Los Angeles Department of Orthopedics. And with our new acoustic lenses, we hope to help build systems that improve ultrasonic imaging and ultrasonic surgery.”

Biomedical applications and experimental mechanics have been an element of Caltech solid mechanics research for most of the time Professor Emeritus Wolfgang Knauss has been at Caltech. “I believe the strong adherence to experimental work makes us unique,” Professor Knauss says of the Caltech solid mechanics group. “Until about 10 to 15 years ago, the GALCIT solid mechanics group was virtually all experimentally based. There are so few experimentalists in the world, in particular in the United States. But Caltech is strong in that regard. Many people essentially wait for experimental results so they can go on with the theory; I think that’s where our strength has been, and I hope we don’t lose that in spite of the more recent addition of a formidable numerical analysis component.”

With regard to biomedical applications, Knauss recalls his research 30 years ago with the Doheny Eye Institute at the University of Southern California (USC). "Before there was laser treatment for nearsightedness, a surgical procedure called radial keratotomy was used to correct myopia," he explains. "Surgeons made little radial cuts in the cornea of the eye, and by carefully placing the cuts, controlling the depth and number of cuts, they could correct acuity. A Russian doctor, Svyatoslav Fyodorov, invented this procedure in 1974, when a 17-year-old accident victim came to him with eyes that had been lacerated by glass shrapnel. When the eyes healed, the patient had better vision than before. Fyodorov postulated that the central portion of the lens is curved outward because of a ligament around that part that constricts it and bends it outward. If that ligament is cut, it flattens or changes the lens shape. So the USC doctors consulted with me as a mechanician because they could not find the ligament. But to me it was clearly a fracture problem! You're introducing cracks in a specific material, and when there are cracks coupled with pressure (of the eye), the geometry changes. One of the problems we tackled was that long after healing had occurred, the eye wasn't the same as on the day when the surgeons made the cuts, so we tried to understand how to compensate for that, to make the operation last longer."

Another application of Professor Knauss's research on time-dependent mechanical processes relates to nuclear power plant safety. He explains, "One other area that is close to my heart besides the fracture of viscoelastic polymers is high-speed crack propagation. There were some real issues relating to that in the late 1970s to early 1980s, when nuclear power plant safety was a highly rated issue. Funding was available to develop theories and frameworks to enable prediction of how reactors could

Guruswami (Ravi) Ravichandran

"Cells are living in a three-dimensional world, so we explore the mechanics of cells in 3-D. We want to know the mechanical forces involved in cell division, because doing so can lead to a better understanding of the physiological processes involved in tissue engineering."

Guruswami (Ravi) Ravichandran, *John E. Goode, Jr., Professor of Aerospace and Professor of Mechanical Engineering; Director, Graduate Aerospace Laboratories* break up if they were suddenly cooled. When something goes wrong in a reactor, it is flushed with water, which quenches everything and, in turn, causes tremendous thermal stresses. What we tried to understand was how fast the cracks could propagate, and determine the possible consequences. In that process, we were able to explain the discrepancy between the theoretical estimate and the measured maximal crack speed attained, the theoretical value being typically about twice the measured values."

Many solid mechanics research applications are transforming our world and benefiting society, but new applications and discoveries rely on fundamental knowledge. Professor Guruswami (Ravi) Ravichandran explains, "Our research in solid mechanics is focused on engineering science problems. We are not working on today's relevant systems or technologies, but we are working on mechanics problems that will impact future technologies. For example, I apply rigorous mechanics to the study of cell mechanics and interaction with biomaterials. Most cell experiments are performed on glass slides, on two-dimensional substrates, but that's not really a physiologically relevant environment for the cells. Cells are living in a three-dimensional world, so we explore the mechanics of cells in 3-D. We want to know the mechanical forces involved in cell division, because doing so can lead to a better understanding of the physiological processes involved in tissue engineering. We need to know the mechanical properties of the extracellular matrix in artificial tissues or organs. As scientists try to grow organs, they will need to know what forces are involved, and how to best mechanically match compliance of the cells with elasticity of the matrix. If there is a mismatch, for example, in creating artificial vessels for grafts, the grafts could be too stiff, and the cells are not going to like that. One must have the right match between the mechanical properties of the extracellular matrix and the cells, so the cells can properly function."

Professor Ravichandran is also studying how materials deform or change shape at different scales and temperatures when struck by a high-speed projectile. This work is of special interest to the U.S. Army Research Laboratory, which is funding a $90 million initiative to improve protective gear and vehicles for sol-

Julia Greer rollerblades through campus.

diers. Several members of the Caltech solid mechanics team will be working on this initiative, including Julia R. Greer, Assistant Professor of Materials Science and Mechanics. "I think this initiative is going to represent a big thrust in solid mechanics—in part because it is work by experimentalists such as Ravichandran and I in collaboration with computationalists, like Dennis Kochmann and Michael Ortiz," she says.

Professor Greer describes her research in the context of the Army initiative this way: "To understand the physics and the mechanics of materials deformation, we want to know what's happening at the atomistic level, because materials don't behave in the same way when they're very small. We bring a little fresh air into the atmosphere of classical laws, which break down at the nanoscale. I'm in 'nanosolid' mechanics, and I've been studying the behavior and response of nanosolids to mechanical deformation and investigating what within their microstructure gives rise to their unique properties, which are different from those of the same solids but with large dimensions. We are finally at a place where we have a pretty good understanding of the fundamental mechanical behavior and want to use these nanosolids as building blocks to construct tangible materials. The idea is to capitalize on the very unique properties that are offered by nanomaterials to create hierarchical structures, such as three-dimensional lattices, or scaffolds. For example, we have built microtrusses, which were recognized as the world's lightest material and could sit on top of a white-top dandelion without perturbing it. We are now building nanotrusses, where every dimension is less than a couple of microns, so you can't see the structure with your eye. With the microtruss, you can see very clearly that it's a structure and can say, 'Oh, this is a bunch of octahedrals sitting on top of each other.' But when you make every dimension below a micron, your eyes can't resolve the structure and so it looks like a cloud just sitting in your hand—it's very cool! To actually make these nanosolids into useful materials and structures, we have to figure out how to cheaply and effectively manufacture materials that have nano-constituents."

The newest member of the solid mechanics group, Dennis Kochmann, Assistant Professor of Aerospace, shares Professor Greer's passion for creating materials from the nanoscale up. He explains, "It all comes down to: How do you carefully design a material's microstructure so that you get whatever macroscopic properties you want? You start at the lower scales, e.g., by combining several existing materials into a new artificially designed composite material, and one thereby normally combines materials that have desirable individual properties, such as one that is very strong and stiff and one that dampens vibrations by absorbing energy. (These two properties are generally exclusive in nature, and therefore materials that

Julia Greer holds microtruss structure in the palm of her hand.

> *"We want to know what's happening at the atomistic level, because materials don't behave in the same way when they're very small. We bring a little fresh air into the atmosphere of classical laws, which break down at the nanoscale."*
>
> Julia R. Greer, *Assistant Professor of Materials Science and Mechanics*


Dennis M. Kochmann

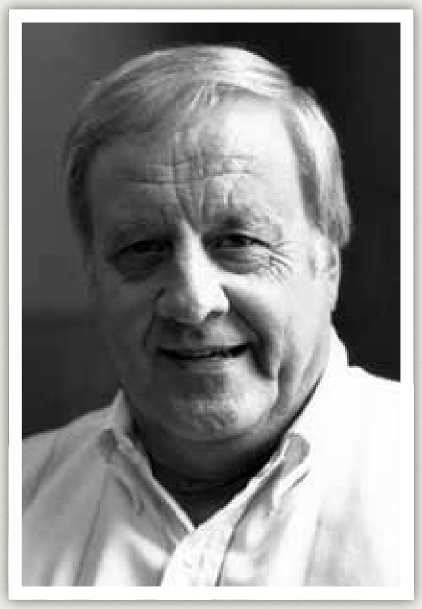
> *It all comes down to: How do you carefully design a material's micro-structure so that you get whatever macroscopic properties you want?*
>
> Dennis M. Kochmann,
> *Assistant Professor of Aerospace*

combine both properties are of urgent need in engineering applications.) As part of our research, we study composites that include active or tunable materials that respond to external stimuli such as temperature or electric fields. This way, you can create new materials whose properties are tunable over wide ranges by applying the appropriate external stimulus (e.g., changing the temperature, applying an electric voltage, etc.). Doing so will trigger mechanisms on the microscale, which give rise to significant change in the macroscopic properties." He goes on to describe his long-term research vision: "I hope to extensively explore this idea in the experimental lab and computationally. Our everyday engineering applications always require materials that are harder, stiffer, stronger, lighter, more resistant and durable. Someday, we would like to be able to switch the properties of artificial materials to exactly what is needed. We want to be able to design future materials on demand."

Professor Kaushik Bhattacharya expands on this idea. "The scales at which we are beginning to do engineering are merging, and the great challenges in solid mechanics are giving rise to a language that bridges materials science and mechanical engineering," he says. "Today, we teach our mechanical engineering undergraduates how to manipulate the properties of materials to engineer large structures. Now we also look at microstructures, and the toolbox with which we control structure is dramatically changing. It's no longer about beating, heating, or cutting a blob of metal. It is much more complex today. Our challenge is not to shape the material to get the function we want, but how we create a specific material that already possesses the function we want. We are in fact merging both material and machine—and that is absolutely exciting!"

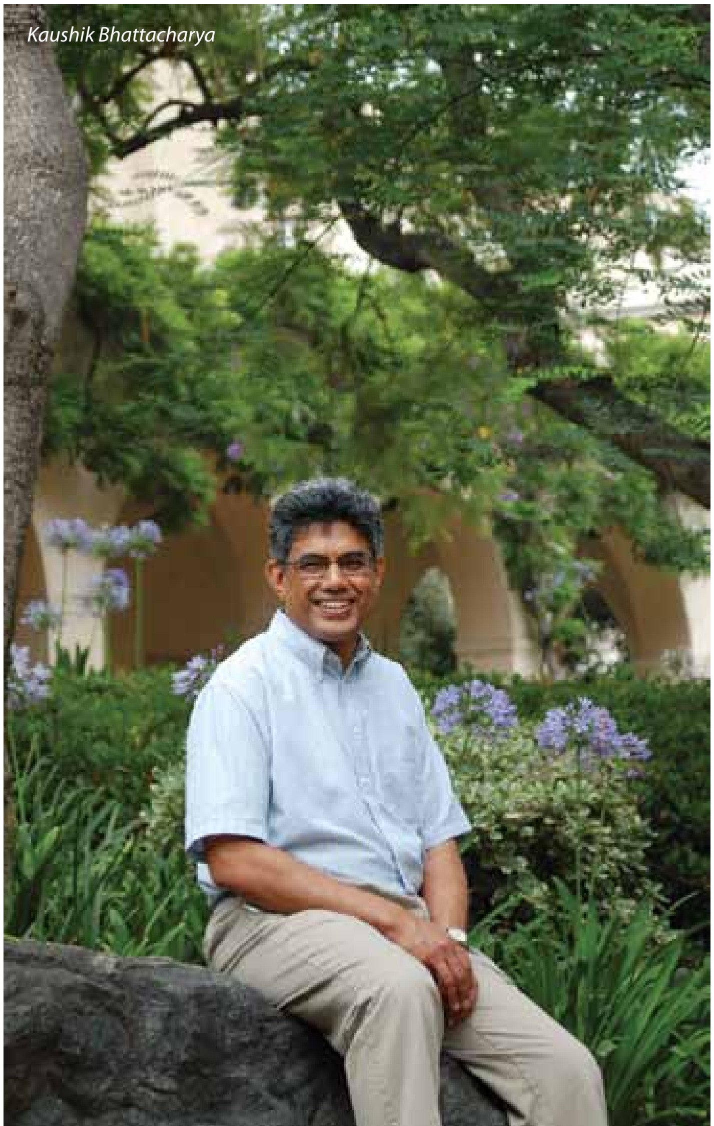
Professor Bhattacharya's excitement is shared by a strong and active student group that organizes a yearly solid mechanics symposium in celebration of the late James K. Knowles, Caltech's William J. Keenan Jr. Professor of Applied Mechanics, Emeritus. Professor Knowles made fundamental research contributions to the mathematical theories of materials and structures. He was a special teacher and mentor who inspired and influenced multiple generations of students and scholars through classes in mathematics and mechanics. Continuing this visionary thinker's contributions to solid mechanics and encouragement of young researchers are his junior colleagues, who continue to take Caltech's solid mechanics research in innovative, interesting, and new directions. "Jim was the greatest mentor I ever had," says Professor Rosakis. "He held my hand when I first came to Caltech as an assistant professor. He also taught me how to teach. He would look for the spark in people's eyes and help them make their dreams a reality. As we at Caltech seek to create the best mentoring opportunities for our young faculty, we are guided by his example." ENG

