ENGenious

ISSUE 12, 2015

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

Caltech

DIVISION OF ENGINEERING & APPLIED SCIENCE

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

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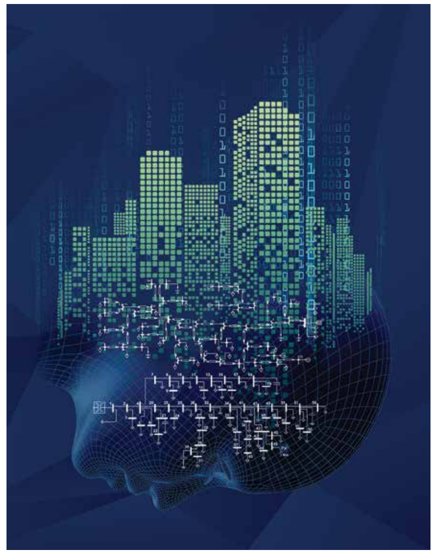
The Caltech Division of Engineering and Applied Science consists of seven departments and supports close to 90 faculty who are working at the leading edges of fundamental science to invent the technologies of the future.



Interplay Between Humans and Technology

This illustration depicts the power of the human mind to elucidate information from data that can be used to take action—for example, the optimization of electrical output in existing and proposed smart grids to better meet our energy needs.

The illustration was inspired by the work of Computing and Mathematical Sciences faculty featured in “From Data to Information to Action” on page 12.

Ares Rosakis and Guruswami (Ravi) Ravichandran are shown here in the newly renovated Charles C. Gates Jr.–Franklin Thomas Laboratory's Division Chair office.

Dear alumni and friends of the Division,

After six and a half successful years, Ares Rosakis, Theodore von Kármán Professor of Aeronautics and Mechanical Engineering, has stepped down as the Chair of the Division of Engineering and Applied Science (EAS), and Guruswami (Ravi) Ravichandran, John E. Goode, Jr., Professor of Aerospace and Mechanical Engineering, has been appointed as the Otis Booth Leadership Chair, effective September 1, 2015.

Since becoming Division Chair in 2009, Professor Rosakis has overseen many notable accomplishments, including a major restructuring of the Division in 2010 and the creation of a new department, Medical Engineering, in 2013. This restructuring has enhanced the Division's effectiveness in a variety of areas, including teaching, research, recruitment, technology transfer, and fundraising. One mark of this enhanced effectiveness is that Caltech attained the top position in the *Times Higher Education* world university rankings in the subject area of engineering and technology for multiple years under Professor Rosakis's leadership. Another measure is in the number of EAS faculty who have received prestigious academic honors and awards, including membership to national and international academies.

I had the opportunity to sit down with Professors Rosakis and Ravichandran during this exciting time, and I asked Professor Rosakis what he hopes to be remembered for. He said, "I am proud of the very talented and promising faculty who have been hired during my tenure. As preeminent engineers and applied scientists, they are continuing the EAS tradition of serving as strategic interfaces within Caltech and with the rest of the world." He added, "I am very pleased by the results of our fundraising efforts, which amounted to over $200 million during my tenure as Division Chair. I am also delighted that one of my last philanthropic successes was working with Foster and Coco Stanback to bring to fruition a magnanimous gift to establish the Center for Autonomous Systems and Technology."

Professor Ravichandran joined the Caltech faculty in 1990 and has served as the Director of the Graduate Aerospace Laboratories (GALCIT) since 2009. He has received numerous honors and awards, with the most recent being his election to the National Academy of Engineering in 2015. On the subject of his first steps as Division Chair, Professor Ravichandran shared that he "would like to understand the needs and aspirations of the Division and continue many of the initiatives Ares started, including diversity hiring, building renovations, and providing seed funding for groundbreaking early-stage research."

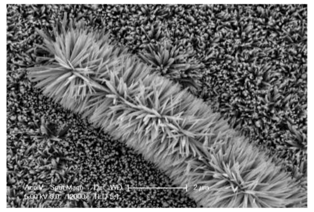
The Division will continue its efforts to engage the alumni with special events such as a full-day Electrical Engineering symposium at Caltech on Saturday, January 30, 2016. "We are extremely proud of the alumni achievements and would like them to know that we continue to attract outstanding faculty and students who are performing cutting-edge research and inventing the world that is yet to be," said Professor Ravichandran.

I asked him to share his vision and plans as the new Division Chair. "I will advocate for and articulate the vision for the Division to advance the interests of the faculty and facilitate achievement of their aspirations," he explained. "I will promote the EAS Division through further collaborations within Caltech and JPL while maintaining our identity as engineers and applied scientists. The alumni and friends of the Division play a key role in our success, and I am looking forward to being actively engaged with them, because they are our best advocates and champions." He added, "I want the Division to be a vibrant place and a world leader in undergraduate and graduate education, research, mentoring, technology transfer, and outreach—a Division that is diverse, inclusive, and unified! We need to attract the best minds in the world, whether it be faculty, students, or staff. These minds, in combination with our unique ability to drive advances that benefit humanity through basic research, will guide us in remaining at the forefront of the technological revolution."

I anticipate another era of success in the coming years as the Division continues its trajectory under Professor Ravichandran's guidance. Please enjoy exploring the pages of this issue of *ENGenious* for a glimpse of recent news and research highlights, as well as our special feature on the Computing + Mathematical Sciences department—an outstanding group of faculty with a drive to produce foundational advances in computing and mathematical sciences that hold the promise of lasting impact on future technologies.

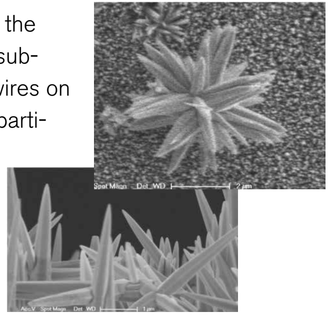
As always, I look forward to receiving your thoughts and comments.

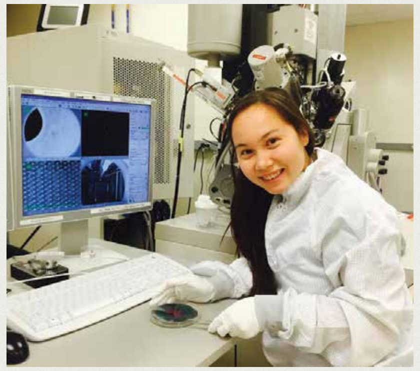
Trity Pourbahrami
Editor, *ENGenious*



Medical Engineering Research to Aid Diabetes Patients

Current technology requires individuals with diabetes to undergo painful, inconvenient, and discontinuous measurement processes several times a day. Summer Undergraduate Research Fellowship (SURF) student Kelly Woo has been working with Hyuck Choo, an assistant professor of electrical and medical engineering, to create more convenient and accurate ways of measuring glucose levels by utilizing surface-enhanced Raman spectroscopy (SERS) techniques. SERS utilizes molecular vibrations to extract the properties of the sample and is highly sensitized through the application of metallic nanostructures. To accomplish commercially viable SERS technologies for glucose detection, an optimal substrate must be designed with higher electromagnetic enhancement so glucose can be detected in low concentrations from fluids in the body, not necessarily blood. To create these substrates, Woo hydrothermally grew zinc nanowires on silicon wafers and then deposited gold nanoparticles. She has successfully manipulated the synthesis process to produce controlled zinc nanowire growth on the silicon substrate by varying parameters of growth.





Cancer Detection Using Affordable Implantable Technology

Early detection of cancer can improve a patient's survival chances by up to 85%. Implantable cancer biosensors, which last up to several years in the body and provide continuous detection of cancer biomarkers, have the potential to provide a low-cost and accurate alternative to existing methods of cancer detection. Accurate detection of cancer biomarkers necessitates sensitivity of detection instruments in the nanomolar range. The sensitivity of currently available micro-scale implantable sensors can be improved by using electrical engineering principles of CMOS technology to enhance electrode design. Summer Undergraduate Research Fellowship (SURF) student Anna Winnicki has been working with Professor Axel Scherer to design and develop implantable electrochemical sensors of nitric oxide, a well-known cancer signaling molecule that dictates both tumor growth and inhibition. Over the summer, she designed electrodes with optimum sensitivity and fabricated the micro-scale electrodes at Caltech's Kavli Nanoscience Institute.

Sustainable Vehicle Club

Last year, with the support of the Resnick Sustainability Institute, a group of students founded the Caltech Sustainable Vehicle Club to promote sustainability through exploration of the design and construction of vehicles. The club's inaugural project has been to transform two defunct go-carts into electrical vehicles (EVs)—one battery powered and the other a fuel-cell vehicle. The parts for the vehicles were prototyped and built in the Jim Hall Design Laboratory. Mechanical Engineering undergraduate student and club president Rob Anderson explained, "Our projects wouldn't be possible without Caltech alumnus and racing legend Jim Hall's contributions! In June we had the chance to meet Jim and show him our first vehicle. He gave us very valuable advice on designing and testing our vehicle. He even gave us some tips on the handling of our vehicle after he took it for a spin around campus!" Professors Guillaume Blanquart, Azita Emami, and Richard Murray are faculty advisors to the club and will be teaching a systems design class in the fall to support this and other projects at Caltech.

To learn more,
visit *www.its.caltech.edu/~cevc/*.

Caltech Sustainable Vehicle Club members meet with with Jim Hall (BS '57).

A Clear Path for Diversity

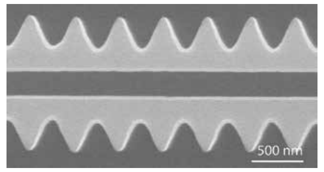
In April 2015, Caltech hosted the California Alliance for Graduate Education and the Professoriate's second annual retreat, entitled "The Next Generation of Researchers." The Alliance was formed in 2013 by Caltech, UC Berkeley, UCLA, and Stanford to support underrepresented minority graduate students in the fields of mathematics, the physical sciences, computer science, and engineering. More specifically, the Alliance aims to provide a clear path for underrepresented students and postdoctoral scholars to aspire to and populate the ranks of the faculty at competitive research and teaching institutions. The Caltech retreat brought together graduate students, postdoctoral fellows, research scientists, and faculty from the four institutions and national labs in California for mentoring and network-building opportunities. Caltech is addressing the challenges highlighted by the Alliance through the development of new programs and the strengthening of existing ones that create access to resources, build community, and leverage relationships.

To learn more about the Alliance and Caltech's involvement, visit *www.california-alliance.org*.

From Exotic Quantum Materials to Photonic Probes of the Brain

For over a decade, the Kavli Nanoscience Institute (KNI) at Caltech has been an intellectual hub and facilitator of cross-disciplinary research in the area of nanoscience and nanotechnology. It houses an advanced nanofabrication facility that supports the research endeavors of many Caltech faculty and has been critical to realizing exciting breakthroughs in nanoscale photonics, materials science, and biotechnology. The Fletcher Jones Foundation co-directors of the KNI, Professors Nai-Chang Yeh and Oskar Painter, with help from the Kavli Foundation, are planning to provide funding to several nascent research projects that exemplify the new directions that "nano" science is taking at Caltech. Selected projects range from the creation of new quantum materials of photons and atoms made by embedding laser-cooled gas-phase atoms in porous nanostructured dielectric materials, to the development of neurophotonic probes for massively multiplexed mapping of brain activity. The KNI will also be starting a new KNI Scholar Program that will recognize exceptional nanoscience-related research by tenure-track faculty at Caltech.

To learn more, visit *kni.caltech.edu*.



This "alligator" nanoscale optical waveguide is used by H. Jeff Kimble, William L. Valentine Professor and Professor of Physics, and colleagues to optically trap gas-phase atoms.

Engaging Students in Science and Engineering Policy

The Science & Engineering Policy at Caltech (SEPAC) club was formed by a group of students in February 2013 to educate its members on the policies governing research and innovation. According to Environmental Science and Engineering student and current president of the club Zachary Erickson, "Policy can determine the viability of entire fields of academia, such as stem cell research. In other instances, science policy translates research results into action, as in the adoption of catalytic converters in cars, a result of Environmental Protection Agency emission regulations spurred by atmospheric chemistry research. Yet students do not often encounter science policy during their studies, meaning they can be under-equipped to engage with it in their future careers."

To address this concern, SEPAC facilitates student-led discussions on science policy issues and sponsors luncheons. In February 2015, the club collaborated with the Graduate Aerospace Laboratories of the California Institute of Technology (GALCIT) to organize an all-day event focused on student research and culminating in a keynote address by Dr. Wanda M. Austin, president and CEO of the Aerospace Corporation. SEPAC has also supported members in attending a national Congressional Visit Day in Washington D.C.

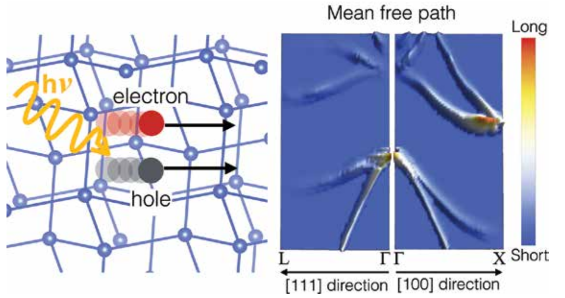
To learn more, visit *sepac.caltech.edu*.