Learn more about the faculty at eas.caltech.edu/people, and visit www.mce.caltech.edu/events/knowles_lecture for more about the Caltech Solid Mechanics Symposium.



The annual James K. Knowles Lecture and Caltech Solid Mechanics Symposium celebrates the contributions of the late James K. Knowles, a remarkable scholar, teacher, and friend.

Kaushik Bhattacharya



"Our challenge is not to shape the material to get the function we want, but how we create a specific material that already possesses the function we want. We are in fact merging both material and machine—and that is absolutely exciting!"

Kaushik Bhattacharya, *Howell N. Tyson, Sr., Professor of Mechanics and Professor of Materials Science; Executive Officer for Mechanical and Civil Engineering*

Janet Blume:

Academic Leader, Educator, and Innovator with a Commitment to Time and Care

Janet Blume (PhD '86) was the first woman to earn a PhD in applied mechanics at Caltech. She is the Associate Dean of the Faculty at Brown University, where she is also Associate Professor of Engineering. She has won several awards for her teaching and advising. A solid mechanician, she focuses on mathematical issues in the behavior of solids undergoing large deformations. One of her current research projects focuses on head trauma. Blume spoke candidly with *ENGenious* about her Caltech experience—how she learned to learn, to teach, and to pay it forward by following her professors' commitment to a "time and care" approach to teaching. She describes her years at the Institute as "game-changing."

game-changing

***ENGenious*: What inspired you to be an engineer?**

Blume: As an undergraduate, I planned to major in physics or math in support of my original goal, veterinary school. But in my sophomore year, someone suggested I take an engineering course that focused on strength of materials. I totally loved it—how everything fit together. It appealed to me in a way that nothing else had before. I thought I could combine engineering and biology, but this was before bioengineering, and I had to declare a major. I remember asking the professor of my strength of materials course if I should do biology or engineering, and he said, "Oh, we definitely want you in engineering." That remark, by a professor whose name I can't even remember, stays with me to this day! By the end of my undergraduate experience, I knew what I wanted to do was pretty much what I'm doing now, and I applied to graduate school with an eye toward teaching. Now, I try to talk to students the same way: I want them to know we are interested in them.

***ENGenious*: What was your experience as Caltech's first female graduate student in applied mechanics?**

Blume: I'm surprised that it was the mid-1980s and there were still firsts like this for women. At the time, I didn't think about it. On one hand, it was helpful to me. I think I had more attention from faculty because I was female. My thesis advisor, Eli Sternberg, Professor of Mechanics, was a feminist and very supportive. He did everything with the utmost care and devotion, or he didn't do it at all. I'm honored to know I was first—and it's nice to think I may have made it a little easier for other women to succeed here.

***ENGenious*: How did your Caltech experience influence you?**

Blume: That first year was like no other. First, I was lucky enough to be here with a phenomenal group of students—great people I'm still in touch with to this day. And this is very important: We students took the teaching very seriously because Caltech faculty take great pride in teaching. I soon realized that everything I thought I knew, I really didn't. I knew what an equation was and when I was supposed to use it, but at Caltech I learned where that equation came from organically; I could derive it ten different ways, and knew when to apply it and when I shouldn't. I came to own the material, to internalize it in ways I had never done before.

***ENGenious*: Did your Caltech experience help you become a better educator?**

Blume: Oh, yes. My time at Caltech was a game-changer in that respect: what I thought I knew, I realized I didn't. Take fluid mechanics. As an undergraduate, whatever I learned left me as soon as the exam was over; it was gone. At Caltech, my professors made very complex stuff easy to grasp. I recently wrote to Wilfred (Bill) Iwan, Professor of Applied Mechanics. I took his dynamics and vibrations course, which I now use as a model for teaching. Professor Iwan didn't just teach dynamics to me, he taught me how to teach dynamics. What I learned in graduate school is how to learn, and I was lucky enough to learn how to teach. I learned that even if

"At Caltech I learned where that equation came from organically; I could derive it ten different ways, and knew when to apply it and when I shouldn't. I came to own the material, to internalize it in ways I had never done before."

you're not teaching, you have to be able to communicate your work.

Professor Sternberg was a phenomenal advisor. I couldn't have imagined a better experience. His advising and teaching, and the incredible care he took, along with other faculty, showed me how to work with a graduate student. I learned you really don't gain anything by rushing through material. You put whatever time you need into teaching. When I started teaching, I decided: This was how I learned—and this is how I'm going to teach. It's hard to start out as a faculty member—there are many competing pressures. When I started at Brown in 1986, I was told by a faculty member at Brown, "Don't spend too much time on your teaching." And I thought, "Don't tell me that, because taking time is the way it works."

***ENGenious*: What are your thoughts on engineering education?**

Blume: We know students learn best in a hands-on, interactive environment. We take a project-based approach, and give students calculation-based design experience early on. Lectures are a part of the process, but most of the real learning takes place outside the classroom, when they're building their projects. If students get enough personal attention, everything falls into place. I think the experience of connection to a professor, to the departments, to engineering as a whole, encourages students to stay and graduate. The goals are to help them feel welcome and supported, and give them opportunities.

***ENGenious*: What about students who are great at teamwork and project work but fare less well on written tests?**

Blume: I used to write somewhat clever tests. The problems required a strong test-taking ability. I would think, "Oh, these are clever questions," and pat myself on the back. Students who were good test-takers would do fine, but I realized the tests were sinking others. Yet, these failing test-takers were made for engineering! They were very good at projects and organizing, always did the work on time, always attended office hours. It was heartbreaking—I wanted them to succeed! So I decided to stop being Miss Clever-Exam-Writer-Woman and rewrote the tests. The new versions included opportunities for both quantitative and qualitative input, and for partial credit.

Professor Janet Blume testing exercise equipment built by students in project course.

***ENGenious*: Did rewriting the tests make a difference?**

Blume: Yes, but it's a delicate balance. We don't want to push people through and set them up for failure later on. We work to gradually bring people up to the level necessary for a career—not to get all *A*s, but to give them the personal attention and the tools they need to succeed. We try to recognize differences in learning styles and levels of understanding. Everybody gets to the same point so they can do the design projects, but more advanced students spend less time on the fundamentals. In the end, everyone has what they need to do the projects—and they do them together. We take care of everyone.

***ENGenious*: Everything you say has time and care in it.**

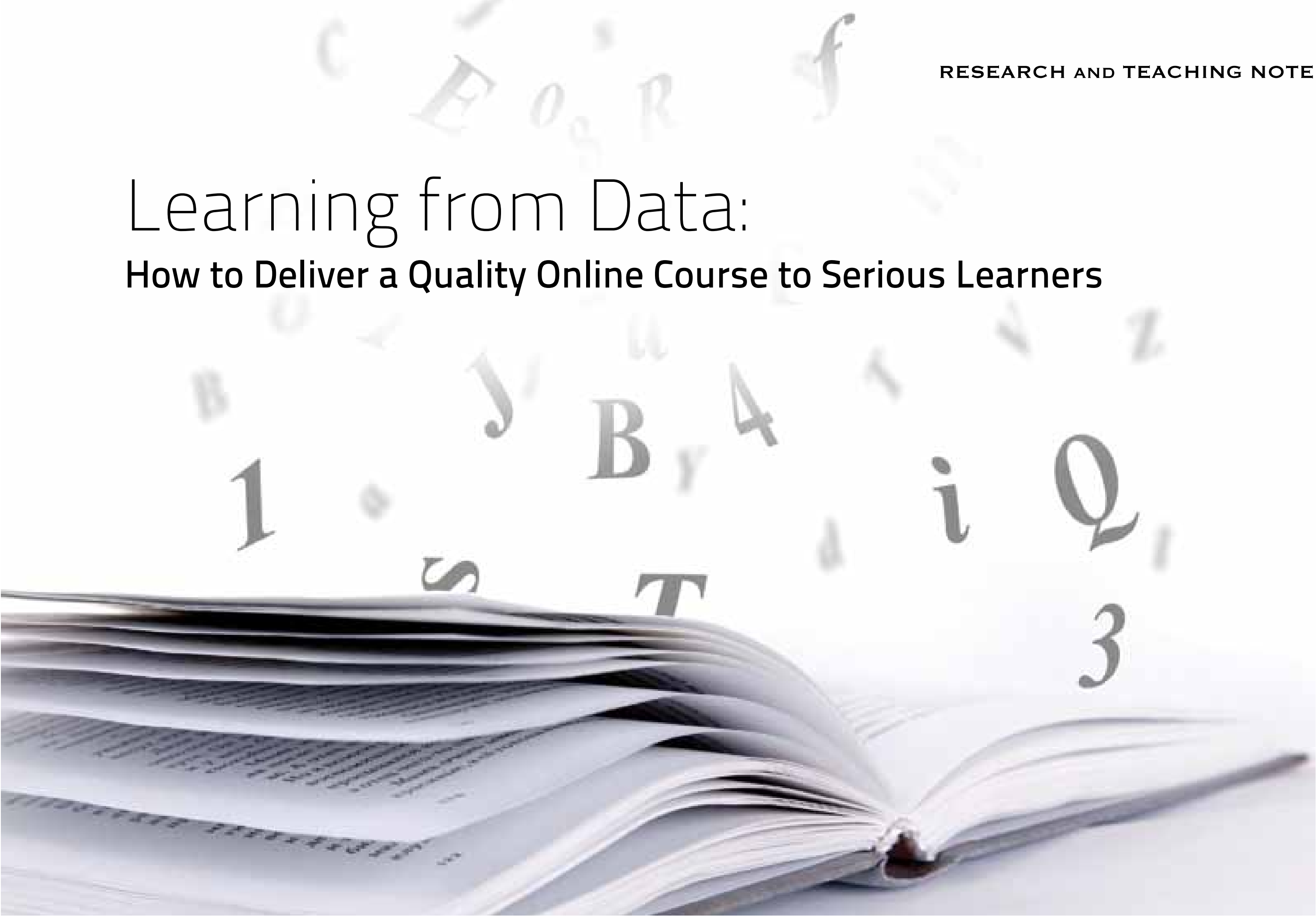
Blume: As James K. (Jim) Knowles, William J. Keenan Jr. Professor of Applied Mechanics, said many years ago when I thanked him for all of the time he put into us students, "That's why we're here." E N G

Janet Blume is Associate Dean of the Faculty and Associate Professor of Engineering at Brown University.