Caltech graduate students and SEPAC officers Katherine (Kat) Saad and Thomas Catanach attend Congressional Visit Day on March 12, 2014.

New Faculty

Marco Bernardi

Assistant Professor of Applied Physics and Materials Science

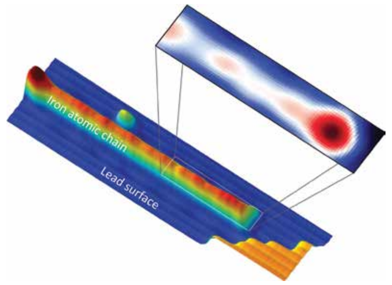


This illustration depicts dynamics of excited electrons during the first picosecond (millionth of a millionth of a second) after sunlight is absorbed in a silicon solar cell. Shown on the right is the average distance excited electrons travel before losing energy to heat. This distance, called mean free path, is calculated for electrons with a range of energies and moving in different crystallographic directions.

Marco Bernardi develops and applies *ab initio* quantum mechanical calculations to study the dynamics of electrons and excited states in materials. His research combines theory and cutting-edge computational tools based on density functional theory and related excited-state methods. Employing massively parallel computational algorithms and using the structure of the material as the only input, his new developments and techniques are enabling understanding of energy in materials with Angstrom space and femtosecond time resolutions. Applications of his research include novel materials and technologies for energy conversion, as well as optoelectronics and ultrafast science. Marco Bernardi holds a BS in materials science from the University of Rome in Italy. He obtained his PhD in materials science from the Massachusetts Institute of Technology in 2013. His PhD work combined theory and computation to study novel materials and physical processes in solar energy conversion. He was then a postdoctoral scholar in the Physics Department of UC Berkeley from 2013 to 2015, where his work focused on calculations of ultrafast dynamics of excited electrons in materials. He has received a number of awards, including the Endeavour Research Fellowship from the Australian government (2007) and the Intel PhD Fellowship (2012). His research has been featured in many online news articles and magazines, including *Wired*, *Scientific American*, and MIT's *Technology Review*.

Stevan Nadj-Perge

Assistant Professor of Applied Physics and Materials Science



This image shows a self-assembled chain of iron (Fe) atoms on the surface of lead (Pb), taken using a scanning tunneling microscope (dimensions are 15 nm x 4 nm). At low temperatures, lead becomes a superconductor with a finite superconducting energy gap. Due to its magnetic properties, iron atoms create electronic states inside of this gap. The resulting electronic structure of the chain at zero energy is shown in the inset. Increased local density of states localized at the chain end (marked in red) suggests the existence of topological excitations, called Majorana bound states, in this system. Measurements were performed by Professor Ali Yazdani's group at Princeton University.

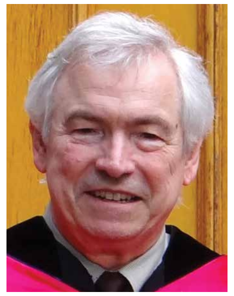
Stevan Nadj-Perge is interested in the development of mesoscopic devices for applications in quantum information processing. Such devices also provide a playground for exploring exotic electronic states at (sub-)nanometer length scales. For his research, he is using scanning tunneling microscopy and electrical transport measurement techniques at cryogenic temperatures. Nadj-Perge received an MSc in theoretical physics from the University of Belgrade in 2006. He then moved to Delft University of Technology for a PhD in applied physics. During his graduate studies, he developed electrically controlled spin-orbit quantum bits based on semiconductor nanowire quantum dots. After obtaining his PhD in 2010, he became interested in topological states of matter, and in 2011 he was awarded the Marie Curie Fellowship to continue his scientific career. He worked as a postdoctoral researcher at Princeton University and Delft University of Technology. At Princeton he used scanning tunneling microscopy to investigate topological properties of engineered material systems and to pursue novel ways to create Majorana bound states, potential building blocks for a topological quantum computer. Currently in Delft, he is leading a research team that studies electrically tunable two-dimensional topological insulators and exotic states in superconductor-semiconductor junctions. He will join the EAS faculty in January 2016.

Moore Scholar

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.

James R. Rice

Mallinckrodt Professor of Engineering Sciences and Geophysics, Harvard University



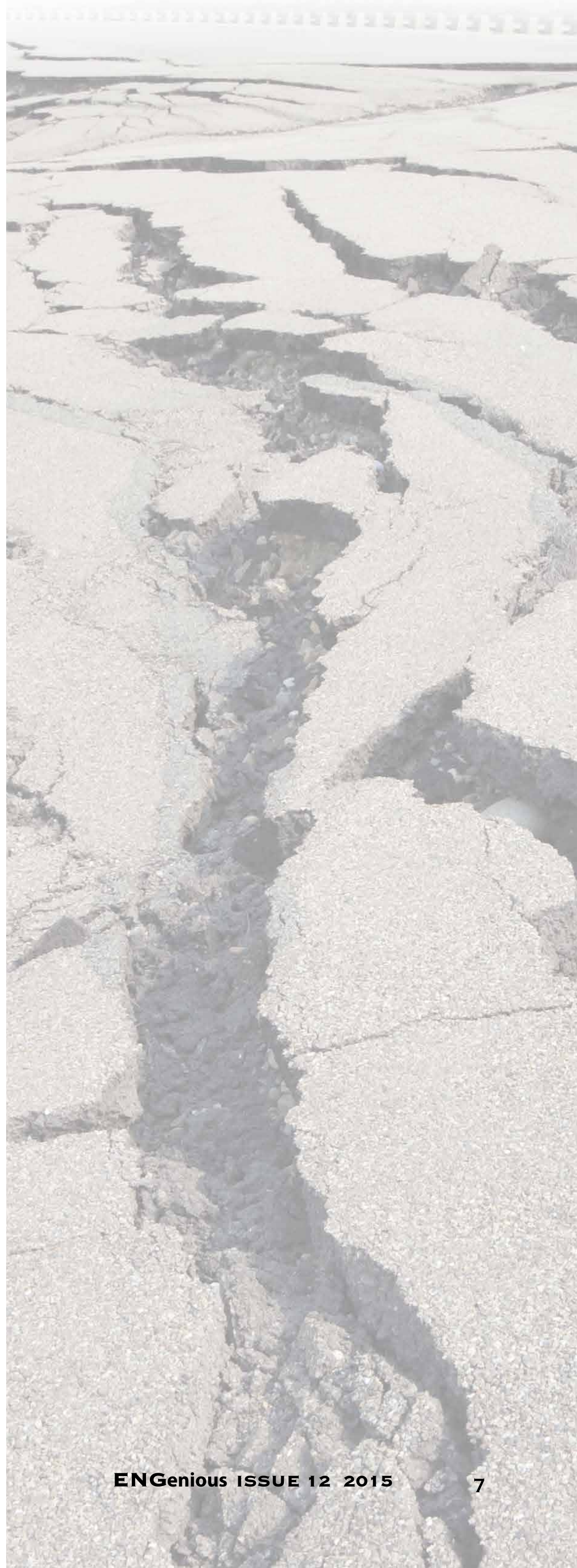
James R. Rice is jointly appointed in Harvard's School of Engineering and Applied Science and in its Department of Earth and Planetary Sciences. From 1965 to 1981 he was a faculty member in the Division of Engineering at Brown, and his education prior to that was at Lehigh, where he received an ScB in engineering mechanics and an ScM and PhD in applied mechanics.

His teaching has included solid and fluid mechanics, thermodynamics, fracture, computational mechanics, hydrology, geomechanics, earthquake processes, and applied math topics such as differential equations and complex function theory.

Rice's earlier work addressed cracking and plastic or creep deformation in engineering metals and ceramics. His more recent research is directed toward earth and environmental problems relating to such areas as friction and rupture in earthquake and landslide processes, tsunami propagation, glacier and ice sheet dynamics, and general hydrologic phenomena involving fluid interactions in deformation, flow, and failure of earth materials. His path-invariant *J*-integral methodology, originally developed with cracking of ductile metals in mind, was quickly extended to help model transitions to unstable slippage in landslides and tectonic earthquakes and has found recent applications in his ice-sheet mechanics studies of transitions from slipping to locked basal regions.

His work has been recognized through numerous awards, including the Timoshenko and Nadai Medals of the American Society of Mechanical Engineers, the von Karman and Biot Medals of the American Society of Civil Engineers, the Reid Medal of the Seismological Society of America, and the Bucher Medal of the American Geophysical Union. He has been elected to the National Academy of Engineering and the National Academy of Sciences and to foreign membership in the British Royal Society and the French Académie des Sciences, and he has received honorary doctorates from several universities.

Rice is scheduled to receive the 2015 ASME Medal (in November at the ASME 2015 Mechanical Engineering Congress & Exposition, Houston) "for seminal contributions in the field of applied mechanics, particularly the *J*-integral method in elastic-plastic fracture mechanics that has been broadly applied in mechanical engineering and related disciplines," and in early December he will receive the Sigma Xi Monie A. Ferst Award at Georgia Tech, "to recognize significant contributions to scientific research by an educator."



The Space Solar Power Initiative

Left to right: Sergio Pellegrino, Harry Atwater, and Ali Hajimiri

Three Engineering and Applied Science professors have joined forces to work with Northrop Grumman Corporation on the largest sponsored research project from industry that Caltech has undertaken in recent history. The project is called the Space Solar Power Initiative (SSPI), and the co-investigators are applied physicist and materials scientist Harry Atwater, electrical engineer Ali Hajimiri, and aeronautics and civil engineer Sergio Pellegrino.

Soon after the official announcement by Caltech and Northrop Grumman, the professors sat with *ENGenious* to discuss the idea, their plan for moving forward, and the implications of their success.

SSPI is a strikingly ambitious and challenging plan to send millions of clean kilowatts to an energy-hungry planet imperiled by climate change.

The goal: the creation and launch into orbit of thousands of identical space vehicles to form a constellation that maintains a precise shape. In the airless weightlessness of space, each vehicle will transform itself into an element of a modular power-generating space station with the square mileage of a city park, each module unfolding into a structure with the thinness of paper, made up of a network of billions of greeting-card–size tiles.

Control systems on board the station will maneuver these giant tile sheets to keep one side continually facing an unsetting sun. The sunlit-side surface will be a layer of material nanostructured to capture the energy of the illuminating sunlight. As this captured energy passes through the tiles, another structured layer will continuously convert it into radio-frequency power, which in turn will be beamed to Earth using focusing mechanisms similar to those now used in phased-array radars, which will send the radio-wave power earthward, in real time, to receiver ground stations located at specific destinations on our planet.

The ground stations will be receivers that can absorb the radio-frequency power and convert it into electrical energy. Some of these receptors will feed into existing electric utility grids. Others may be isolated micropower networks at remote off-grid locations or even individual farms or factories, all receiving a continuous infusion of power from the sky, 24 hours a day.

A tiny fraction of the solar energy captured will be converted on board to electrical energy to power the data-processing and communication modules that maintain and repair the station's structure and respond to signals from Earth.

Each of the three leaders of the Caltech team is tackling a different part of this formidable system. First, one surface of each tile in the immense array must be able to capture solar energy efficiently. The research group led by Professor Atwater will design and prototype ultralight photovoltaic tiles, taking advantage of the reduced structural demands of zero-gravity conditions.

The solar energy captured by these tiles must then be converted into radio-frequency (RF) power that can be efficiently transmitted through clouds and atmosphere to Earth, even on cloudy days. Professor Hajimiri's research team will create the integrated system that will convert the direct current (DC) solar power to RF power and send the RF power from the phased array, which can then route RF beams to a single or to multiple receiving ground stations.

Finally, Professor Pellegrino's research group will design and prototype the key components needed for the architecture of a hundred meter-scale, self-folding, origami-like, flexible, ultralight structures that can adaptively change shape and orientation in real time.

The starting point and basic conceptual element for the project is the "tile," a 10 x 10-centimeter solar-power converter and RF transmitting antenna that has already been created in mockup form by the SSPI team.

A functional prototype tile is several years away. But because the system design is modular, once a prototype tile is realized, the scale up to systems consisting of thousands or millions of tiles does not add significantly to the system complexity. The modular design and realization of scalable systems are aspects of the project that deeply engage all three leads, who believe this approach can be a model for future space engineering enterprises. The three are attacking the technical issues of tile and system design in a sequenced manner tied to success milestones—in which a series of significant but achievable steps add up to the capability of realizing a transformative outcome—that has proved to be a successful approach for large-scale engineering projects. Hajimiri likens the process, and its eventual results, to "the power of an army of mice over a big elephant. The ability of a large number of smaller identical units working in tandem, working in synchronization, to create more than the sum of the parts."

The project grew out of a working group on future space technologies for renewable energy, established by former Caltech President Jean-Lou Chameau. Ares J. Rosakis, then Chair of the Division of Engineering and Applied Science, saw the potential opportunity. "Ares said, 'You might want to begin a dialogue on this subject and see what can be done,'" Atwater recalls. From this initial dialogue, insights and ideas arose that finally culminated in the establishment of the $17.5 million project.

"The Space Solar Power Initiative brings together electrical engineers, applied physicists, and aerospace engineers in the type of profound interdisciplinary collaboration that is seamlessly enhanced at a small place like Caltech," said Rosakis in his announcement of the project in April.

Hajimiri notes that the idea of beaming solar power to Earth from space goes back at least as far as a 1941 short story by Isaac Asimov called "Reason," in which a manned space vehicle with this mission is the scene of an exploration of the author's famous Three Laws of Robotics. (The unmanned SSPI station, however, will be far different from Asimov's, which carried a human crew.)

Space is a logical place for solar power, the team maintains. Solar power, Atwater says, has long been seen as a hopeful source of cheap and clean energy, but on Earth it has clear limits. "Solar arrays, no matter how efficient, only generate power when the sun is illuminating them," explains Atwater. "So if solar power is going to be the principal so-called 'dispatchable' baseload source of power that replaces today's fossil-fuel–powered electric-generating stations, inherently you have to have the generating source be available all the time. This is not possible for ground-based solar energy without some complementary form of electrical energy storage, which adds significantly to the cost of solar electricity generated on Earth."

But, he adds, space provides a solution: "The great thing about space is that [orbits exist where] there's no nighttime. And so we have the prospect of making dispatchable power, power that flows continuously and that can be instantly sent to where it is needed."

The potential benefits are enormous, Atwater says. "About a quarter of humanity has no electric power whatsoever. And so this is an enabling technology that could leapfrog the electric-power transmission grid on Earth, and have the same effect that the cellular phone system had on communications," giving access to phone use in places without existing copper wire–based landline phone infrastructure.

And the benefits extend beyond Earth. Large-scale power for development in space is another looming need, notes Atwater: "One of the limits on the ability to further develop technologies in space is providing sufficient power to get around in space. And solar-driven electric propulsion

using ion thrusters could dramatically lower the cost of going, say, from low Earth orbit to geostationary orbit. That opens up a whole new pathway for large-scale development in space that wouldn't otherwise be possible."

The architecture of the overall structure is another challenge, notes Hajimiri, and an exciting one. "For the space power station to operate as a single unit, and send the power to a localized area, you need to form a highly synchronized array," he says. "And the modular tile architecture actually makes this easier because of the same electronic integration that makes the tile and tile assemblages lightweight. Instead of having a large number of different components, you have one very small component that captures a lot of functionalities. And that also couples electromagnetically to the parts of the structure which are the electromagnetic radiating structures, the antennas."

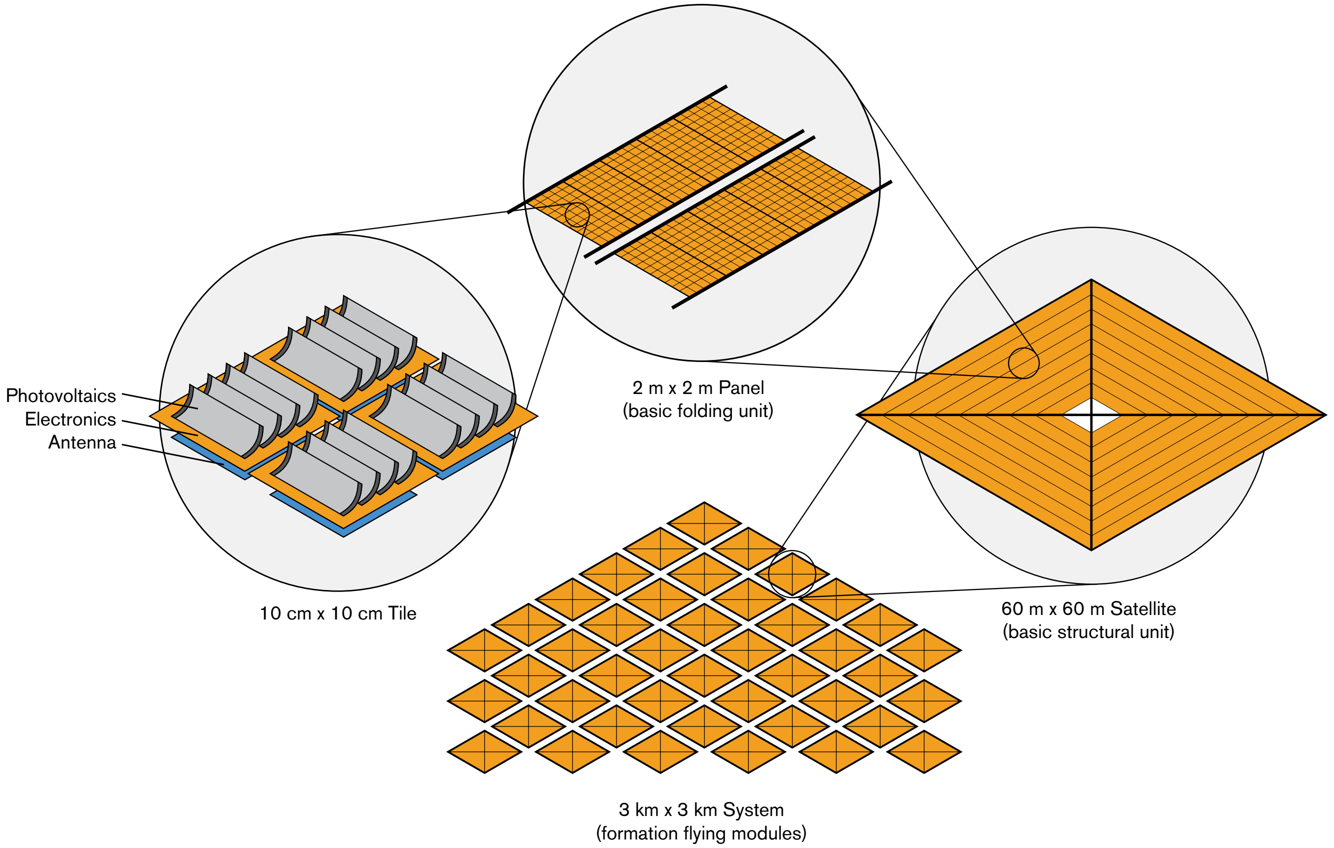
He continues: "The beauty of it is that it's a combination of a top-down and bottom-up approach. Top-down, you are looking at the application and deciding how you want to implement it. Bottom-up, you have these technologies and capabilities. So how will you apply them? The hammer looks for a nail. We have found a way we can use the collective thinking power of all the groups to come up with this idea and this instrumentation."

This top-down bottom-up reinforcement and self-correction mechanism also pervades work going on in Atwater's lab. "One of the things that's happening in my world of optical nanophotonics is the wholesale importation of scientific concepts from the [well-established radar/radio] and millimeter-wave array and antenna design field into the optical and infrared-optical materials and meta-materials design," he says, pushing insight and technologies from one set of wavelengths to another. "Therefore some of the lessons that we've learned about making nanophotonic structures out of ultralight materials and then using radio-frequency engineering concepts at optical frequencies are going to be a very exciting area in the future."

Sergio Pellegrino and Ali Hajimiri meet with SSPI students and postdoctoral scholars.

The future possibilities of this collaborative research effort also inspire Pellegrino. "I've actually never tried to do anything on this scale," he says. "I've collaborated with people who directed me into a little piece of a technology. But this time we started with a really big objective but little detail, and so a plan evolved in very broad outline form."

For Pellegrino, this provided an opportunity. "On the structure side, there is a consistent line that I've been following since the day I finished my PhD. I had seen many structures that, although they looked beautiful, were very complicated to build. Therefore over the years, I've been trying to conceive structures that are conceptually much more sophisticated and actually look extremely simple. And are even simpler to build." This continues to be his work path. "For me, as a structural engineer, the theme is still that of creating extremely simple structures."



This modular-tile architecture schematic of a 3 x 3 km space power system shows details of a single 60 x 60 m satellite, consisting of 2 x 2 m parallel strips [panel] formed by identical 10 x 10 cm tiles.

In the case of SSPI, says Pellegrino, simplicity helped solve a key problem. "Weight considerations took a more emphatic turn in the planning," he explains. Initially, "we identified costs as predominantly the launch cost and did not start arguing over potential new technology that might lower the launch costs. We said, 'Maybe the launch costs will come down. But let's assume that none of that is going to happen. Let's just try to make the structure superlight.'"

Fortuitously, the discussions about the SSPI project, notes Atwater, came "at a time when my group was beginning to have success removing flexible, high-efficiency solar cells from their rigid, heavy supporting substrates, which seemed to be a natural enabling technology for space solar power."

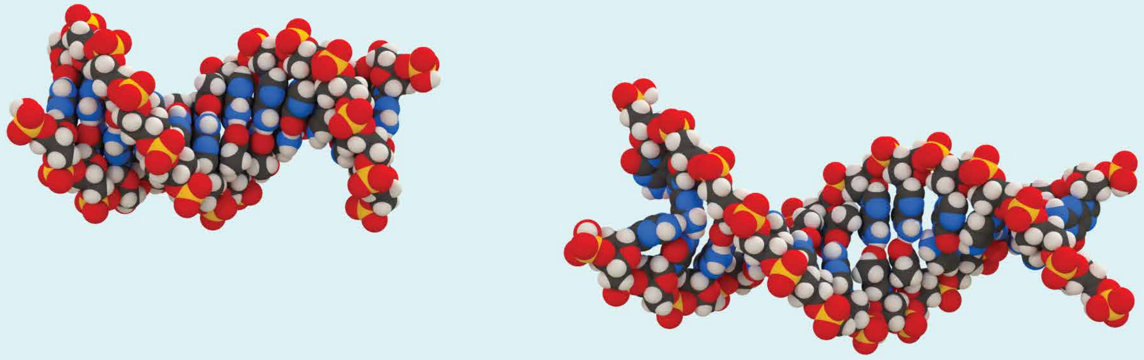
All three faculty members and their research teams are enthusiastically working toward building a prototype—at first to test on Earth, and eventually in space. "It's a wonderful project," Pellegrino exclaims, "in terms of all the things we get and need to do!" Hajimiri says, "It is just the right level of difficulty for the state of the art. It is difficult, but it's not impossible. And that especially pushes the boundary and the limits of engineering and science." Atwater adds a venerable bit of engineering wisdom: "The difficult we have in hand; the impossible takes a little longer."

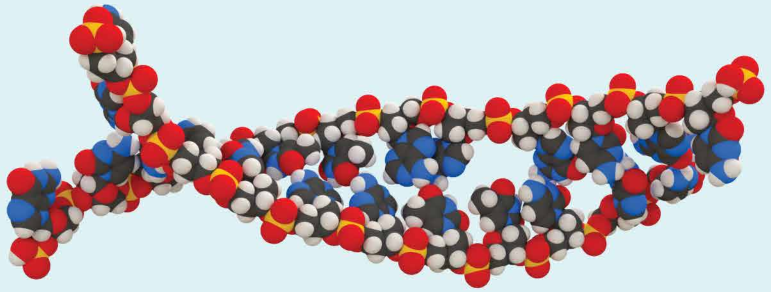
Furthermore, the association with Northrop Grumman is natural, and a key ingredient, Atwater says. "We're interested in making real things, things that can be manufactured at scale. To do that we need partnerships with people who could actually do the manufacturing." Hajimiri adds, "Their experience keeps us grounded—figuratively, not literally."

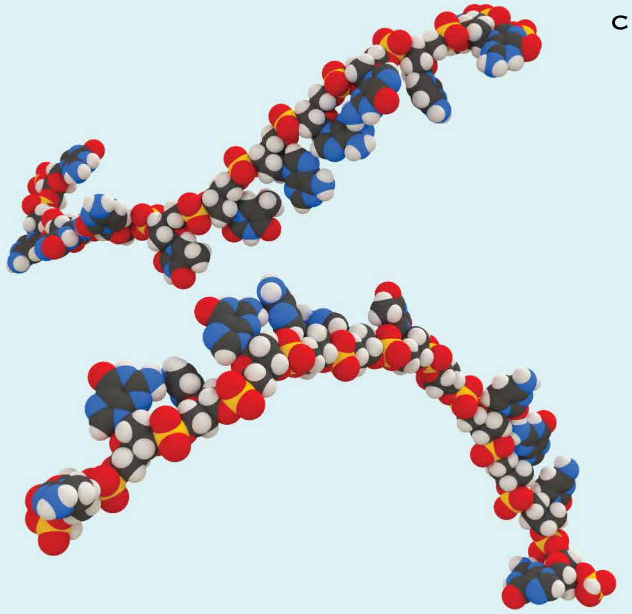
Harry Atwater is Howard Hughes Professor of Applied Physics and Materials Science and Director of the Joint Center for Artificial Photosynthesis. Ali Hajimiri is Thomas G. Myers Professor of Electrical Engineering and Executive Officer for Electrical Engineering as well as Director, Information Science and Technology. Sergio Pellegrino is Joyce and Kent Kresa Professor of Aeronautics and Professor of Civil Engineering and Jet Propulsion Laboratory Senior Research Scientist.