Visit research.brown.edu/research/profile.php?id=1106970186.

Learning from Data:

How to Deliver a Quality Online Course to Serious Learners



Yaser S. Abu-Mostafa is Professor of Electrical Engineering and Computer Science at Caltech. His main fields of expertise are machine learning and computational finance. He is a recipient of the Richard P. Feynman Prize for Excellence in Teaching, and he has won multiple Caltech student teaching awards throughout his career. In 2005, the Hertz Foundation established a perpetual graduate fellowship named the Abu-Mostafa Fellowship in his honor. *ENGenious* interviewed him to learn more about his research and his approach to teaching.

***ENGenious*: Why did you decide to create "Learning from Data: Introductory Machine Learning Course," Caltech's first-ever live broadcast of an entire course?**

Abu-Mostafa: From a Caltech perspective, it's a good way to provide public service. And it's an opportunity for people to understand what Caltech is about—to see inside a Caltech class. This is a real class, delivered as I always teach it, with real students attending. In my opinion, there are many people in the world who could take a Caltech course and do adequately well, perhaps just not at the level we expect of our doctoral students. That doesn't mean they shouldn't have access. To enhance accessibility, I adjusted the presentation material to fit the medium, but the content and delivery are the same. And many people completed the course. When we reach out in this global way, Caltech becomes less remote; we are approachable, yet we offer the highest-quality learning experience.

***ENGenious*: What do you mean when you say your course is a "real" Caltech course?**

Abu-Mostafa: Before creating the course, I surveyed other online university, non-profit, and commercial courses. The measure of success for some seems to be the number of followers, and the desire to get more followers often led to lowering the bar for the course content. But I wanted to deliver the real thing for disciplined students with a

serious approach to science. So I kept the online course at the exact level of my Caltech course. It's not a video game. And I've had positive feedback about this approach. Some have even donated to Caltech as a result. One alumnus who graduated decades ago but had not previously given to Caltech sent a check after viewing my course. I believe the high quality of the course is key.

***ENGenious*: Why did you choose the subject of machine learning?**

Abu-Mostafa: Machine learning is my research area. It has theory, mathematics, and algorithms, and it also carries a wide range of applications in multiple domains. For instance, retailers want to anticipate clients' tastes and present choices they like. I recently consulted with a women's fashion company and ended up making recommendations to women I never met about fashion items I have never seen. My recommendations were preferred by customers over those of professional stylists! Do I need to know fashion to do this? No. The key is to extract the correct information, which is based on the right data. The ability to impact such a wide variety of applications keeps me intrigued with the field, and makes the appeal of machine learning courses quite broad. Almost 150 Caltech students from 15 different options took the course this year. Machine learning also has profound theoretical questions that need answers and algorithms and new techniques under development.

***ENGenious*: What is machine learning?**

Abu-Mostafa: Put simply, machine learning is a branch of computer science that enables computers to learn from experience. It makes computers "smarter" than humans for a broad range of tasks. The most critical components of any machine-learning system are the data. Machine-learning algorithms can take existing data, search for patterns, and make predictions based on those patterns. Whether we know it or not, we encounter this process in many ways: Web searches result in more useful links, Internet shopping is tailored to our preferences, medical lab results are more accurate—even dating services are more likely to find you a potential partner.

Various machine learning paradigms exist, and each develops its own attributes. Supervised learning is one such paradigm, and the most common. For example, supervised learning is used in medical diagnosis. Researchers can "supervise" a machine's learning process to identify cancerous cells by "training" the computer with image data that includes cancerous or noncancerous cells. The algorithm will learn to apply certain cell attributes—shape, size, and color, perhaps—to identify malignant cells.

Another paradigm is called reinforcement learning ("trial and error"). For example, a roboticist can design an algorithm that experiments with different kinds of limb movements that mimic those of a human. The algorithm will learn which movements, such as a particular gait or grasping technique, are most efficient—and which are not. As the learning process develops, both we and the machines learn correct actions for different situations: the best movements or actions are reinforced, and less reliable movements or actions are avoided.

The mathematical theory of machine learning primarily focuses on the problem of "overfitting" the data. We look for genuine connections that fit the data while avoiding patterns that cannot be trusted. Another interesting challenge is the temptation to throw too much computing power at a problem. How can more power hurt? If the algorithm is too aggressive—that is, if it is using too sophisticated a model to fit a limited data sample—it could mislead itself by detecting coincidental patterns in a sample that does not reflect a true association.

An important point to remember is that machine learning works only for problems that have enough data. Machine learning does not create information; rather, it gets the information from the data.

***ENGenious*: How are interested people accessing your online course?**

Abu-Mostafa: The course is offered through iTunes U, YouTube, and of course the Caltech server, in many formats and multiple bandwidths. On iTunes U alone, there are more than 60,000 course subscribers. People register, submit homework, and are graded automatically, or they can grade themselves using solution keys. We reach a broad audience of different backgrounds, including a large international following. Furthermore, there's no language barrier, because YouTube features automatic translation capability.

Many people who are proficient in machine learning have watched the course and are intrigued by my approach to the topic. This carries far-reaching professional dividends at the intellectual level. A winner of the National Medal of Technology took the course. A Caltech trustee took the course. There are postdoctoral groups who have taken the course together. If it's 100, 10,000, or 2 billion people, that's fine; my main mission has been achieved: delivering a quality course to serious learners.

***ENGenious*: What surprised you?**

Abu-Mostafa: Other than how much time it took to prepare the slides and how tricky it was to design meaningful multiple-choice homeworks, the impact of the course on people who already know machine learning was surprising. I have some non-mainstream views in machine learning, and I completely polished my arguments and offered them through this course, which is a permanent record—not just for students, but also for my peers. When your peers buy into new ideas, new research follows, and this was an unexpected professional reward.

Also, a live online course had not yet been done at Caltech, so the stakes were high. I very much appreciated the Caltech community's strong support for this effort. They had unmitigated confidence that this would come out right. The Division of Engineering and Applied Science, the Information Science and Technology initiative, and the provost's office provided the funds, Information Management System and Services (IMSS) and the Academic Media Technology office provided the technical support, and many Caltech units, including the Alumni Association, took care of publicity. I received strong encouragement from everyone, and you need encouragement to go through such an intense experience.

***ENGenious*: What did you learn?**

Abu-Mostafa: Robert Heinlein said, "When one teaches, two learn." The diversity of the online audience introduced me to a deeper understanding of how people view and apply the material. But if I hadn't done this, I never would have learned the difference between real-time feedback in a classroom setting and the delayed feedback you get with videotaping. My subjective conclusions on how I did after class weren't always correct. When I viewed the videos, I learned how to adjust my style to accommodate the medium.

At the educational level, I learned that delivering a quality online course is incredibly time consuming. For example, I thought a white board wouldn't fit the medium. But the speed one normally writes on a board is about the same pace people can follow and understand the details—you don't lose your students. So I produced almost 3,000 incremental viewgraphs for the video to match a board-writing pace.

***ENGenious*: How will the next session be different?**

Abu-Mostafa: I think this course is very much the way I want it to be. I've taught the course many times and have also written a book. I am happy with the way it came out, and I will continue to offer it online based on the recorded lectures as long as the material remains viable. It takes a huge time commitment and effort to create a new online course of the right quality.

***ENGenious*: What inspires you?**

Abu-Mostafa: Doing the right thing. I know it sounds clichéd, but it's not necessarily the easiest thing to do. In this case, the outcome offsets all the difficulty. E N G

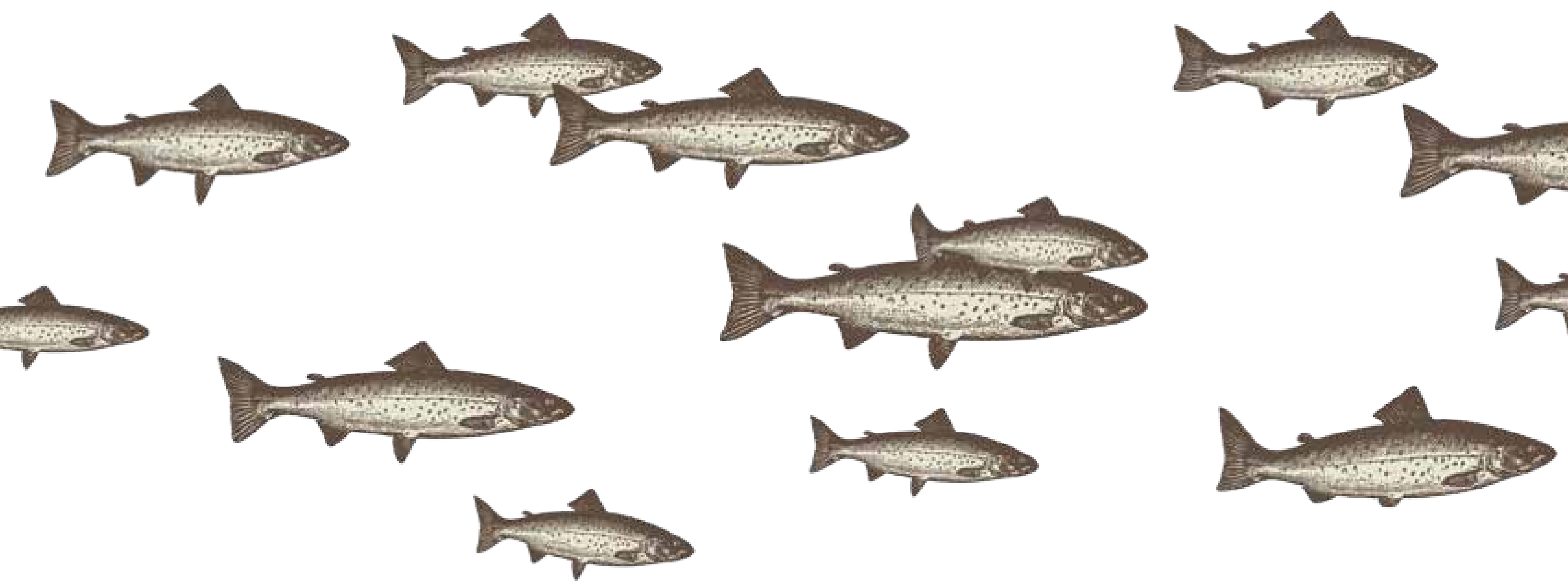
Yaser Abu-Mostafa is Professor of Electrical Engineering and Computer Science.