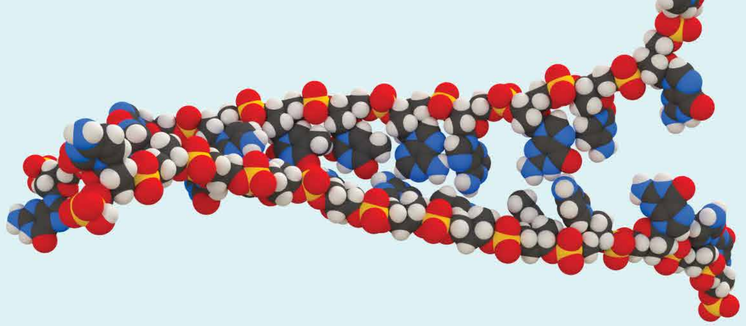
From Data to Information to Action

Computing + Mathematical Sciences Faculty









With an ever-increasing need to understand complex behaviors at the molecular level comes a high demand for computational methods. Professor Desbrun's group has proposed an efficient and scalable numerical method to run molecular dynamics simulations about 30 times faster than current algorithms. The new fine-grained parallelizable numerical scheme can handle a variety of simulations, from DNA strand unbinding (depicted here) and protein folding to nanotube resonators.

For millennia, engineers and applied scientists have brought mathematical tools to bear on problems impacting people, their lives, and their possessions. The Computing + Mathematical Sciences (CMS) faculty at Caltech are working in this tradition, creating tools and conducting research to move from data and problems to information and action. Their passion and research are rooted in the fundamentals and rigor of mathematics, with the ultimate goal of helping society make decisions and take action. Caltech students are heavily drawn to this approach, and to serve them better, the CMS faculty have created a new CMS PhD program.

ENGenious met with a subset of the CMS faculty to learn more about their interests and approach. The conversation explored the relationship between their research and energy, music, economics, special effects in movies, synthetic biology, and, of course, the nature of decision making.

"I provide tools for engineers," said Mathieu Desbrun, John W. and Herberta M. Miles Professor of Computing and Mathematical Sciences and the first Executive Officer of the CMS department. "So I'm no longer a bona fide engineer in the sense that I don't do big computations of tsunamis, but I do develop discretizations and computational methods so that other people can, including companies such as Schlumberger or Pixar."

Desbrun started in computer graphics before moving to the more theoretical field of applied geometry, doing so after an encounter with the late Caltech applied mathematician Jerrold Marsden, Carl F. Braun Professor of Engineering and Control and Dynamical Systems, who pointed out that some of his computer-graphics work on geometric discretization could be described by exterior calculus. "I had no idea what it was," says Desbrun. "But once he said this, I started scratching a little bit of the surface to see what he meant. And he was right!" It was a career changer: "I moved from graphics to becoming a tool designer for engineers, both in terms of computational methods and geometry processing."

The influence of this approach can be seen in the Information Science and Technology (IST) initiative, which was born out of the observation that information science on one side and science and engineering on the

> *"In the '60s when [computer graphics] started, there was no equipment, not even a monitor able to plot images . . . We have made a huge amount of progress; today's special effects in movies and video games are a visual testament to that. The impact on medical applications and parallel computing architecture is less visible but just as significant."*
>
> Mathieu Desbrun, *John W. and Herberta M. Miles Professor of Computing and Mathematical Sciences*

Mathieu Desbrun

other can lead to new synergies at their interface that give rise to whole new sets of insights in a variety of areas, including medicine, science, and society. "For example, quantum systems as systems which perform computation," says Peter Schröder, Shaler Arthur Hanisch Professor of Computer Science and Applied and Computational Mathematics. "What new insights for computation as well as physics does this allow? Or the insides of a cell as a giant network—like the Internet, with messages being sent everywhere. One can then bring in information theory (measures of information content and transmission bandwidth) to help understand regulatory networks in a cell."

Desbrun continues: "In the '60s when [computer graphics] started, there was no equipment, not even a monitor able to plot images. It was super complicated to do, but now graphics have been so successful that everybody has a graphics card with power that, back in the '60s, would have required a whole city full of computers. We have made a huge amount of progress; today's special effects in movies and video games are a visual testament to that. The impact on medical applications and parallel computing architecture is less visible but just as significant."

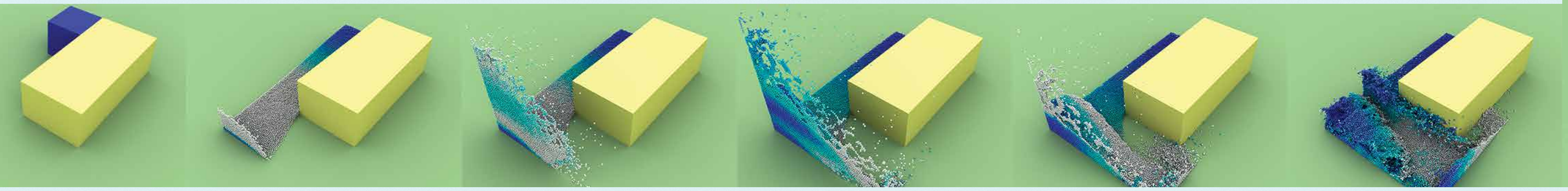
One of Desbrun's applied mathematics colleagues is Yizhao Thomas Hou, Charles Lee Powell Professor of Applied and Computational Mathematics, who is an expert in the very traditional research task of pulling patterns out of masses of incoming data, particularly the behavior of fluids, and has learned to do this using extremely fine-scale mathematical modeling.

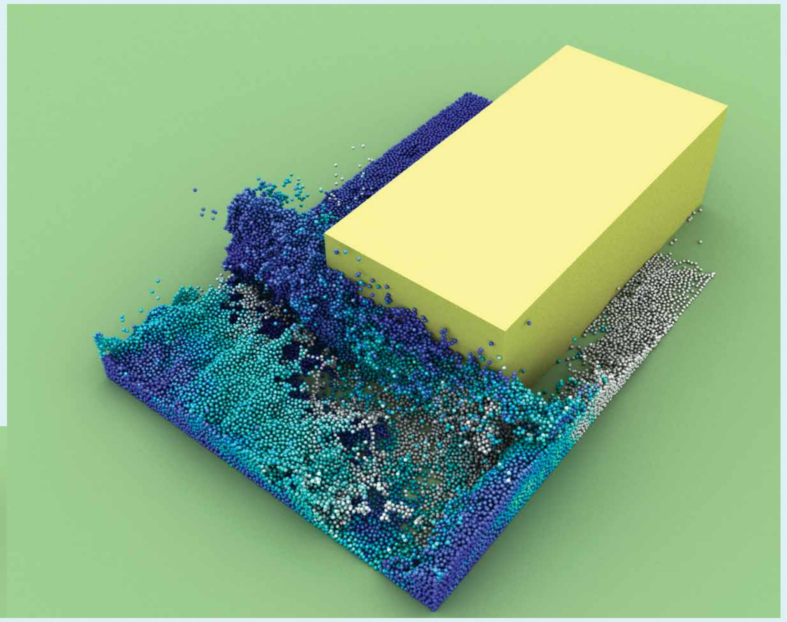
His research has expanded the scope of classic works like the earlier Euler and subsequent Navier-Stokes equations, which govern the motion of inviscid and viscous flows and are used in efforts to predict phenomena ranging from ocean currents to blood flow to weather. But the equations have run up against limits in attempts to expand them to wider parameters and smaller scales. A very well-known Millennium Problem is whether the solution of the Navier-Stokes equations will remain smooth for all time if one starts with sufficiently smooth initial data, or whether it will break down in finite time. A $1 million prize awaits the researcher who can answer this question, a prize Hou is seeking. While conducting this search, Hou and his colleagues recently discovered a scenario that leads to a previously unsuspected "singularity," an irregular point interrupting or redirecting flow, which provides a promising scenario for further investigation of the potential singularity.

Some of Hou's early work in the area of fluid behavior modeling has had applications in the energy sector, where oil company engineers use it to simulate two-phase flow to enhance

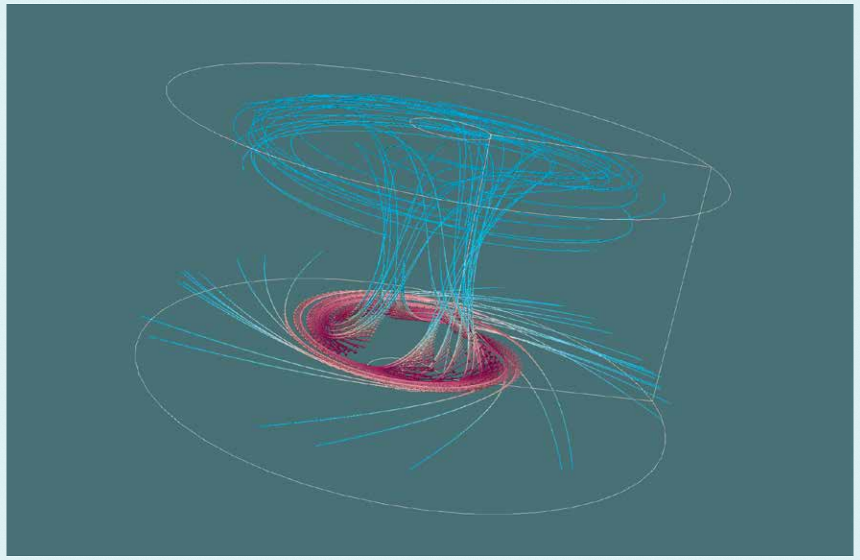
Yizhao Thomas Hou

> "*You could use it on your cell phone to measure your pulse. It solves the optimization problem on the spot and sends the data to your doctor. The doctor can then determine if you really have a problem and are at risk or not.*"
>
> Yizhao Thomas Hou, *Charles Lee Powell Professor of Applied and Computational Mathematics*

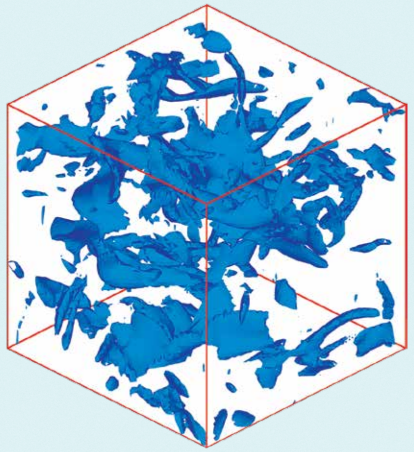




Fluid motion is a visually rich and complex phenomenon that remains a challenge to reproduce numerically. While Lagrangian methods excel at generating fluid motion with few degrees of freedom, they often suffer from numerical artifacts that severely impact the liveliness of the flow. The Applied Geometry Lab recently proposed a radically different Lagrangian method using a particle-based approach to simulate incompressible fluid. Particles are considered as non-overlapping fluid parcels that partition the space occupied by the fluid through a time-evolving power diagram. By leveraging computational tools for power diagrams, the researchers formulated a time integrator for the "power" particles that precisely controls particle density and pressure forces, without kernel estimates or significant artificial viscosity. The versatility of the Applied Geometry Lab's solver (colors of particles indicate their velocity) is demonstrated in the "wall-confined dam break" sequence, simulated with 65,000 particles. It shows water first splashing against the opposite wall before ricocheting onto the inner wall (yellow box), then splashing at the end of the domain and finally settling.



Above: The velocity field and stream function plot of a tornado-like flow for the three-dimensional axisymmetric Navier-Stokes equations.



Left: Iso-surface plot of vorticity in a three-dimensional incompressible turbulent flow.

oil recovery. Hou has also found a new way to customize general analytic methods to specific formations. In addition, his theoretical efforts have found application in an area seemingly remote from oil recovery: in blood flow, specifically a mobile-device–based application that can sense, read, and analyze live data. “You could use it on your cell phone to measure your pulse,” he says. “It solves the optimization problem on the spot and sends the data to your doctor. The doctor can then determine if you really have a problem and are at risk or not.”

The dynamics of large structures, such as bridges, can also be diagnosed using Hou’s work. “In the past, if we wanted to measure the forces on the bridge on a windy day as a truck was passing, it would have required a lot of time and expense,” he explains. “But today, remote sensors on the bridge detect the frequency of vibrations.” Theoretically, analysis of these data could be used to determine the strength of the forces. But the analysis requires sophisticated new mathematics, and after years of collaboration, Hou’s team is closing in on the solution.

Professor Schröder is another creator of mathematical tools. “I don’t build cars,” he says. “I build engines. I build the motor underneath the hood that makes the machine purr. So what that means, practically speaking, is that I think about algorithms and numerical techniques that can take the physical laws that describe, for example, how a piece of cloth dangles in the wind, and then turn those physical laws into efficient computations so that the simulation can be used to move the shirt of a character in a Pixar movie.”

The standard is high, he says. “The eye, because of our species’s years of genetic optimization, is extremely good at being able to see whether something is real or not. To use an example from real life, you might see somebody walking down the street at a great distance where your eye can’t actually tell their face, but you recognize the person by their walk. This is an example of how incredibly in tune we are to qualitative things. So in computer graphics for entertainment purposes, the measure of fidelity is to capture this in numerical ways. This is not all we do, but this is an important part of what we do. And here, as in other places, we have learned that you have to get the physics right.”

Schröder loves the complications involved not just in getting it right but in doing so efficiently and elegantly. The ideals are algorithms that help this adaptive process: “algorithms that very quickly give us a rough idea. Then the same algorithm should be able to give us more and more precise answers as we give it more time.”

Schröder’s road to Caltech was unusual. “I left high school in Germany to travel around the world, and then to study psychology,” he explains. After years of exploration, he trained as a shiatsu specialist and worked with clients in a private practice in Manhattan. Then a friend showed him the 1982 American science fiction film *Tron*, which was transformative. It led him to take a course on mathematics for computer graphics at a graphics conference in 1984. One of the lecturers in that course was a Caltech professor of computer science, Alan Barr. Little did Schröder know that he would be Professor Barr’s colleague one day. Schröder’s newly discovered passion for mathematics subsequently led him to the MIT Media Lab, a Princeton PhD, and then his faculty position in the CMS department.

He loves the CMS culture, which he says is about “bridge building, and not just bringing a technique from this field to that field but really having a new synergy occurring where both sides go, ‘Wow, we can do all kinds of new things we didn’t know how to do before.’” The CMS students, too, impress Schröder: “They have something burning inside of them like a fire that cannot be quenched.”

Natural phenomena like cacti (left) exhibit characteristic branching patterns in an effort to maintain evenly spaced features. Schröder’s algorithm allows one to quickly and automatically synthesize similar patterns that seamlessly cover arbitrary surfaces (right).

Peter Schröder

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Peter Schröder, *Shaler Arthur Hanisch Professor of Computer Science and Applied and Computational Mathematics; EAS Division Deputy Chair*

> *“As my field of optimization moves forward, it aids decision making, turning into a standard, mature, and reliable tool that can be used easily and seamlessly to quickly obtain actionable and interpretable information from data.”*
>
> Venkat Chandrasekaran, *Assistant Professor of Computing and Mathematical Sciences and Electrical Engineering*

Venkat Chandrasekaran

The experience of Venkat Chandrasekaran, Assistant Professor of Computing and Mathematical Sciences and Electrical Engineering, is similar. “Much of the research that happens in CMS is grounded in the mathematical foundations, more so than at other computer science departments,” he says. “And that comes across in the way we interact with students and is successfully transferred to them.”

In his research, Chandrasekaran investigates the conceptual foundations of optimization, a branch of applied mathematics that focuses on designing the most efficient approach to accomplishing a task. This methodology is useful for engineering optimal machines and systems.

“People who work in my area have had impact in domains as varied as computational finance, medical imaging, aircraft design, and power flow in the smart grid,” he says. “Statistics is an application domain that serves as a major motivation for a lot of my work in optimization.”

CMS is an ideal place to carry out this work. “Within the Caltech community, it’s special in that it’s a very outward-looking department,” Chandrasekaran explains. “I don’t know of any other major research institution that has applied mathematicians and computer scientists and control and dynamical systems engineers sitting in the same internal department.”

And the CMS effort is gathering momentum, he notes: “To borrow from the mission statement from the CMS graduate program, we are trying to do research in the pipeline that takes us from data to information to action. This last leg, going from information to action, is something that I think is unique to us. As my field of optimization moves forward, it aids decision making, turning into a standard, mature, and reliable tool that can be used easily and seamlessly to quickly obtain actionable and interpretable information from data.”

Chris Umans

Chris Umans, Professor of Computer Science, works in closely adjoining areas using an approach he calls “understanding computation as a phenomenon.” He hopes to build up “a framework in which we can think about computation and do things computationally in a principled way that’s not hacking.”

This means getting down to roots. “I spend a lot of time thinking about fundamental algorithms for fundamental problems,” he says. “These are problems that people identify as fundamental because they’re at the core of a lot of different applications. If we can improve performance on these, by finding more sophisticated math, then we can solve those problems in either a faster or in a fundamentally different way, which can affect many applications that build out from there.”

Umans reflects on the importance of stepping back from the conventional approach and trying alternatives—not necessarily from computer science. “Computer science is a really young field, and mathematics has been around for thousands of years,” he says. “The thing that seems to keep happening is that the kinds of questions that we as computer scientists ask are close to the kinds of questions that mathematicians are interested in, but not quite. So we get inspiration from the way that they’ve dealt with things.”

The work of Leonard Schulman, Professor of Computer Science, has been inspired by—and amplifies in new directions—the work of Claude Shannon, who seven decades ago cre-

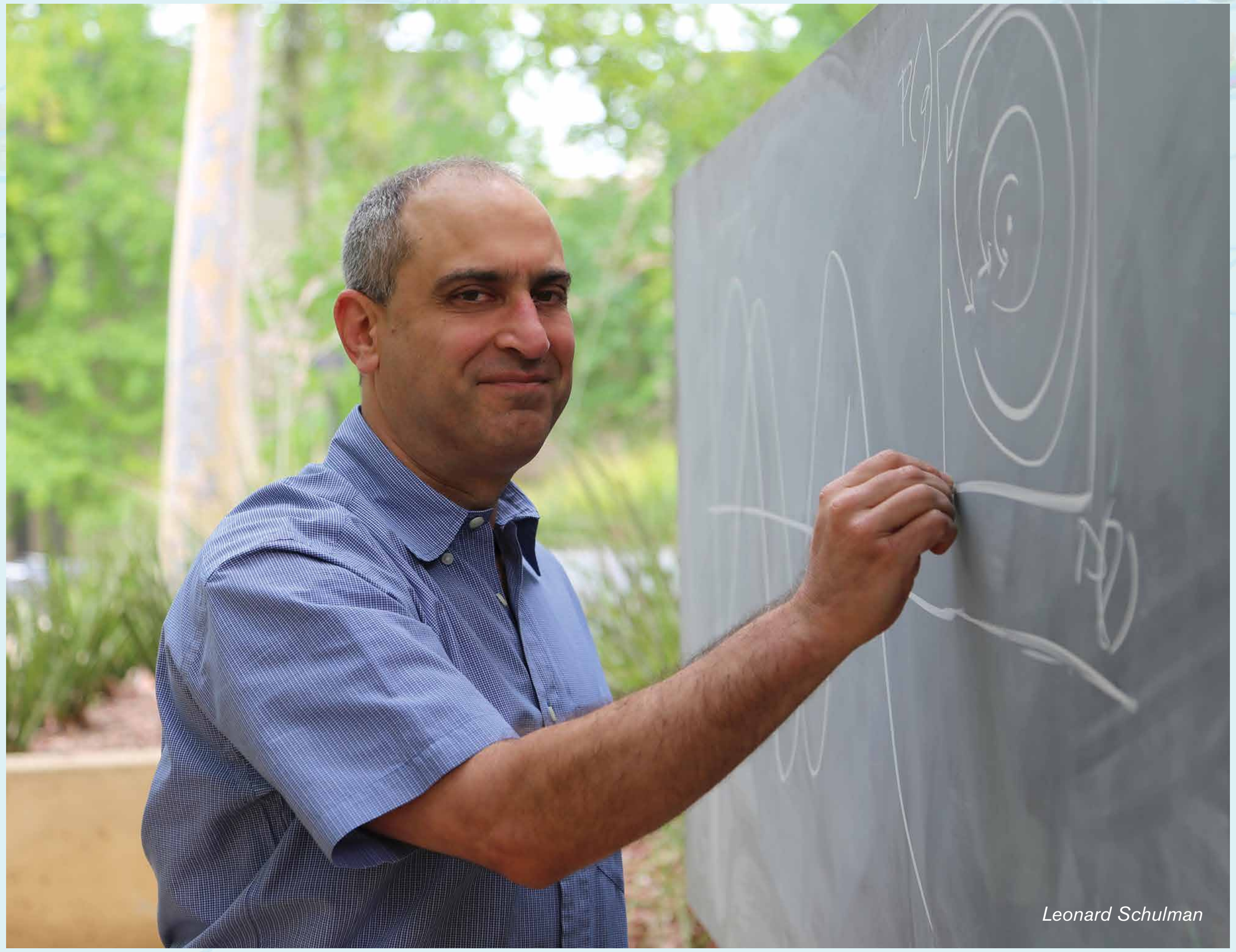
> *“I spend a lot of time thinking about fundamental algorithms for fundamental problems. These are problems that people identify as fundamental because they’re at the core of a lot of different applications.”*
>
> Chris Umans, *Professor of Computer Science*

ated the mathematical definition of information, including the possibility of error-free transmission despite any amount of noise. This is now a part of our everyday life. “Though no one using a cell phone really cares how the coding theory is done, it wouldn’t be there if it weren’t for coding theory,” says Schulman.

Schulman is dealing with “the next generation of this problem, when communications are highly interactive and at very high rates of interaction.” In these situations, he says, “with a huge amount of interaction happening and very short bursts of communication back and forth over a long period, orthodox Shannon error-coded communication can become unwieldy.”

The consequences of a glitch in such a dense mix can be large. Even in human conversations, he notes, “a small misinterpretation can derail into a huge miscommunication or misunderstanding between the people and/or groups involved. This can happen with non-human communications, as well, and can be even worse when we get to the world of arbitrary network protocol. But if we try to solve it the old-fashioned way, by just putting a large amount of redundancy and error correction into each individual message, it would slow it down a significant amount—essentially an unbounded amount, unless an algorithm is found to speed it up.”

Such communication conflicts, statistics, and algorithmic workarounds are basic parts of the Schulman research agenda. Running deeper is a motivation to maximize human communication: “There’s been a lot of work in the field of algorithms and machine learning on [such questions as]: How do we analyze data? How do we cluster it? How do we find structure in it? But when you actually look at how scientists, business people, and government officials really use data, it is to make a decision. Therefore, what we really want to answer are not the academic questions of the existence of correlations but the more crucial one of analyzing whether correlations are causal or accidental.”



Leonard Schulman

This is a very hard problem, but Schulman believes his group’s recent work on a novel analytic model to distinguish between the two is promising, with potentially extremely far-reaching impact. More specifically, he explains, “the ‘usual’ way we determine causality is by running controlled experiments, such as giving half the subjects treatment A, half treatment B, and observing how they fare. But often we can’t do that for a variety of reasons, including it being unethical or even impossible. So, like it or not, we have to extract inference about causality from purely observational data. In the most general framework, this is impossible, but with some extra conditions on the structure of the system, remarkably, it is sometimes possible—emphasis on ‘sometimes.’ Currently, the theory establishes this to be possible only under very restrictive conditions. My work is geared toward relaxing those assumptions. The ultimate goal is to be able to make scientifically rigorous statements about causal connections, based only on passive observational data. This could apply to many scenarios—in medicine, public health, educational policy, welfare policy, ecology, and the environment.”

Assistant Professor of Computing and Mathematical Sciences Thomas Vidick’s research aims to guide the problem-solving process at an earlier stage. He is working on mathematical methods to evaluate solutions to hard problems for which exact solutions are impossible to find—but approximate values are. “So it has to do with understanding what kind of problems are hard, and how hard,” he says. “Traditional complexity theory has been able to say that finding the exact best solution to a certain problem can be computationally extremely hard. But what if you’re happy with something that’s 99% as good as the optimum—how hard is that?”

Vidick is working at the boundary of computer science and quantum information theory, with particular attention to computational possibilities and limits. His aim is to create tools that ideally can tell an engineer that “if this is the kind of question you’re asking, then there’s just no possible way to get an answer.” He hopes his work would help guide researchers in determining in timely fashion that they can’t go down a road, and that they must change their direction.

Vidick’s work in cryptography considers the challenges of developing cryptosystems—the mechanisms used to transmit sensitive information, such as a credit card number, through public channels, including the Internet, that are based on the laws of quantum mechanics. Such cryptosystems can in theory be much more secure than classical cryptosystems. But quantum hackers have shown they are also much more prone to “side-channel attacks” that exploit vulnerabilities in the implementations. “My work is trying to develop cryptosystems that use quantum mechanics but do not need

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> Leonard Schulman, *Professor of Computer Science*

Thomas Vidick

> *“Introducing the weirdness of quantum mechanics . . . into the conceptual frameworks of complexity theory and cryptography produces insight . . . This is what makes the research challenging and exciting: you take a rich framework, you throw in a completely new ingredient, and you get beautiful chemistry!”*
>
> Thomas Vidick, *Assistant Professor of Computing and Mathematical Sciences*

to rely on the trustworthiness of the quantum devices used to implement the protocol,” Vidick explains. “So that even if the devices malfunction, or the attacker has some control over them, the users will be able to detect this and abort the protocol.”

This work fuels Vidick. “Introducing the weirdness of quantum mechanics, such as quantum entanglement, into the conceptual frameworks of complexity theory and cryptography produces insight into quantum mechanics, the global nature of entanglement, and properties such as the monogamy of quantum correlations,” he says. “This is what makes the research challenging and exciting: you take a rich framework, you throw in a completely new ingredient, and you get beautiful chemistry!”