Visit work.caltech.edu/telecourse.html.

Finding the Balance:

New Perspectives on the Complex World of Water Management

John Hall is Professor of Civil Engineering at Caltech. From 1980 to 2005, his research interests included earthquake engineering, structural dynamics, strong ground motion, finite element modeling, and earthquake reconnaissance. He served as Caltech's Dean of Undergraduate Students from 2005 to 2010 and then spent a sabbatical year in Sacramento, California, where he immersed himself in a new field of study: water.



***ENGenious*: Why did you take a sabbatical to go to the California Department of Water Resources in Sacramento?**

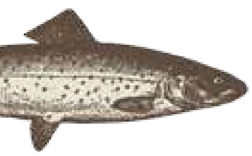
Hall: After five years as Dean of Students, I wanted to get back into academia but try something different. I always had an interest in water, so I sought out a position with the Department of Water Resources, the agency that manages the California State Water Project (SWP), the nation's largest state-built water development and conveyance system. It provides water for 25 million Californians and 750,000 acres of irrigated farmland. Immersing myself in this way helped me transition into a new area of study.

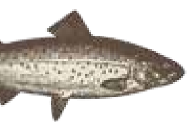
***ENGenious*: Tell us more about the California SWP.**

Hall: Built in the 1960s, the SWP has a system of reservoirs, aqueducts, power plants, and pumping plants that store water and distribute it to suppliers who deliver it to two-thirds of California's urban population as well as several large irrigation districts. In Southern California, we have two other aqueducts that deliver water—one, owned by the City of Los Angeles, traverses the eastern Sierra up to the Mono Lake Basin. A third one is owned and operated by the Metropolitan Water District that taps the Colorado River. I'm interested in learning more about all three of these, not only from an engineering perspective but also because of the environmental, legal, and political issues that may represent some threat to our water supply.

***ENGenious*: What are some examples of such issues?**

Hall: In the Sacramento-San Joaquin River Delta, some fish populations have become reduced to near extinction levels, and some people blame this situation on the large amount of



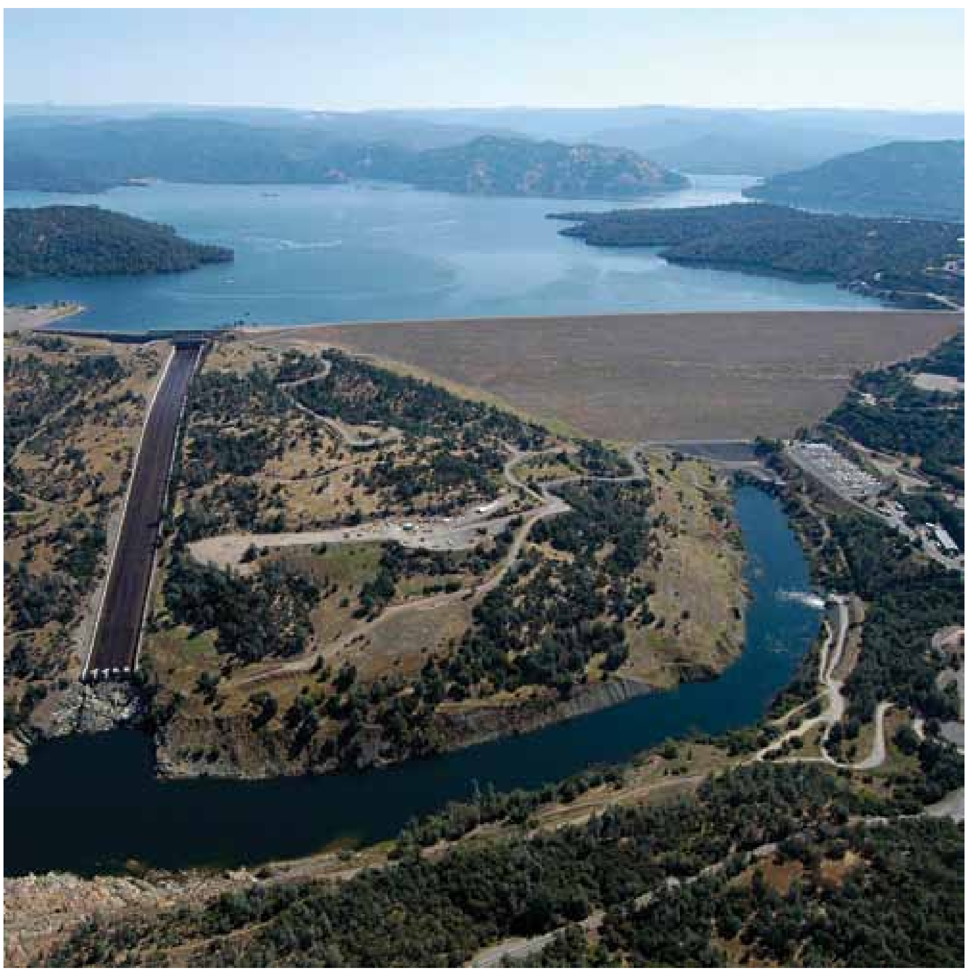


water pumped out of the delta by the SWP (as well as a similar federal water project) for shipment south via the California aqueduct. The Endangered Species Act allows for lawsuits, and the judicial system has the power to shut down the whole water system if there aren't safeguards in place. A current proposal to protect delta wildlife involves building a new tunnel system that takes the water out much farther upstream. While in Sacramento, I worked on feasibility studies for this project, which actually consists of two tunnels, each 100 feet underground and about 33 feet in diameter, 35 miles long. It would take about ten years to construct, with initial costs on the order of $12 billion. Fish and marine biologists are working in concert with hydraulic engineers to determine the consequences of such a project. They've constructed a mathematical model of the entire delta—flow patterns, salinity, temperature, oxygen content, whatever the fish need to survive—and are using it to access how the water extraction affects the whole ecosystem. Hopefully the project will not only benefit fish, it will increase the reliability of our water supply, which is presently

John F. Hall

vulnerable to earthquakes, floods, and future rise in sea level. Such events could destroy the levee system in the delta, flooding our aqueduct with salt water.

It's a very interesting mix of scientific and engineering problems with legal and political issues, and of course the environment is at the middle of all of it. Take, for example, the 100-year-old City of Los Angeles aqueduct that diverted the source of water that fed Owens Lake, which eventually dried up. Since 1928, that dry lake bed—100 square miles—is the largest source of particulate air pollution in the country. To abate the pollution, almost 20 percent of the capacity of the aqueduct (enough water for about a million people) is now being returned to the dry lake bed just to keep the surface moist so dust doesn't form. Additionally, another 15 percent of the aqueduct capacity is now being returned to Mono Lake to protect it from a similar fate. Mono Lake is a crucial stop-over for migrating birds. Because of these and other environmental issues, the Los Angeles aqueduct is delivering only about half of its capacity. But people shouldn't have to develop lung cancer so others can have water, and the wildlife deserves protection. It's interesting that after 100 years of transporting water, we are still struggling to find a balance.



Lake Oroville and reservoir is the largest storage facility for the State Water Project.

The Colorado River water is even more complicated, since seven western states share this resource. The Department of the Interior decides on each state's allotment. Dams have been constructed and huge reservoirs hold much of the water so that year-round access to water is possible. But as the upper-basin states start taking their full share, California has to make do with less water, which creates tension between cities and farms. Some water transfers from irrigation usage in the Imperial Valley to urban usage in Los Angeles and San Diego are already starting to dry up the Salton Sea. The state is currently working on a plan to keep the Salton Sea from turning into another Dead Sea, at a cost of many billions of dollars. The Colorado River aqueduct was built in the 1940s, and yet we're still dealing with these problems.

So I find the intricate legal, environmental, and political issues and complexities of all three of these systems fascinating.

***ENGenious*: As a civil engineer training future generations of engineers, how do you effectively address the complexity of these kinds of issues?**

Hall: For the first time in quite a while at Caltech, I'm teaching a course in hydraulics—how water flows under various conditions, such as canals and rivers. But to operate in the world I just described, one needs to also understand water chemistry and environmental biology, *and* be well versed in all the applicable laws, such as environmental protection legislation. I intend to focus on improving the hydraulics course, then add some environmental fluid mechanics,

Waterways meander throughout farmlands in the Sacramento-San Joaquin River Delta.

and ultimately expand into related legal, political, and environmental areas, and even sociology.

***ENGenious*: What a good example of how engineering can have a strong societal impact!**

Hall: Yes. Everybody needs water. But the problems related to water are complicated, and we really need to be smart about the future. Maybe we shouldn't be playing by the same old rules. To keep the water flowing and maintain harmony with the environment, we need to step back and take a global approach—and to work together. I'm not sure that we can really engineer our way out of the situation that we're in now.

I'd like to see us look at the entire picture and start over. A lot of it comes back to whether water is a public resource or something that can be privatized. Certainly there's a role for government in sorting it out. I'd like us to rethink the whole scheme of water rights, how to divide up the water between cities and farms, and still consider water conservation technologies.

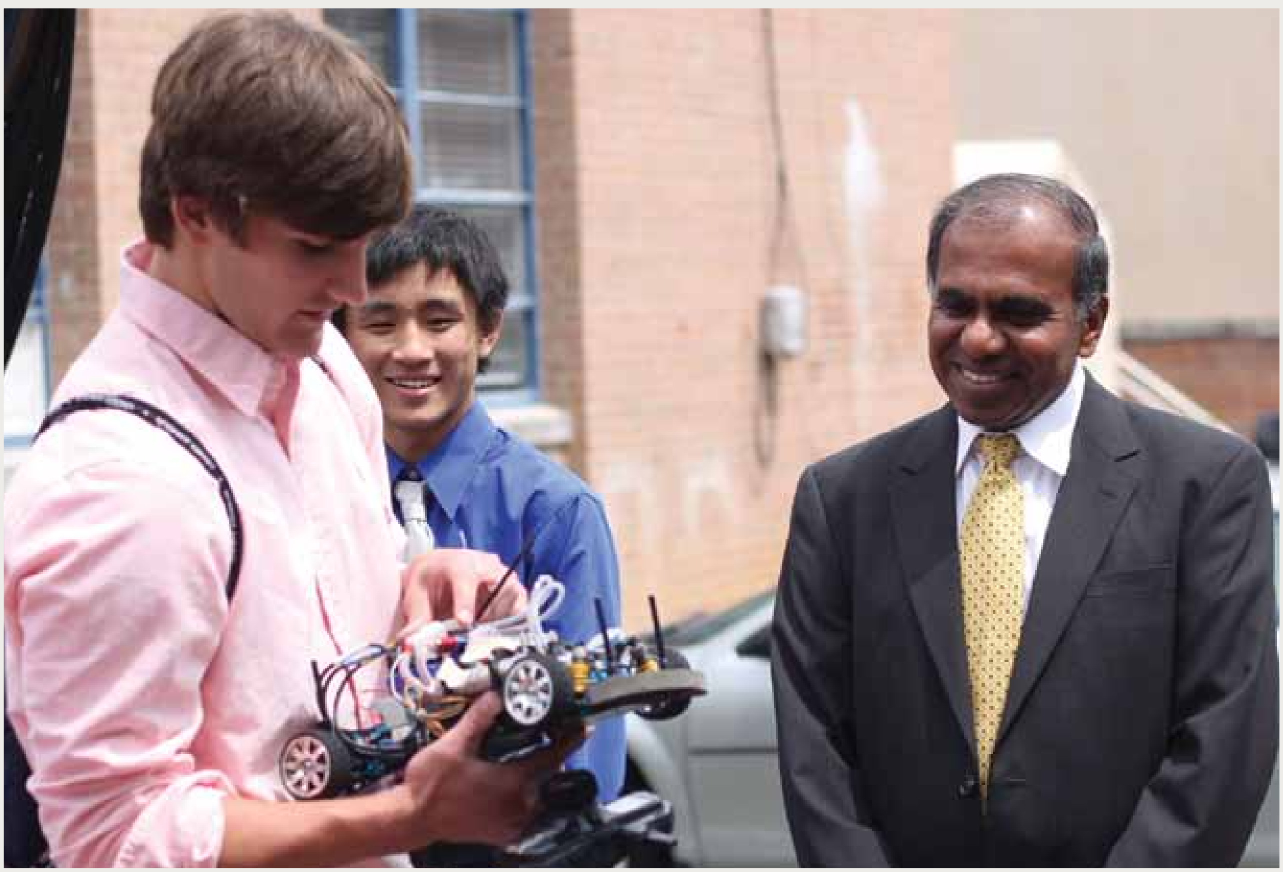
A lot of water is wasted; if we continue growing as we are, our resources will not meet our needs. We can make progress with technology—water recycling and desalination are two emerging areas where science and engineering could help. But looking ahead, especially when you factor in the effects of climate change, the three water systems I've described still need to reach a steady state—a balanced state.

One of my ambitions is to write a non-technical book about water that offers a clear explanation of where we've come from, where we are, and where we need to be with these issues. This puts me in the social science arena, since water impacts economics, political science, law, and the environment. But I also have the advantage of understanding ground water, how canals work, how pumping plants work, what the energy costs are, and so on. So maybe I can offer new insight, a fresh perspective. ENG

John F. Hall is Professor of Civil Engineering.

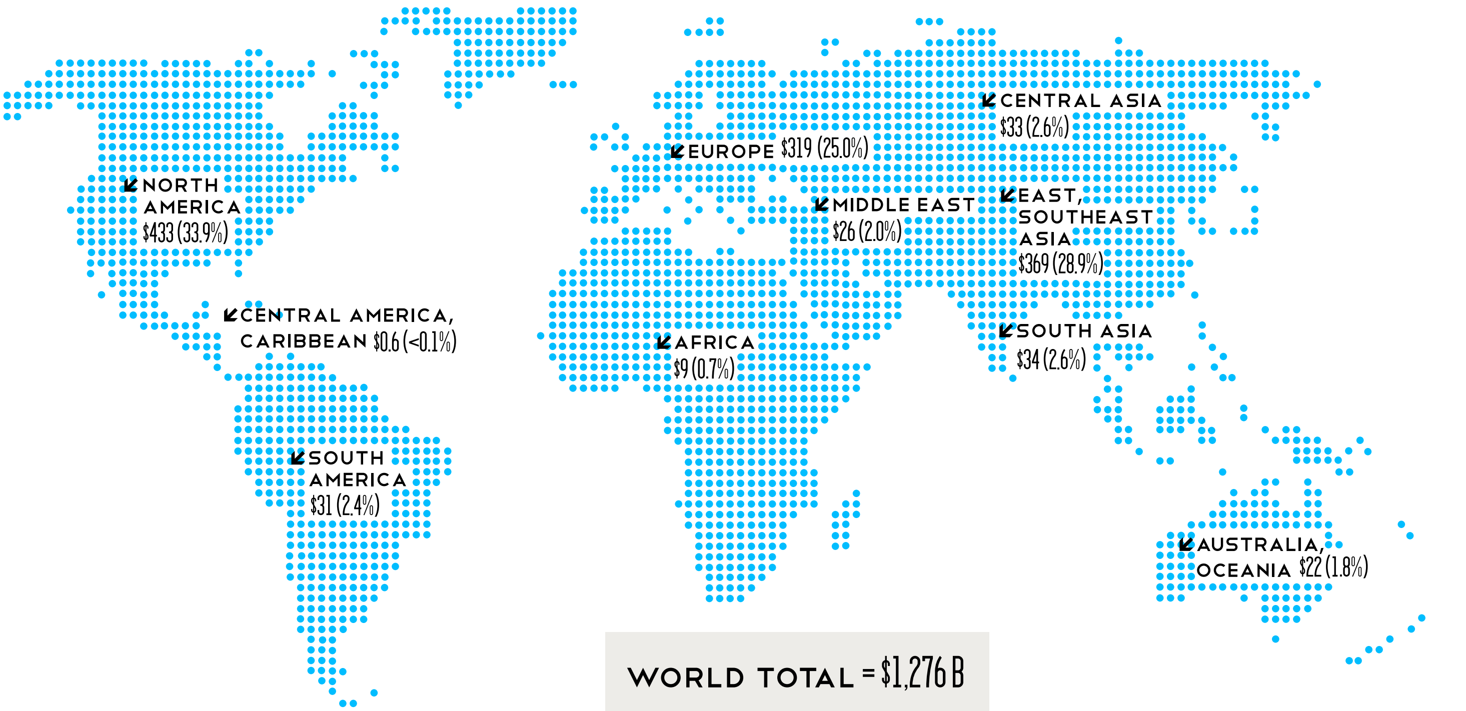
Investing in Engineering and Science:
We Can't Afford Not To!

Dr. Subra Suresh is a distinguished engineer and professor and is the current director of the National Science Foundation (NSF). His academic homes have included the Massachusetts Institute of Technology (MIT), University of California, Berkeley, Brown University, and Caltech, where he was the Clark B. Millikan Visiting Professor at the Graduate Aerospace Laboratory and Division of Engineering and Applied Science Moore Distinguished Scholar.



Kevin Karn, a student at Thomas Jefferson (TJ) High School for Science and Technology, describes his electric-car research to NSF Director Subra Suresh and others during the annual TJ Science and Technology Symposium to Advance Research in Science and Technology (TJSTAR) on May 30, 2012. The NSF director toured the Fairfax County, Va., school and was the symposium's keynote speaker.

Global R&D Expenditures and Share of World Total, by Region: 2009 (Billions of U.S. Purchasing-Power-Parity Dollars)



Prior to his NSF appointment, Suresh served as dean of MIT's School of Engineering. He is currently on leave from the Vannevar Bush Professorship of Engineering at MIT. His innovative experimental and modeling work with nanoscale materials, which connects cellular nanomechanical processes and human disease states, has helped quantify the onset and progression of devastating diseases such as malaria. His academic research has won him a number of awards over the years, including election to the U.S. National Academy of Engineering, the U.S. National Academy of Sciences, and the American Academy of Arts and Sciences. More recently, he has been awarded the prestigious Timoshenko Medal from the American Society of Mechanical Engineers (ASME). *ENGenious* interviewed Dr. Suresh to learn more about the challenges and opportunities facing engineering and science in the United States.

***ENGenious*: What is the greatest challenge facing engineering and science in the United States?**

Suresh: For the last half-century, the United States has been considered the undisputed leader of global innovation. Despite an ongoing economic crisis, maintaining America's leadership role is critically important. Many other nations' economies are also suffering, but nevertheless they see engineering and science investment as the ticket to innovation and prosperity. For the last decade, other countries' increased rate of funding has been significantly more than ours. If our funding reductions continue for several years, we'll pay a very heavy price. Our

"Despite an ongoing economic crisis, maintaining America's leadership role is critically important. Many other nations' economies are also suffering, but nevertheless they see engineering and science investment as the ticket to innovation and prosperity."

Above: *At an exhibit about hazard and disaster research in September 2011, Dr. Suresh discusses the NSF-funded Giant Screen Films production* Tornado Alley *with co-producer Deborah Raksany.*

Right: *Dr. Suresh talks with Robin Murphy, a professor in Texas A&M's Department of Computer Science and Engineering and director of the Center for Robot-Assisted Search and Rescue (CRASAR), in September 2011.*

second and third challenges have occurred in the last couple of decades. We are in a global competition for talented scientists and engineers. We will remain an innovation leader if we can continue to attract and keep top talent from all over the world. And our aging infrastructure—experimental facilities for physical sciences, for example—need updating, which is expensive. By building newer infrastructure, other countries can leapfrog technologies.

***ENGenious*: Despite the economic challenges we are facing, NSF has received strong support from Congress. What do you think is fueling this success?**

Suresh: At times of tight fiscal constraint, there's often a flight to quality. In past economic crises, strong research universities have actually seen increases in research funding. There is general awareness that global leadership in technology and innovation directly depends on the quality of a country's research and education in science and engineering. In this area, NSF plays a key role, and so I've been making the argument that now is the time to increase support—not because it's self-serving, but because the data support it. Although we see more competition from other countries, engineering and science funding for basic research carries no political agenda; even in periods of global unrest, international cooperation in research continues.

***ENGenious*: Why did you choose to serve as director of NSF?**

Suresh: A continuous connection to education, research, and the political process makes NSF a very unique institution. As its director, I deal with researchers, educators, young scientists, students, and administrators in about 1,800 institutions across the country, engage in numerous national and international activities, and enjoy access to the global scientific community.

***ENGenious*: What do you hope to accomplish as NSF director?**

Suresh: Though resources are tight, with clear strategies and careful leveraging, we have launched a number of new ideas and initiatives. For example, some of our best practices have been elevated to agency-wide levels, such as the Career-Life Balance Initiative, a ten-year plan to provide greater work-related flexibility to women and men in research careers and facilitate reentry after family leave with minimal loss of momentum. We received strong encouragement for this initiative from the White House, which is concerned about the importance of supporting and retaining women and girls in STEM (science, technology, engineering, and mathematics) careers.

Another example is our Integrated NSF Support Promoting Interdis-

"When you bring diversity to science—that is, geographical, cultural, and ethnic—the quality of the science is greatly enriched."

At a STEM education event in Philadelphia in September 2011, Dr. Suresh joined U.S. Congressman Chaka Fattah (right) and Andrew Williams (with robot), who coaches the Spelbots team at Spelman College.

ciplinary Research and Education (INSPIRE), which expands on NSF's existing interdisciplinary work. If a young university researcher has an idea that doesn't fit into established funding pockets or traditional disciplines, we can nurture and sustain support for that idea through this new initiative. INSPIRE encourages agency-wide, cross-disciplinary

"I know by experience that migration from one field to a seemingly unconnected field is possible. Ten years ago, I went from mechanical engineering to microbiology and infectious diseases."

collaboration and co-funding, so that each participating program office provides only a fraction of the total cost, which is then centrally matched. I know by experience that migration from one field to a seemingly unconnected field is possible. Ten years ago, I went from mechanical engineering to microbiology and infectious diseases.