Katrina Ligett, who holds a joint appointment in computer science and economics with interests that bring together the Division of the Humanities and Social Sciences and the Division of Engineering and Applied Science, is also interested in data security and privacy. One of her research goals is giving formal guarantees on what a computation cannot leak. This fans out through a huge range of potential societal impacts and foci related to a fundamental question: What data privacy environment do we want?

“What’s interesting about privacy is not so much what people or organizations are doing or not doing but rather the description of a data-leaky environment and strategies for dealing with it,” Ligett says. “What could and should organizations and people do? Answering this question opens doors for investigation.” She adds, “Key elements that need to be understood include the benefits of using this information, risks and costs of such use, the ways in which these

Katrina Ligett

> *“What’s interesting about privacy is not so much what people or organizations are doing or not doing but rather the description of a data-leaky environment and strategies for dealing with it . . . There are lots of questions to be asked in this space, and I think it’s a fun research place to play in.”*
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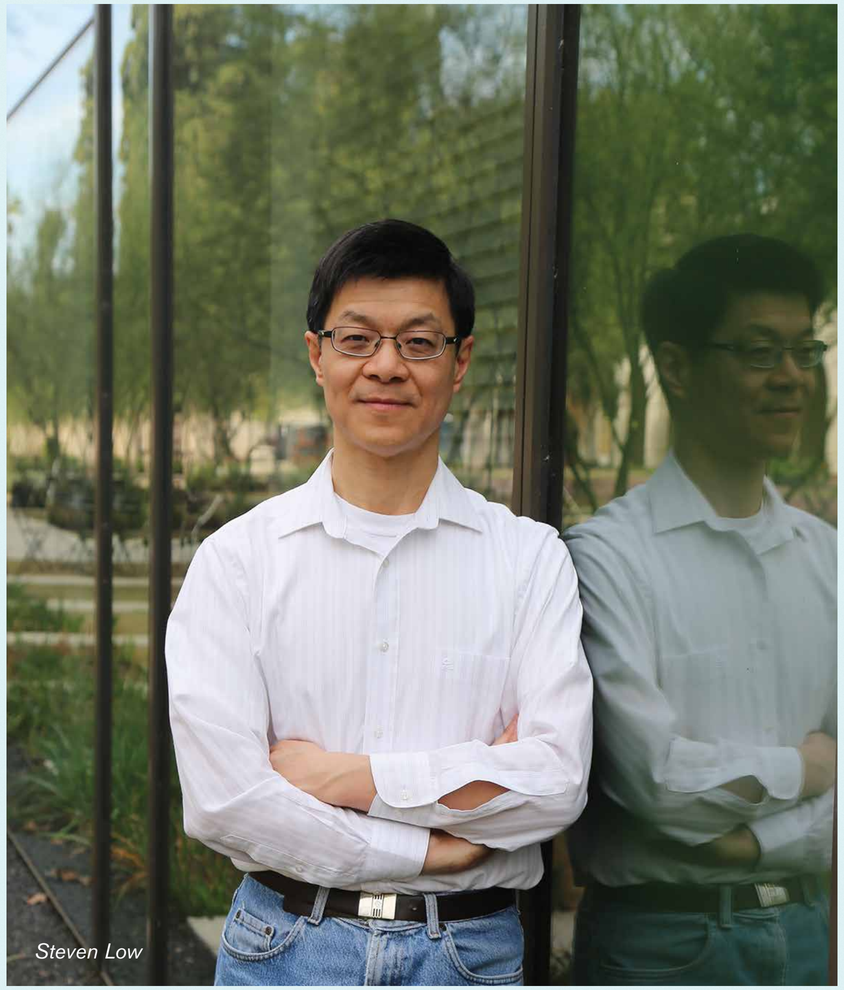
> Katrina Ligett, *Assistant Professor of Computer Science and Economics*



Steven Low

> *Our research . . . starts by assuming that there will be a lot of renewables and we are going to have a lot of active endpoints that are intelligent but yet doing their own things. Then we ask, 'What are the new fundamental challenges that will arise?' These challenges are not only in engineering but also in economics. How do we design markets to incentivize the right behavior?*
>
> Steven Low, *Professor of Computer Science and Electrical Engineering*

data are transacted on, bought, sold, computed on, and tracked."

She goes on to explain that "almost everyone has to make these risk-benefit calculations, in a legal and social environment. Society has to decide the rules governing them. So I'm interested in really starting afresh in how we think about all of these interactions that we have with personal information and trying to figure out if we can do it differently. There are lots of questions to be asked in this space, and I think it's a fun research place to play in."

The work of Steven Low, Professor of Computer Science and Electrical Engineering, is deeply involved with information and energy infrastructure, which he says have "completely changed the way we live and work since their overlapping inceptions about 130 years ago."

While information infrastructure led to the Internet in the past few decades, the power network has not undergone much of a transformation. "California Edison still has transformers which are many decades old and working fine," says Low. "But the power network is now undergoing a drastic change on the order of magnitude of the information revolution that produced billion-dollar players like Google and Facebook."

Low is studying how this new transformation will proceed, and his efforts include calculations to determine how to optimize the process. "By changing the characteristics of the power grid, we can control it," he says. "We can minimize the loss. We can route power to avoid congestion on the grid. We can better guarantee power quality at the extreme loads. Power electronics are very important pieces of the equipment that will allow us to change the power grid and avoid congestion in ways that were not possible before."

The new vision of the grid is made up of "a network of intelligent endpoints that allow us to control much more actively, to close loops much faster, and to improve the efficiency, robustness, reliability, and security of the entire system in a way that we cannot do today," Low explains. "Our research at Caltech on the smart grid starts by assuming that there will be a lot of renewables and we are going to have a lot of active endpoints that are intelligent but yet doing their own things. Then we ask, 'What are the new fundamental challenges that will arise? These challenges are not only in engineering but also in economics. How do we design markets to incentivize the right behavior?"

Richard Murray

It's a complicated undertaking. "To solve this huge energy problem, we not only need power system expertise but also control and dynamical systems, computer science, applied math, and economics," Low says.

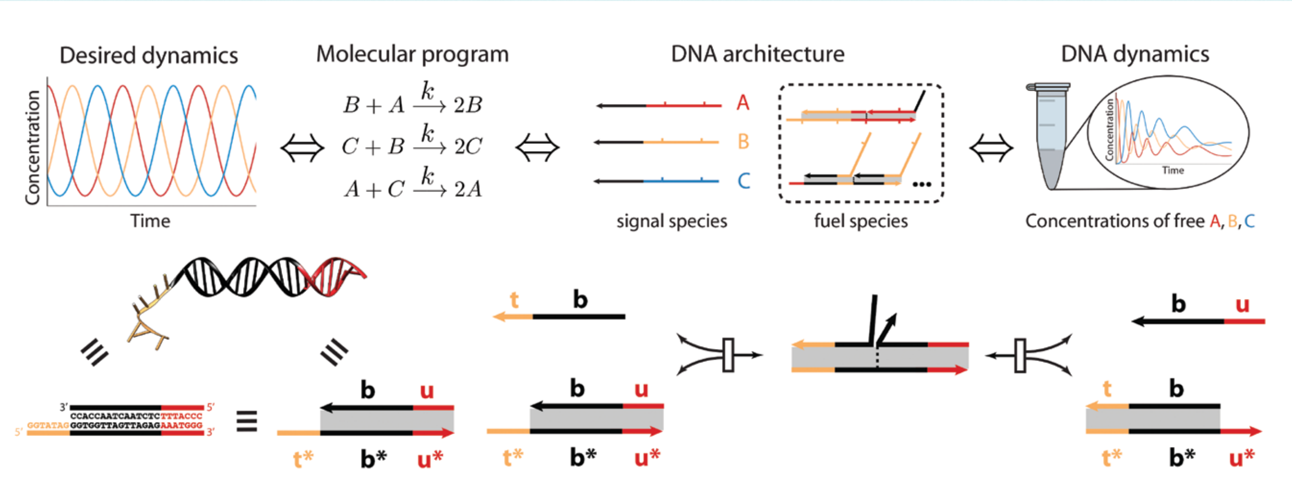
> *We don't know yet whether or not a decade or two from now, synthetic biology is something that we all take for granted and we go into our house and it's got a whole bunch of biological components that react to us being there and do smart things.*
>
> Richard Murray, *Thomas E. and Doris Everhart Professor of Control and Dynamical Systems and Bioengineering*

> *We've built a DNA system that oscillates. So it's like a little biochemical clock, but no enzymes are involved . . . It's a dynamical system, and computer scientists love systems that have programmable behaviors.*
>
> Erik Winfree, *Professor of Computer Science, Computation and Neural Systems, and Bioengineering*

“This is why CMS is the ideal place. We look at the underlying fundamental core, especially the mathematical aspects of those problems, and bring them together.”

Mathematical tools to regulate networks and systems are also one of the keys to the work of Richard Murray, Thomas E. and Doris Everhart Professor of Control and Dynamical Systems and Bioengineering. Murray's current focus is another growing field, biological systems—specifically biomolecular feedback systems.

Erik Winfree



This figure shows the framework for a molecular programming compiler based on strand displacement. In the first step, an abstract chemical reaction network is designed to obtain the desired chemical kinetics; in the second step, this molecular program is translated to a specification for DNA “signals” and DNA “fuels” that will carry out the desired reactions; and in the third step, specific DNA sequences are designed and synthesized and observed in the laboratory. Interactions between the DNA signals and fuels take place in the absence of enzyme or other biological components, making use of a mechanism known as toehold-mediated strand displacement, in which an incoming single-stranded DNA molecule can bind to a toehold (yellow and red) and displace one strand of a helix that contains an identical subsequence (black).

Application of biology network technology is still far from the explosive everyday application level of the data networks that concern Low. So discussing the societal impacts is difficult, says Murray, “because we're not there yet. I think what people would like to be able to do is build systems out of biological parts, DNA, RNA, proteins, in ways that perform useful functions. It can mean environmental remediation. It can mean just useful devices that process information and remember things and compute. We're at a very early stage. We don't know yet whether or not a decade or two from now, synthetic biology is something that we all take for granted and we go into our house and it's got a whole bunch of biological components that react to us being there and do smart things.”

But Murray is confident that if the fundamental research moves to global change, Caltech will be part of it. His progression to studying biological systems was evolutionary. “I started in mechanical engineering because I was interested in robotics, but my degrees are in electrical engineering, so from the beginning I was bringing disciplines together,” he says. “Then I began working with people in computer science and got interested in the role of feedback and control theory in biological systems. I wanted to explore the potential role of my field of control theory in biological, biochemical, and biomolecular applications—which led to what is now probably two-thirds of my group focusing on synthetic biology and the other third continuing to do things related to more traditional electromechanical systems and the software that sits on top of it.”

Murray maintains that Caltech offers an ideal environment for movement in new research directions. “I decided to research synthetic biology,” he says, and “that meant I needed a relatively large wet lab. But I didn't have to force Caltech to do something that it didn't want to do, but rather share what I was excited about and the specifics of what I needed to be successful. Then a way was found to make all of it work. This type of flexibility, involving helping the faculty move in new directions by providing seed funds, is one of the special things about Caltech and a key to our success.”

Erik Winfree, Professor of Computer Science, Computation and Neural Systems, and Bioengineering, is also studying information processing in biomolecular systems, a research destination he arrived at via an unexpected route. As a high-school student, Winfree loved mathematics but hated “wet science”—“I decided I would never do biology or chemistry,” he says. But now he, like Murray, has a bioengineering wet lab where he is adapting and programming molecules

Adam Wierman

> *Caltech as a whole is going to benefit from investing in developing an understanding of how to process large problems, and how to store and operate on large datasets. Despite our small size in CMS, almost everything at Caltech is touched in some part by computing and the CMS faculty.*
>
> Adam Wierman, *Professor of Computer Science; Executive Officer for Computing and Mathematical Sciences*

to carry and transmit information and use it to control chemical system behavior. The work centers on the natural information carriers DNA and RNA, but the scope is much wider.

In fact, he says, "we now have a general-purpose way of building molecular machines that implement arbitrary chemical reaction networks. So although we haven't done it for every possible chemical reaction network, we have a very detailed engineering argument that if you give us a set of reactions that does something interesting—$A + B$ goes to $X + Y$, Z goes to $P + Q + R$, etc.—we can hit 'go' and it will get compiled down into DNA molecules. Although we are now studying dynamical behavior, the original goal was to establish a connection between crystallization and self-assembly on the one side and computer science and algorithms on the other side." Hitting "go" is different for biochemical and electronic computing; translating electronic circuits into chemical ones will not be achieved immediately. But Winfree is quick to note recent advances: "We've built a DNA system that oscillates. So it's like a little biochemical clock, but no enzymes are involved. No fancy chemistry. Just a basic machinery that releases DNA strands, changing who's partnering with who. It's a dynamical system, and computer scientists love systems that have programmable behaviors."

Researchers with a range of skills and specialties are working on getting to "go." "A lot of us are mathematicians, with a very strong emphasis on the theoretical, rigorous foundations of what we do," says Winfree. "There's a metaphor of the cathedral of science, where every scientist has the opportunity to put one brick on the cathedral. We want a strong building, and if we build with a bad brick that falls apart and cracks, well, that's not so good. Therefore, emphasizing the mathematical foundations is important for creating a really solid understanding that other people can build on."