A third example is on an international scale. We recently hosted a Global Summit on Scientific Merit Review and launched the new Global Research Council (GRC). Participants included research council heads from 47 countries—representing both developed and developing nations. GRC seeks to develop better harmonization of global science through which all scientists can benefit.

Other programs where NSF has made major strides during the past year include the NSF Innovation Corps (I-Corps), which was launched to maximize the impact of NSF-funded basic research discoveries, and several international collaborations for American scientists facilitated through the Science Across Virtual Institutes (SAVI) initiative.

Thus, NSF can provide leadership globally, nationally, and locally with the goal of moving the boundaries of knowledge in every field of engineering and science and related education. I'll be very satisfied if we can build on last year's momentum and connect on all these levels during my tenure.

***ENGenious*: You've stated that "good science anywhere is good for science everywhere." Why is this approach important?**

Suresh: I have a caveat to that, which is good science must be practiced in an open and transparent way; we should publish openly, share resources, and work together through a proper peer review process along with an infrastructure that ensures research integrity and respect for intellectual property. Basic science requires verification—it must be independently reproducible. The more people that do that, the better it is for science. When you bring diversity to science—that is, geographical, cultural, and ethnic—the quality of the science is greatly enriched.

***ENGenious*: You've spent time at both Caltech and MIT. Can you speak to their differences, similarities, strengths, and weaknesses?**

Suresh: They are mainly different in size and scale. I was Dean of Engineering at MIT, which is the largest of its five schools. MIT engineering is 50 percent larger than all of Caltech in terms of number of faculty. Caltech and MIT are both very powerful. Each has its own culture, its unique flavor; yet each has been extraordinarily influential in its own right.

Caltech is verdant and colorful; the MIT campus is part of an urban environment. MIT's size gives it the advantage of a bigger footprint, not only in engineering but also in other areas from political science to management to the humanities. Caltech's advantage is its small size. Demarcation between divisions or departments is less, so it's easier to move across campus. I know that Jean-Lou Chameau, President of Caltech, met with each and every faculty member after first arriving on campus. So the interaction between individual faculty members and senior administrators is much easier, and conducive to a more family-like atmosphere. The same is true with student interactions, which are more personal.

***ENGenious*: What did you learn from the time you spent at Caltech?**

Suresh: Caltech has always been a very scholarly place but with a relaxed atmosphere—a fun place. It is a place that I have known through many visits and many people. Ravi (Guruswami Ravichandran) was a student in one of my classes. I have known Ares Rosakis since the 1980s, as well as Michael Ortiz and Wolfgang Knauss, since the mid-1980s. What have I learned? I learned that sometimes serendipitous things work very well. For example, I was at the Red Door Café with Ares more than ten years ago. We realized we both had patents on something that we could do jointly. We actually went from the Red Door to the Caltech Office of Technology Transfer, and that coffee hour formed the basis for a new Caltech patent on coherent gradient sensing, or CGS. Now Caltech has several patents in this area, and Ares and I jointly filed patents with some Caltech postdocs and MIT students. A real collaboration, and another lesson I learned: how two institutions can work very well together.

Dr. Suresh and Professor Ares Rosakis, Theodore von Kármán Professor of Aeronautics and Professor of Mechanical Engineering; Chair, Division of Engineering and Applied Science

***ENGenious*: What is at stake for engineering and science during the 2012 election?**

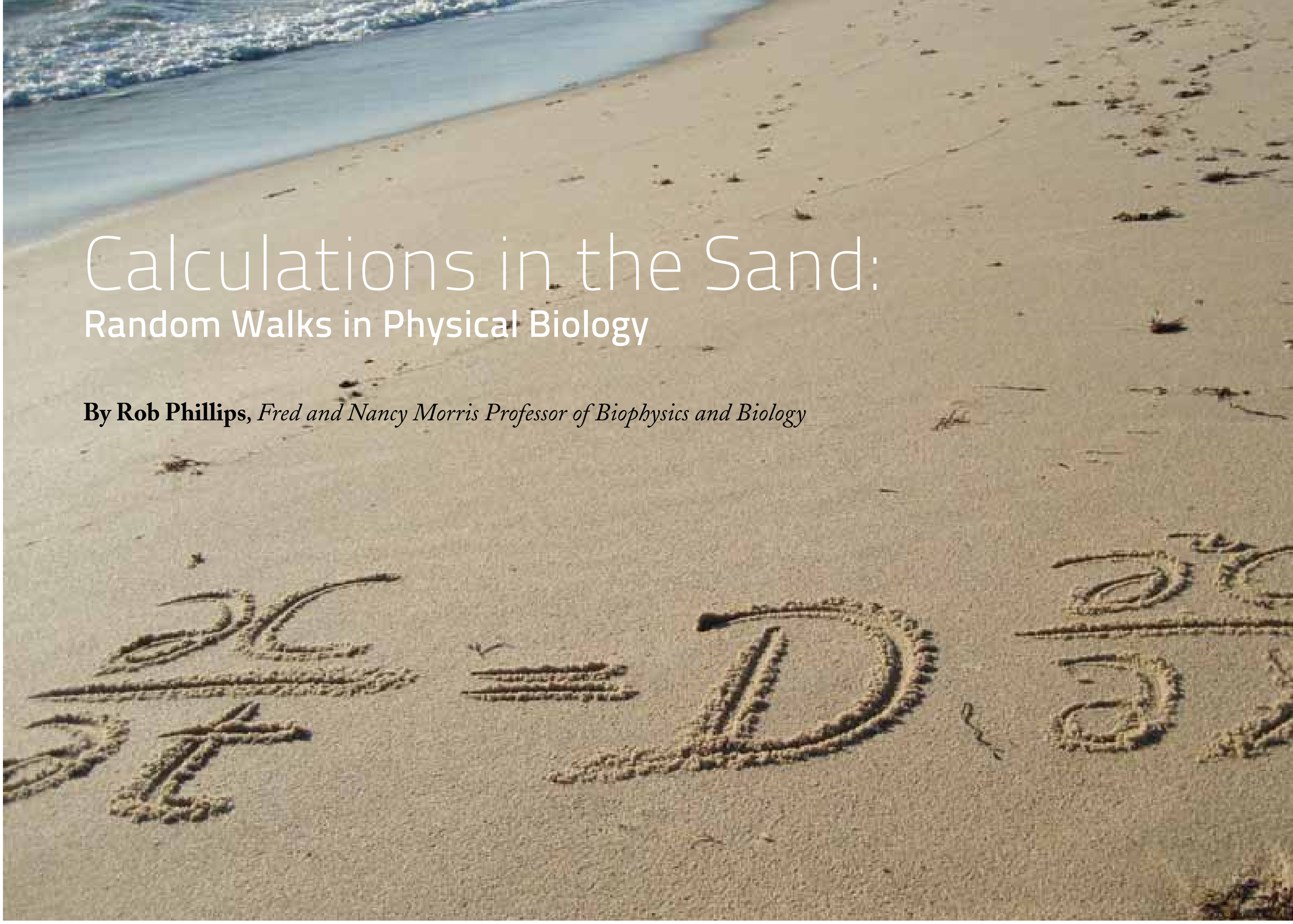
Suresh: The importance of focusing on basic research, education, and innovation generally takes a secondary or tertiary role in the political debate compared to other topics. But we all need to understand that we cannot afford not to support innovation through research and education in engineering and science.

***ENGenious*: What engineering and science questions should we ask of the individuals running for office?**

Suresh: What is their perspective on the importance of science, engineering, research, and education for the twenty-first century? All citizens will need a basic level of expertise to thrive in any profession. Our communication tools are increasingly sophisticated and require us to think more quantitatively even in our daily lives. A strong commitment to education at all levels will prepare us at the very least for survival, and hopefully for success, in stiff global competition. The question will be: How will our elected officials help society evolve in that direction? E N G

Subra Suresh is Director of the National Science Foundation (NSF).

Visit www.nsf.gov.



Calculations in the Sand:

Random Walks in Physical Biology

By Rob Phillips, *Fred and Nancy Morris Professor of Biophysics and Biology*

One word could summarize my interest in science: "Change." It may be a cliché to say nothing stays the same (although true), but the scientific study of change is a central preoccupation of physics and chemistry, with the word "dynamics" cropping up at every turn. And in the science of life and living organisms, "evolution"—the process whereby species change over time—is regarded by most as biology's greatest idea.

change

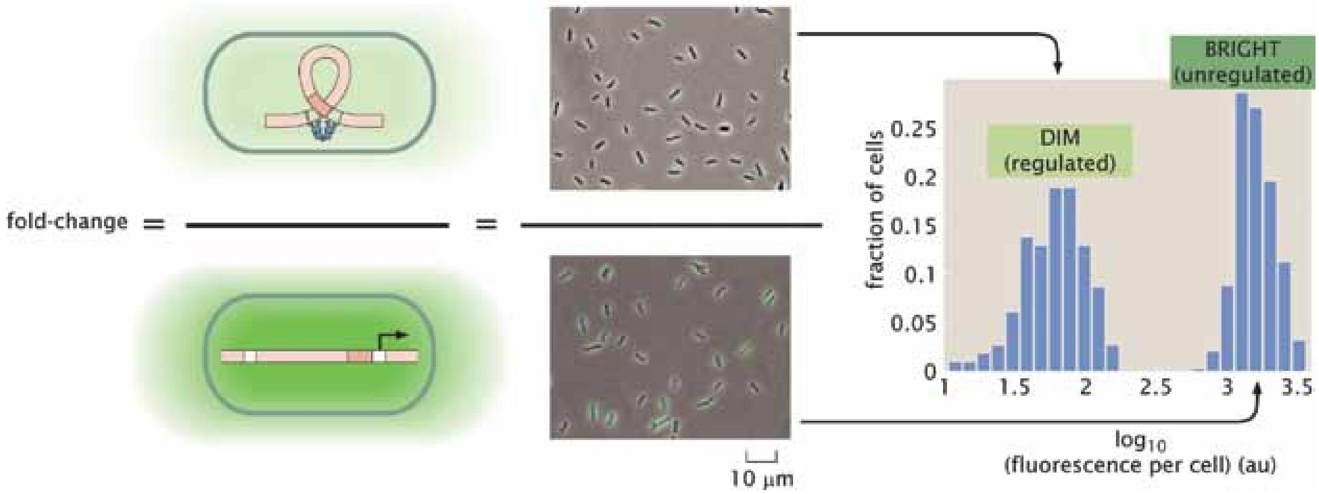
> *"One could argue that life science is engaged in a period of explosive growth that rivals or even outpaces that of the fields of physics and astronomy after the invention of the telescope."*

extra sense

Left: *Though there is a long tradition of "back of the envelope" estimates, we like to think of models that are simple enough that calculations can be done with a stick in the sand. This shows the equation that describes biological problems ranging from the diffusion of the sugars that cells like to eat to the geometric configurations of DNA molecules.*

My own path to biology certainly required many changes. After nearly a decade as professor in the solid mechanics group at Brown University, I came to Caltech as an applied physicist with an eye to using the move as an opportunity to start something new. The idea was to pursue a long-standing interest in the living world, but to keep one foot squarely planted in my original field by approaching biological studies with the familiar languages of mathematics and physics. Speaking of his school days in his autobiography, Charles Darwin (1809–1882) noted, "in after years I have deeply regretted that I did not proceed far enough at least to understand something of the great leading principles of mathematics, for men thus endowed seem to have an extra sense."