Such rigor is also central to the research approach of CMS professor Adam Wierman, who is part of the Linde Institute of Economic and Management Sciences and the Resnick Sustainability Institute. His basic research thrust concerns the care, management, and security of networked systems, including those distributing data and power. The engineering issues involved in these areas relate directly to economic and social inputs and consequences, as the Linde Institute connection emphasizes. "There's this real interplay between engineering and economics. We try to do a lot of foundational theory with respect to that interaction across different disciplines," Wierman says.

One economic area central to his work is IT energy demands, which, according to Wierman, are huge and growing. The groundwork has changed. "Memory is no longer the bottleneck. It's very cheap. Data is the bottleneck," he explains. "And access to these terabytes of cheap information raises energy issues. If access to all contents of thousands of servers has to always be available instantly, the power demand is maximized: everything has to be working at top speed all the time. But if the service can be tailored to urgency, large energy savings are possible. Even more is possible by two-way communication between the power grid and data system controllers."

The skills necessary for such technical and economic balancing acts have been emerging from the work of several CMS faculty and have been one of the inspirations for the new CMS degree program. "We have tried to develop a new intellectual core and wrap a PhD program around that rather than forcing people to merge their silos and go outside of their traditional fields to add to a degree what they actually need and care about," says Wierman. "We think this approach is core to doing science, engineering, and information sciences in the next 10 years, an area that includes optimization, machine learning, stochastic processes, algorithms, networks, and economics. This is how the core curriculum in the new PhD program came together, and we are excited to welcome the first class this fall."

To Wierman, this is a key movement in the right direction. "Data is the bottleneck not only to development of applications, programs, and research but to science and engineering progress in general," he says. "Caltech as a whole is going to benefit from investing in developing an understanding of how to process large problems, and how to store and operate on large datasets. Despite our small size in CMS, almost everything at Caltech is touched in some part by computing and the CMS faculty."

Joel Tropp

Another architect of the new CMS PhD program is Joel Tropp, Professor of Applied and Computational Mathematics. Tropp works in the field of parsimonious modeling, also called sparse approximation. An observer in imaging science, machine learning, communications, or statistics often tries to analyze a flow of data to find patterns, assuming the data are the result of an undetermined but determinable mathematical relationship. This is a difficult general problem, but Tropp has found algorithms that help find such mathematical ties in specific cases.

He uses music as an analogy to illustrate, starting from the point of view of a mechanical listener: "It turns out that if recordings didn't have any structure, they would sound like static, whereas they tend to have dominant frequency components, much stronger tones and overtones. And they're also localized in time and space, so there are silences."

He continues: "Sheet music is a very efficient way to represent what can be a very complicated piece of music. Thus the idea is that if we can identify this kind of representation for data, then we can compress the data significantly. This is the key. Once we realize that there's an underlying pattern, then we can write down the piece of music much more efficiently."

> *"Sheet music is a very efficient way to represent what can be a very complicated piece of music. Thus the idea is that if we can identify this kind of representation for data, then we can compress the data significantly."*
>
> Joel Tropp, *Professor of Applied and Computational Mathematics*

> *"Machine learning can be used to help build smarter cancer detection methods using imaging analysis tools. It takes a radiologist's time to understand an X-ray, and researchers have been thinking about using more automated techniques for imaging analysis to improve the detection process both in time and accuracy."*
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> Yisong Yue, *Assistant Professor of Computing and Mathematical Sciences*

Yisong Yue

Coincidentally, Tropp's research has found applications in sound analysis, where observers are trying to pick unknown signals out of a flow. Using the right software to compress a representation of the signal, he has found ways to improve the analysis and make finding the signal easier. A similar result comes from tables of information, referred to as randomized linear algebra. "When we are trying to find structure in a very big matrix or a table of data, surprisingly, we can identify the structure automatically just by taking random combinations of the data that we've seen," says Tropp. "The random combinations contain the same underlying structure as the whole, which the algorithm more efficiently finds."

Yisong Yue, Assistant Professor of Computing and Mathematical Sciences, also works on ways to understand masses of data in a less abstract context. He studies machine learning, "the automated process of turning data and experience into knowledge and actionable items. Today, when we do anything on the Internet that is commercial, there's some sort of machinery under the hood that's trying to predict what it is we are interested in. The predictions we see can be helpful because they could help shorten the amount of time it takes us to find what we are look-

> *“We are trying to infer something about some quantity of interest that depends on an imperfectly known reality, and we turn this into an adversarial or Minimax game where the universe chooses reality and we come up with a model for it.”*
>
> Houman Owhadi, *Professor of Applied and Computational Mathematics and Control and Dynamical Systems*

ing for. These are machine-learning algorithms that take the history of other people’s purchases and browsing behavior and predict what we might be interested in.”

This growing field has come a long way in recent times. “If you go back 10 years and try to shop online, you would think it is a disaster how slow and inefficient it was,” says Yue. Since then, machine learning has stepped in “to convert massive amounts of data, in the form of logs of what people have done in the past, to make things more efficient.”

Shopping is not the only process that machine learning can improve. “Machine learning can be used to help build smarter cancer detection methods using imaging analysis tools,” Yue explains. “It takes a radiologist’s time to understand an X-ray, and researchers have been thinking about using more automated techniques for imaging analysis to improve the detection process both in time and accuracy.”

Another area of interest for Yue is video and tracking data. “Now there is huge interest in studying how different genes impact the brain,” he says. “Neuroscientists manipulate the genes of test animals such as fruit fries and mice, and they observe their behavior. For example, they observe if the fruit fly becomes more fearful or more aggressive after the gene manipulation. Machine learning comes into play because we generate thousands of hours of video that needs to be analyzed to identify if flies are being aggressive or fearful. We don’t want a biology grad student to view thousands of hours of fruit fly videos. It is much faster and more efficient to use machine learning and related techniques to train a system that can automatically detect these types of activities from the video.”

Yue adds: “Of course, there are commercial applications, as well. YouTube is trying to build a better search engine for videos. If you want to find a snippet of a certain action, you want to actually search inside the video rather than just tags of the video, which is what they do now. Video analysis has many other applications, as well, including tracking data for sports and tracking human motion to build realistic cartoon characters. This was part of what I worked on at Disney Research before coming to Caltech.”

Houman Owhadi, Professor of Applied and Computational Mathematics and Control and Dynamical Systems, is also interested in estimating and predicting complex systems with limited information. “For instance, you want to predict the probability that the temperature of the planet will be in a given range in 50 years, but you have incomplete information about the underlying physical processes, limited computational capabilities, unknown probability distributions, limited data,” he says. “How do you do that? Or there are systems that you have to build, but you are never completely sure about whether they are going to fail or not; nevertheless, you still have to make decisions about using them.”

Making predictions and critical decisions with incomplete information is part of the human condition. An engineering label for the area is uncertainty quantification, which, as Owhadi explains, “is essentially a generic term which stands for a field that is emerging at the interface between probability, computational science and engineering, optimization, machine learning, and decision theory. There are many challenges in this field, and we can get an idea of what those challenges are by talking to people in the industry and in the National Labs. Oftentimes there is a need to answer very specific and critical questions, but the methods are not there. The mathematical methods have not been developed. Therefore, in this case, the application itself is driving fundamental research.”

Houman Owhadi

Owhadi continues: “We are trying to infer something about some quantity of interest that depends on an imperfectly known reality, and we turn this into an adversarial or Minimax game where the universe chooses reality and we come up with a model for it. What is most exciting to me is to use these techniques to guide, facilitate, or turn the process of scientific discovery into an algorithm. For instance, the question that I’m currently looking at is: Can the process of discovery of scalable numerical solvers be automated by reformulating the process of computing with partial information and limited resources, such as that of playing underlying adversarial information games?” He concludes: “These games can be difficult because the chessboard doesn’t have 64 squares. It has an infinite number of squares, and calculus on a computer is necessarily discrete and finite. But, nevertheless, if we can develop a calculus to play on this chessboard, then we can turn the process of apprehending models of reality into an algorithm. So where can this take us? Everywhere!”

Visit cms.caltech.edu to learn more about the Computing + Mathematical Sciences department’s faculty.

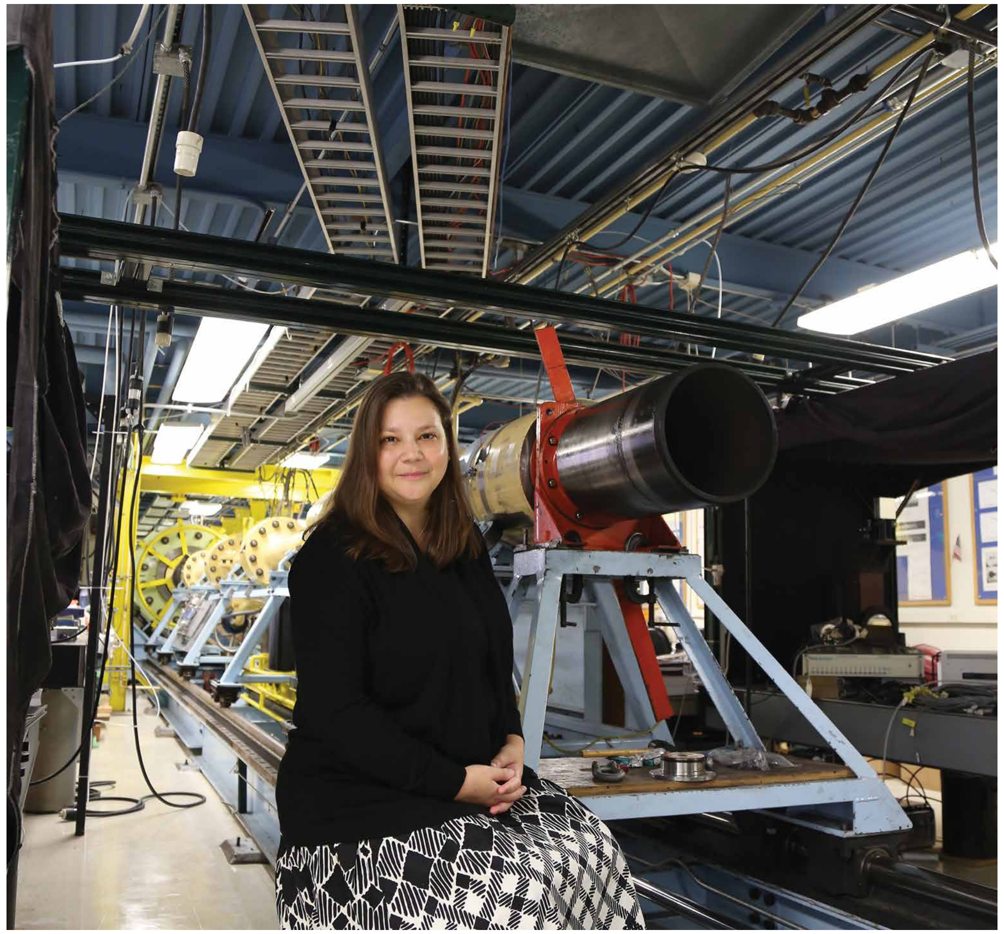
Extending Caltech's Investment in Space Research

by Joanna Austin, Professor of Aerospace

Since returning to my alma mater as a professor in August 2014, I've very much enjoyed working with Caltech students and fellow faculty members—but I have also faced an interesting logistical challenge. In order to forge ahead with Caltech's groundbreaking aerospace research, I've been relocating my research instrument, the hypervelocity expansion tube (HET), from the University of Illinois at Urbana-Champaign, where I built it, to our facilities at Caltech.

This move of the HET to join Caltech's famed T5 reflected shock tunnel creates a full suite of complementary facilities that allows my fellow aerospace engineers and me to explore new ways of preparing space-travel vehicles to withstand the high-speed flows of entry and re-entry into various atmospheres. It's tremendously exciting to see the Graduate Aerospace Laboratories of the California Institute of Technology (GALCIT) investment in laboratory facilities. GALCIT has a long and unparalleled commitment to being at the cutting edge of science, ensuring that we are and continue to be the best at what we do. We are ready to move beyond the limitations that we had previously in terms of access, facilities, diagnostics, and expertise.

Part of taking engineering and science to a new level involves giving us the tools we need, and Caltech's investment in our new laboratory is doing exactly that! Our lab will feature custom-designed infrastructure, including vacuum systems, gas handling, and the next-generation version of the expansion tube. We'll install the HET in its previous state initially, but then we will expand its operating conditions.



Joanna Austin is shown here in the T5 reflected shock tunnel.