But what is the meaning of Darwin's "extra sense"? None of us knows how to listen to a rainbow or see the sound of a musical note. What I think he meant is that the application of mathematics to science sometimes allows us to "see" things that would otherwise remain completely hidden. That passage from Darwin's autobiography reminds me of a similar story surrounding his famed British contemporaries Michael Faraday (1791–1867) and James Clerk Maxwell (1831–1879). Michael Faraday is widely considered one of the greatest experimentalists of all time. His path from bookbinder's apprentice in his



This figure shows how we measure how much a given gene is on by looking at how much green fluorescent light the cells give off. In fact, we measure the level of expression relative to a standard and construct their ratio to find a quantity we call the fold change. The brightness of the two populations of cells is seen in the two histograms on the right. In particular, the two peaked distributions show what fraction of the cells are "bright" and "dim," corresponding to those in which the gene of interest is unregulated and those in which that same gene is turned off.

late teens to a laboratory technician post at the Royal Institution in London, where he became the preeminent discoverer of his time, is remarkable—yet he had no formal training, least of all in mathematics. Decades after Faraday's important contributions to the subjects of electromagnetism and electrochemistry, Maxwell reformulated Faraday's ideas in the famous equations that bear his name. Maxwell's quantitative connection between light and electromagnetism is considered one of the great accomplishments of nineteenth-century physics. In a way, Maxwell used Darwin's "extra sense" to refashion Faraday's thinking in mathematical terms: "As I proceeded with the study of Faraday, I perceived that his method of conceiving the phenomena was also a mathematical one, though not exhibited in the conventional form of mathematical symbols." Maxwell effectively "translated" Faraday's ideas "into a mathematical form." Today, work in my group tries to follow the Faraday-Maxwell example in our own small way, but in a completely different setting: namely, biology.

One could argue that life science is engaged in a period of explosive growth that rivals or even outpaces that of the fields of physics and astronomy after the invention of the telescope. In our view, many biological discoveries are themselves conceived in a mathematical form, even if not expressed by traditional symbols. So our group aims to mathematicize cell biology. All our work is under the umbrella of physics meets biology—we are engineers and physicists who hope to bring fresh and useful insights to biology by thinking about biological problems mathematically.

We use several distinct case studies to illustrate that approach. Our work spans a range of problems—for example, we're looking at how bacteria respond to sugar or salt in their environment, how cells organize their massive genomes (in human cells, one meter of DNA is packed into the tiny nucleus, which has a size less than one-tenth the width of a human hair), and how viruses transfer their genetic material as they infect their hosts.

We're exploring the use of mathematics as a criterion to determine whether the outcome of a given biological experiment is surprising. What our group does is address certain problems at the cellular level, and perform calculations to quantify our results. We are applying Darwin's "extra sense" in situations where we wouldn't actually know if we're surprised unless we quantify the results.

To illustrate, we're working on a problem that is already more than a hundred years old, which focuses on how microorganisms such as bacteria and yeast get the carbon they use to make new cells. In the late nineteenth century, studies on yeast fermentation raised many questions about how cells get their carbon. A more recent version of these questions focuses on how bacteria decide what to eat. Just as you and I might prefer doughnuts to broccoli, bacteria care about what carbon source you give them. If you give them several choices of sugar, they will choose only one. They will use the one source until they've exhausted it, and then they'll choose another. That is, they rank-order their carbon sources—and we're interested in the genes that control this choice. This classic problem resulted in the discovery of the modern theory of gene regulation—yet certain quantitative features are disturbing. That is, they don't make sense when viewed through a quantitative lens.

Some biologists may see this as unimportant—the basic work was already done in the 1970s—but I'm not so sure. Here's why: If you apply polymer physics to DNA, you immediately see that in some circumstances within living cells, DNA is forced into highly curved configurations. We're trying to work out how DNA gets bent and folded and crumpled up inside of cells, and how that activity affects gene regulation. This folding, in turn, is related to behavioral choices of the bacteria: The folding of the DNA has to do with what it chooses to eat (and decisions of many other kinds as well). When it doesn't want to eat lactose, DNA is folded in one way, and when it decides to eat lactose, the protein that folds it lets go and then it turns on the genes that make lactose digestion possible. We are trying to watch the cells' decisions in real-time, and to understand the consequences of flexibility of DNA.

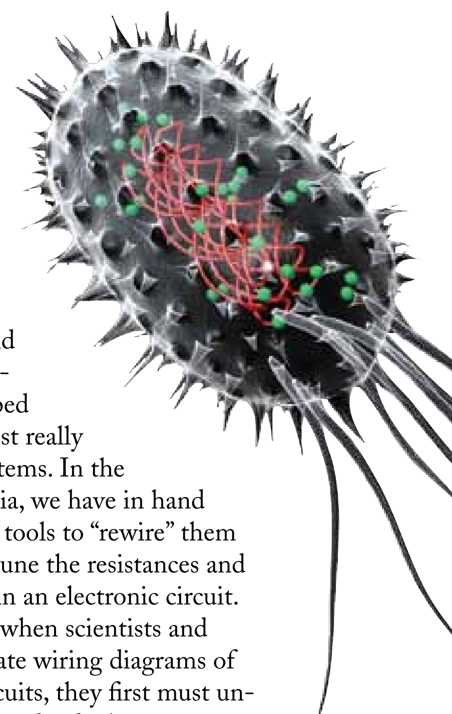
This is where our approach parts with tradition: we first calculate, and then we measure. We measure both *in vitro*, meaning in the test tube, and at the same time, we measure in what some have christened the test tube of the twenty-first century: the cell itself. In other words, we behave first as theoretical physicists by applying calculations that describe what we know about how the gene networks in a bacterium work—what you would call the input/output relationship of the bacterium. We calculate how much of the enzyme needed to chop and eat a specific sugar is present for different cellular circumstances. Based upon differences related to gene circuit wiring, we calculate different input/output relations and produce a mathematical theory of the process. We then take that mathematical theory into the lab and redesign bacteria—that is, we actually "tune" the bacteria by altering the DNA. We go through the strands one by one, examining changes that result from the tuning process. We watch regulation by using a green fluorescent protein from jellyfish that has become a standard way of "reading out" cellular decisions. Our bacteria glow based on how much of the enzyme that digests sugar is present, and this tells us whether our calculations are "right" or not.

Often the most interesting cases are those in which something doesn't make sense, and for the problems we are attacking, to even know that things don't make sense you need a mathematical description of the problem. And this is how we know whether we're surprised: the differences are quantitative—a qualitative viewing of the problem is like trying to see the sound of a musical note.

Why do we study bacteria? A current trend in biology is toward the kind of cells that make up we humans, or eukaryotes—organisms whose cells contain complex structures enclosed within membranes. But in terms of numbers, eukaryotes represent a tiny minority of all living things. In a human body, there are ten times more microbes than human cells. If humans disappeared from Earth, the event would likely be a tiny hiccup in the overall scheme of things. If bacteria disappeared, the whole system would collapse. Indeed, Caltech has recently started an initiative on microbiology, led by Professor of Biology Dianne Newman. The collaborative effort includes researchers from a broad cross-section of the Caltech community who share a fascination with the microscopic living world.

But we also study bacteria because they are simple. The Nobel Prize–winning biologist Sydney Brenner is said to have quipped, "Either work on things that are six months ahead of everyone else, or 30 years behind." We are looking farther back than that, and our logic is this: In order to carry out the kind of systematic interplay between mathematical models and careful experiments described above, we must really "own" the systems. In the case of bacteria, we have in hand the necessary tools to "rewire" them as we might tune the resistances and capacitances in an electronic circuit. For example, when scientists and engineers create wiring diagrams of electronic circuits, they first must understand how individual components, such as a transistor or diode, works. Similarly, our work with bacteria, and *E. coli* in particular, is aided by the previous work of biologists who have figured out how to manipulate the wiring diagram. We use that work as our starting point and create precise

"Bacteria care about what carbon source you give them. If you give them several choices of sugar, they will choose only one. They will use the one source until they've exhausted it, and then they'll choose another. That is, they rank-order their carbon sources—and we're interested in the genes that control this choice."



mathematical forms of the various components that make up the genetic wiring diagram of the cell.

We are also interested in how bacteria react to changes in natural environments. An example of this is how osmoregulation works—the active regulation of the osmotic pressure of a cell's fluids to maintain the homeostasis of its water content. (Osmosis is the main way water is transported into and out of cells.) Just as our human bodies promote survival despite environmental insults such as cold temperatures, bacteria have similar mechanisms to preserve homeostasis in the face of changes in the osmotic state. Red blood cells respond by growing spikes under certain salt conditions, for example, and bacteria have reactions of their own to changes in their environment's salt content. If bacteria suddenly encounter a salt-free solution, water will rush in through their membrane, but they actually will still survive. This is part of a bacterium's normal life, and we're trying to understand how it works. Again, we start with our theoretical calculations and then perform single-cell measurements in a controlled environment. We do this by flooding our bacteria with pure water or various solutions of salt water and watching what happens to cells that are missing some of the proteins that rescue them during these osmotic shocks—essentially, they blow up. We measure that response according to the nature of each insult.

We are living through a historic time—scientists in the field of biol-

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ogy are making discoveries at a dizzying pace. In light of these advances, we and our colleagues at other institutions are becoming interested in building upon those discoveries by constructing simple but predictive models that not only provide a conceptual framework for explaining measurements that have already been done, but make polarizing predictions about experiments yet to be done. My friend and colleague, Tufts University School of Medicine Distinguished Professor, Emeritus, Moselio Schaechter, writes a blog called *Small Things Considered*. He recently asked what the apparent discovery of the particle known as the Higgs boson will do for biology. My own answer is that the study of the Higgs particle exemplifies the kind of interplay between theory and experiment that we should aspire to when describing biological systems, where surprising predictions are made and years of effort then follow to test them.

A new edition of my book *Physical Biology of the Cell* attempts to take stock of the great excitement surrounding efforts to mathematicize our understanding of biological systems. To capture this approach, we used images of calculations in the sand that depict our hopes for the kinds of calculations that one makes when first trying to mathematicize new problems. The images refer to a story about Archimedes of Syracuse (c. 287 BC–c. 212 BC), who is considered to be the greatest mathematician of antiquity and one of the greatest of all time. He is said to have died at the hands of a Roman soldier while performing calculations in the sand. His surviving works were an influential source of ideas for scientists. We are trying to illustrate calculations in biology that are simple enough to do with a stick in the sand. With that inspiration, the book explores the approach being taken by those working at the interface between biology and physics and shows how the basic tools and insights of physics and mathematics can illuminate the study of molecular and cell biology. We describe how quantitative models enable a better understanding of existing biological data and, most important, are the basis of unexpected predictions.

Yes, modern biology is complicated, but through the kinds of boundary-crossing, novel approaches seen in many divisions across the Caltech campus and elsewhere, I believe we will find surprising new ways of looking at important biological problems.

Rob Phillips is Fred and Nancy Morris Professor of Biophysics and Biology.

Visit eas.caltech.edu/people/3153/profile.

Kari Hodge, as Hellena, is wooed by Ryan Trainor, as Willmore, in The Rover.

Cultural Ambassador for Science

Brian Brophy, Director of Theater Arts at Caltech (TACIT)


Brian Brophy

***ENGenious*: What is TACIT?**

Brophy: Theater Arts Caltech (TACIT) originates in the 1897 activities by the Gnome Club to train students in debate, essay writing, declamation, extempore speaking, and—from an innate impulse to connect with people—entertain, educate, and share ideas and stir passionate discussion about science and culture. Starting in 1924, Pi Kappa Delta and the Caltech Drama Club presented an annual classical play, alternating between comedy and tragedy, curtailing their activities on the eve of World War II. During the war years and up until the early 1970s, club activity was sporadic. My predecessor, Shirley Marneus, was hired at that time, and for the next 35 years, musicals and Shakespeare became TACIT's signature offerings. Over the last three years, with great student energy and commitment, the tradition has resurfaced, and this past summer's *Midsummer Night's Dream* is the latest offering. Although the program was created by and for student participants, we now include graduate students, postdoctoral fellows, Caltech faculty and staff, alumni, and the broader Caltech community, including Jet Propulsion Laboratory scientists and engineers. Students can earn credit for taking the class, but many do it because they just want to be in a show with other community members. It's truly a community-based theater arts program.

***ENGenious*: Why is a Caltech theater arts program important?**

Brophy: First, for our students, it's a kind of release from the intense pressure of total immersion in a theoretical world. Students can briefly step outside the abstract and engage in a very physical and psychophysical social experience—to create interpersonal connections outside the research lab. Many students feel a sense of isolation in their academic routine, and theater involvement offers them an instant and expanded social network. For example, we recently performed *The Rover*, the year's main stage production. We had about 30 actors, at least 20 stage and technical crew, professional designers, and choreographers who participated—a group of about 50 people who are still communicating with each other today. Warren Brown, Caltech Professor of History, once described the arts as a pressure valve. Although I largely agree with that assessment, I think the moral imagination of scientists—really, the moral imagination of our culture—can come out of art, the discussion of art, and, of course, performance, a practical application of the imagination. Caltech theater also fulfills the vision of Noyes that cultural studies be a necessary component of science education. TACIT offers social interactivity, as well as skill of movement, of speech, of articulation, through the performance venue. Our students arrive with a kind of native intelligence—a very sophisticated way of approaching the world through abstract modalities. In TACIT, science merges with culture, and our performers end up engaging both sides of the brain. In the process, students gain self-confidence and develop the skills to be leaders.

***ENGenious*: What are your goals for TACIT?**

Brophy: First, the timing of our shows has to be carefully orchestrated. My first play selection as director was Berthold Brecht's classic *Galileo*. We had close to 800 audience members. It was a big production, about 30 actors. I noticed that as we got closer to opening, at least half the student actors were actually backstage during rehearsals, working on their midterms! The same thing happened with Karel Capek's *Rossum's Universal Robots*. It showed great commitment! And it wasn't just bad timing (the fall), but students were spending 60 to 100 hours a term on the plays.

They're not getting a theater arts degree, but many of them would qualify for a performance studies minor at another university. I think a basic performance class should be mandatory for all incoming students. Currently, I am working with International Student Programs (ISP) and the incoming international graduate students on performance exercises. I noticed an immediate increase in their "presence," from eye contact and body expression to a greater ease of movement. The students ended in a happier mood, interacting more casually, seeming relaxed. My goal this year is to reduce the amount of time that students engage in the productions, but offer more opportunities for lesser time commitment—ideally six to eight hours a week for main stage shows.

Kathryn Bikle (CIT Staff), Arseny Vasilyev (G), Raj Katti (UG), Mark Lucas (CIT Staff), Steve Collins (JPL), Alex José (UG), and Diego Caporale (UG) in The Three Musketeers

I also want to focus on doing more musicals, more Shakespeare. This year, for example, we're working on an off-Broadway musical comedy, *Little Shop of Horrors*. We want to create the coolest, biggest mechanical man-eating plant and relocate it to Southern California in this quirky, dark comedy. It has great music and it's a little offbeat, and the students are excited about it.

Another goal is to help find, or create, a real performance venue on campus. We make do now with various lecture halls or outdoor venues, but I'd like to create an external performance laboratory here in the TACIT space, so we have a place to rehearse and perform. A dedicated space, or various small spaces, would benefit both TACIT and others across campus who put on performances. This November, we are presenting a new play on Bobby Fischer, *Mate,* at the Armory Center for the Arts; *Tesla* at the Pasadena Playhouse in April 2013; and *Rashomon* in Descanso Gardens and on the Beckman Mall in the spring.

I'm also here to complement the sciences, so another goal would be to interact with scientists and their research through performance, to provide them with additional tools for personal growth and development, but also help them to exteriorize their concepts in ways that will help the wider community gain an appreciation and understanding of their work. For example, when Professor Ares Rosakis helps us to understand plate tectonics and earthquake ruptures as a dance beneath the surface, it allows us different ways of understanding difficult concepts. This is where we all become, in a sense, cultural ambassadors for science. We've recently started an improvisation class, which supports this idea and how our students process their intense academic research and course work. We bring in professionals to work with the students, and at the end they do a 48-minute comedy set: improvisation, completely unscripted. We do it every term now.

Another way to encourage alternative voices is to offer playwriting opportunities. We want to develop new plays, so we do weekend readings. My MFA in creative writing for the performing arts helps me to facilitate conversations with playwrights who submit material to us—including members of the Caltech community! Yes, we can do Shakespeare, musicals, modernist fare, comedies. But we can also develop new plays about science and culture.

***ENGenious*: What brought you to Caltech?**

Brophy: Returning from my Fulbright to India and wanting a different direction in my life, as well as Bob O'Rourke. India changed the way I think. I had taught for years, and performed in films and on television, including *Star Trek: The Next Generation*. When I heard about this job, I thought it would be a great fit. I think the Fulbright helped—I can adapt to different environments—and I've always had an interest in science and the history of science.

***ENGenious*: Anything you'd like to add?**

Brophy: I'd like our alumni to know that we have been creating a database of Caltech alumni who were involved in TACIT, going back to the early 1970s. We want to bring them back to campus to continue a new tradition we've started: throwing a party and letting them perform again—sing a song, do a monologue, whatever they'd like. People remember TACIT as student-friendly—a place to eat and relax. We'd like our alumni to come back, see what our students are doing now. Through performance studies, through experiencing the confluence of science and culture, they have found Caltech to be an even more exciting and interesting place to be. ENG

Brian Brophy is Lecturer in Performing and Visual Arts and Director of Theater Arts at Caltech (TACIT).

Visit tacit.caltech.edu.

The Earle M. Jorgensen Laboratory has been transformed into a cutting-edge, energy-efficient scientific research facility. Inside are two of Caltech's most vital forces leading the charge in the reinvention of energy: the Resnick Sustainability Institute and the Joint Center for Artificial Photosynthesis (JCAP). The Resnick Sustainability Institute fosters transformational advances in all areas of energy science, sustainability, and technology through research, education, and communication. JCAP is the largest U.S. research program dedicated to the development of an artificial solar-fuel generation technology. The building, which was dedicated on October 19, 2012, helps in uniting these visions of creating a world with clean, abundant sources of energy through science, collaboration, and leadership.

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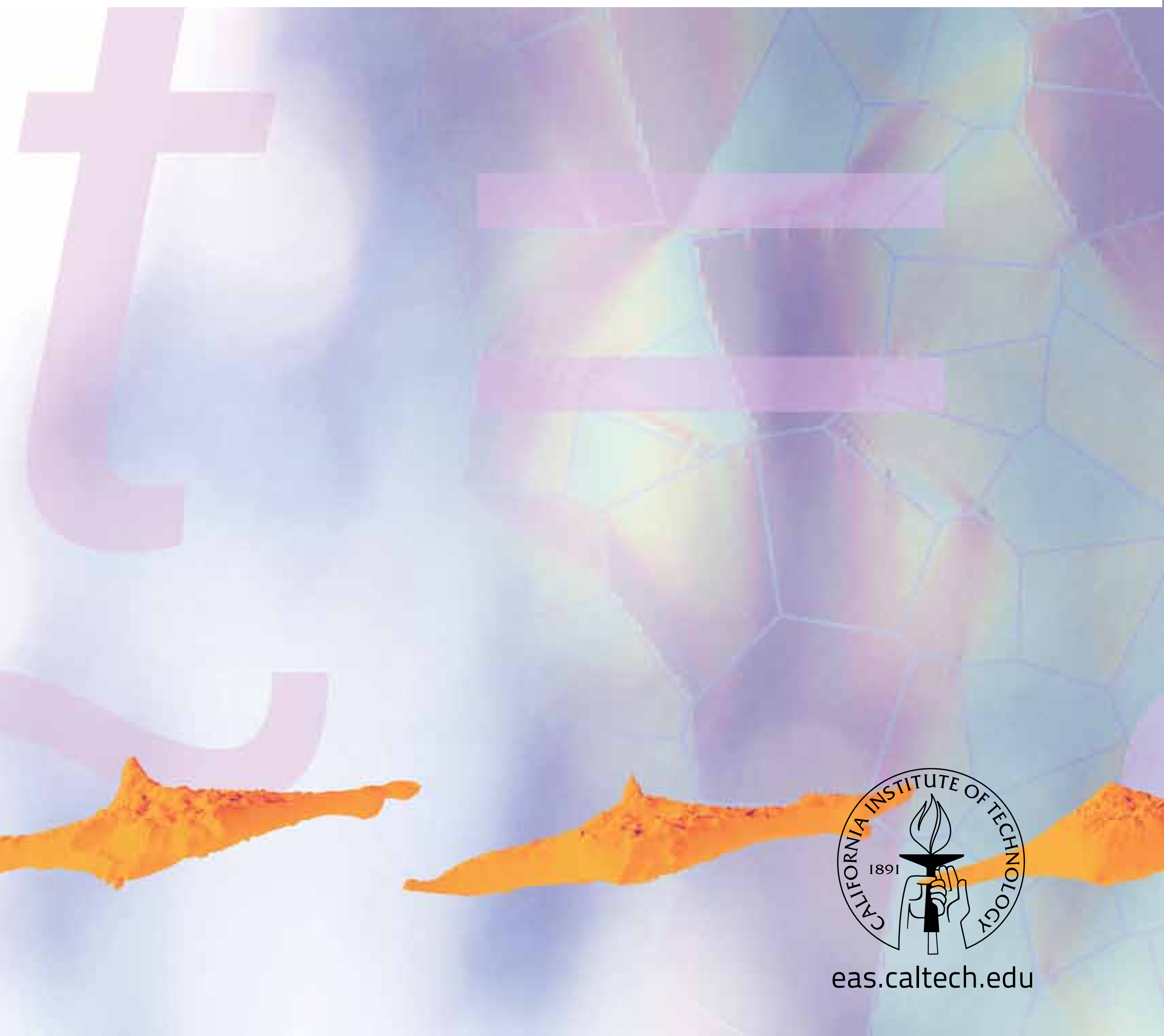

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