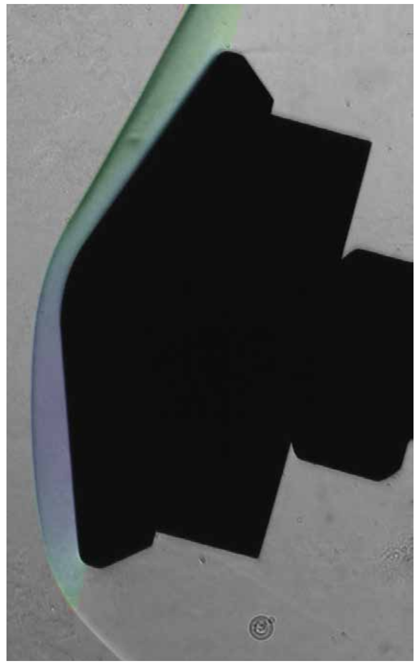
Using the HET and T5 unique suite of experimental facilities, we can simulate flows over objects as they enter an atmosphere. In the case of a Martian mission, for example, our team can create a model of a particular spacecraft configuration, place it in one of these facilities, and then accelerate the gas to replicate the conditions that the vehicle would actually experience during atmospheric entry.

Based on these tests, measurements and various models can be developed to help us understand the conditions and measure the heat transfer to the vehicle surface or heat flux, which is critical to the vehicle's survival. It is important to note that we have just a one-millisecond window or less in which to make all the necessary measurements.

When we have very low-speed flows, we can make some simplifying assumptions, including making the density of the flow constant. As we start to increase the flow velocity relative to the speed of sound, then we start to get into a regime where, as a particle of fluid progresses over our model, the density starts to change. Then we start to get shockwaves interacting and we're in a general regime of compressible fluid mechanics.

I'm particularly interested in the flows as they experience these conditions. For hypervelocity flows, not only is the density of the gas changing, but the gas can be reacting and there could also be exchanges between the different energy states of the gas molecules. We want to understand how the energy exchanges and the chemical reactions that are occurring at a molecular level are interacting with the fluid mechanics.

Such studies are extremely challenging because they focus on when and where the vehicles in question experience the highest heat loads and the highest dynamic pressure loading, a very critical regime for a successful space mission. Creating these conditions in an experimental setting is difficult, yet without really understanding this very challenging regime of flight, it's hard to see us progressing to larger vehicles such that we could meet NASA's goal, for instance, to move beyond some of these smaller vehicles into larger vehicles or assist the Air Force with their needs. We must have a much better understanding of the heat fluxes in different regimes of the flow of the vehicle. With a larger vehicle, there's a potential for what's called transition of the boundary layer. The boundary layer is the flow right near the vehicle. It transitions to a turbulent boundary layer, which has a higher heat flux. So we need to be able to predict the transition better in order not to pay a prohibitive penalty in terms of the protection system.



Schlieren image of high-enthalpy CO_2 flow over Mars Science Laboratory geometry.

Another experiment we have been working on is direct measurements of gas species that occur at high temperatures to help develop models for the chemical and thermal molecular exchanges. Understanding these gas and gas-surface reactions is critical for predicting the flow around the vehicle. We are working on applying optical diagnostics techniques to achieve both temporally and spatially resolved measurements of the species and their temperatures in high-enthalpy hypersonic flows. It's exciting that we are now able to probe the species directly and move beyond inferring what is happening in the molecular interactions from much more indirect measurements.

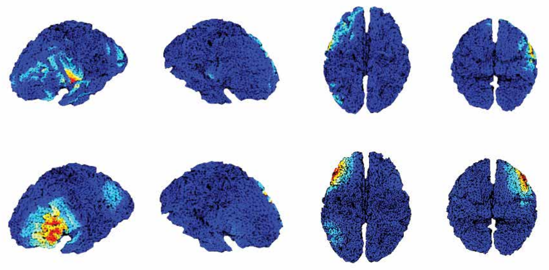
My interests in reactive, compressible flows also spans a broader range of applications beyond hypervelocity flight and planetary entry, including supersonic combustion and detonation, bubble dynamics, and explosive geological events. For instance, our work on voids or bubbles collapsing under dynamic loading waves such as shocks or stress waves is motivated by predicting the significant damage caused to the surrounding material. This work has very diverse applications, from explosives to underwater propulsion to biomedicine. Our experiments are designed to illuminate the hydrodynamic processes of collapsing void interactions for eventual input into device-scale models where, while their impact on surrounding material is critical, the void dynamics cannot be individually resolved. We use a gas gun to generate a loading wave through our sample in which we locate a void or array of voids. We can then use high-speed optical diagnostics to examine the collapse process of the void and the damage mechanisms in the surrounding material. The capability for accurate prediction of damage to the surrounding tissue, for example, has a profound impact on treatment options across a broad range of biomedical applications, including extracorporeal shock-wave lithotripsy, laser-induced plasma surgery, and ultrasound.

Looking to the future, my students' excitement about this research makes overcoming the logistical and other challenges especially rewarding. I always make sure to point out that these are very difficult experiments, but the students respond to that and see that their work makes an impact. They are enthused about working on these types of problems in spite of the challenges! Interacting with my research group is really one of the most rewarding aspects of my career thus far.

Joanna Austin (MS '98, PhD '03) is Professor of Aerospace and co-PI of the Caltech Hypersonics Group.

Athanassios S. Fokas

Professor A. S. Fokas holds the Chair in Nonlinear Mathematical Science at the University of Cambridge in the UK. He has a BSc in aeronautics from Imperial College, London, a PhD in applied mathematics from Caltech, and an MD from the University of Miami.



This illustration of medical imaging techniques for the brain shows magnetoencephalography (MEG) reconstruction comparisons between the MNE software package (top four images), developed at the Athinoula A. Martinos Center for Biomedical Imaging at Harvard University, and the Exact Reconstruction Formula (bottom four images) developed by Professor Fokas. The displayed neuronal current images indicate the absolute value of the radial component of the current present in the brain after a stimulus.

ENGenious: What inspired you to become an applied scientist?

Fokas: When I was growing up in Greece, it was thought that a mathematician could not find a job. This is why my first degree is in aeronautical engineering; I was told that the two most mathematical engineering degrees are aeronautical and electrical engineering, and I thought aeronautics sounded more interesting. I graduated top in my class, and I was offered a scholarship for a PhD in aerodynamics. Since I was going to work in a theoretical area, I thought I should strengthen my mathematics, so I decided to take a year off to get a master's in applied mathematics. This is when I discovered that the applied mathematics department at Caltech was born out of the aeronautics department. Thus, I thought that Caltech would be an ideal place to get a master's in applied mathematics. However, I fell in love both with Caltech and mathematics, so I never went back to do a PhD in aerodynamics. I finished my PhD in applied mathematics and then stayed at Caltech a year longer as a fellow.

ENGenious: Why did you also decide to get a medical degree?

Fokas: I had some correspondence with the late Israel Gelfand, one of the greatest mathematicians of the last century, and I noticed that he was located in the department of biology. Thus I presumed that he was doing mathematical biology (which actually was not the case), and, hence, I decided to take a couple of years off to study biology and medicine. This finally led me to the PhD–MD program of the University of Miami. I enjoyed medicine much more than I expected, and it became a difficult decision whether to follow a residency at Stanford University, where I was doing my internship, or to return to mathematics. In any case, I consider this investment in medicine the most important and most useful investment I have ever made in my professional life. Studying medicine has given me a completely different perspective in life and also has led me to a lifelong fascination with the function of the brain. It should be noted that perhaps the only positive thing about getting older is that our understanding deepens, and this I believe happens by continuously establishing new connections, which is actually a reflection of how the brain is organized. Perhaps this suggests the importance of trying to become a polymath, because the more diverse areas you are aware of, the more connections you can establish, the deeper understanding of various phenomena you can achieve.

ENGenious: How has your Caltech education influenced you?

Fokas: I have been privileged to have had faculty appointments at some great institutions. But in terms of quality density, there is no doubt that Caltech is the best. Unfortunately, you appreciate this fact only after you leave. All of a sudden, you realize that you were in paradise. Taking into consideration the size of Caltech, what it achieves is absolutely phenomenal! Perhaps, as Chair Ares Rosakis has noted in a recent interview, the small size is an advantage: it promotes interdisciplinary approaches, it ensures extremely high-quality faculty, and it allows for a much closer relationship between students and the faculty.

ENGenious: How would you describe your professional life and contributions?

Fokas: Although I am considered an applied scientist, my mentality is closer to that of a pure mathematician, in the sense that the main criterion for choosing a research project is not usefulness but aesthetics. Of course, there is a deep relation between aesthetics and the truth—recall the Latin motto *pulchritudo sigillum veri* ("beauty is the seal of truth")—but also a relation between aesthetics and function. Perhaps this is the reason why some of my contributions appear to have also a commercial value. In particular, our quest with Gelfand to explore the beautiful formalism of the so-called Riemann-Hilbert and D-bar methodology led to the completely unexpected derivation of an analytical formula for the inversion of the attenuated Radon transform. This transform plays the same fundamental role in the important medical imaging technique of single photon emission computerized tomography (SPECT) that the classical Radon transform plays in computerized tomography (CT). This has led to improved image reconstructions not only in SPECT but also in positron emission tomography. Similarly, aesthetics was crucial in my work on electro-magneto-encephalography, whose related patent was financed by Cambridge Enterprise. It should be noted that nothing in my life has happened easily. The above results in medical imaging where the culmination of research efforts of almost 20 years. Also, my most well-known achievement, the development of the so-called Fokas method, was first introduced in 1997, but I started working on this project in 1982! By the way, it was very flattering that just before delivering the Lagerstrom Lecture at Caltech in May 2014, an editorial in *SIAM Review* compared the importance of this method for solving boundary value problems for linear partial differential equations with the impact of the "Fosbury flop" in the high jump.

ENGenious: What advice do you have for the next generation of Caltech applied scientists?

Fokas: The most important thing is to enjoy life while you're at Caltech, because most likely this will turn out to be the best period of your life. Every moment of life must be enjoyed, because every moment is irreversible. Do not waste time in anything that does not involve quality. Remember, success comes only after hard work in an environment that inspires excellence, and Caltech is the epitome of such an environment.

ENGenious: Reflecting on your career so far, has there been a mistake that was critical to your success?

Fokas: I'll tell you a story. At some point, Israel Gelfand convinced me to work with him on one of the most important open problems in biology, the problem of protein folding. As you know, a protein consists of a sequence of amino acids, so, in principle, if you are given the sequence, you should know everything about this protein, including its topology. But no one can predict the topology from the sequence. At first, I was very reluctant to participate in this project because I knew that many great people had worked on this problem. However, Israel was very persistent; thus, I did work for a couple of years with Israel and collaborators on this endeavor. Since this is not an area of my expertise, I could not evaluate the importance of our results. In any case, I recently told my wife that this project was probably a waste of time. Fast-forward to today, when during a prestigious lecture delivered in May, a distinguished scholar who is very well known in this area reported that his group has reached the stage where they can predict the topology with something like 78% accuracy, and this would not have been possible without the breakthrough work of Fokas and Gelfand. So until very recently, I had thought investing in this project was a mistake, but apparently it wasn't. Overall, perhaps the message is that quality work sooner or later gets recognized.

ENGenious: What does the future hold for you and your work?

Fokas: I have done two crazy things in my life. One was to study medicine, because I went from being an associate professor to being a student in an area that I knew absolutely nothing about. The other was six years ago, when I made the decision to start working on the most famous open problem in the history of mathematics, namely the Riemann hypothesis, which is considered a problem in pure, as opposed to applied, mathematics. However, perhaps this decision was not completely crazy, since the Riemann hypothesis is related to the Lindelöf hypothesis, which is a statement about asymptotics, and asymptotics is certainly part of applied sciences. Actually, most of my life I have been involved with asymptotics. In any case, we have developed new remarkable mathematical structures and have established deep connections among different fundamental mathematical entities. Let us not forget that establishing new connections is what science in particular and life in general is all about! Thus, we are hopeful.

Athanassios S. Fokas is Chair in Nonlinear Mathematical Science at the University of Cambridge.

Left to right: Domniki Asimaki, José Andrade, and Nadia Lapusta

Exploring the Unstable World of Geomaterials

From Fundamental Science to Engineering Solutions

The study of the materials and structures that appear solid and reliable but can fail or move violently—including the ground under our feet and buildings—is of great interest to Engineering and Applied Science (EAS) professors José E. Andrade, Domniki Asimaki, and Nadia Lapusta. They develop sophisticated, data-intensive models to computationally investigate solid dynamics and understand how forces move both tiny particles and large-scale geologic formations within the earth.

Some of these now-unpredictable movements are potentially catastrophic: earthquakes, for example, or soil liquefaction. Thus one goal of the solid dynamics effort is to create new computational tools that can accurately model and even forecast such movements.

One critical application in this area is building safer structures and cities by better understanding and anticipating the types of potential motion and how artifacts and the ground they rest on will react to these motions. Another is making better concrete for various structures and in a more energy-efficient way.

The research of Professors Andrade, Asimaki, and Lapusta focuses on multi-scale, multi-physics, nonlinear problems, and the challenge for all is how to translate their fundamental science into triumphs of engineering. Fundamental science does not generate satisfactory solutions to many important problems: too many variables and unknown parameters are in play. Yet empirical understanding is highly limited; in the case of earthquakes, for example, there have not been enough large events to develop a robust empirical understanding of their effects. How does one create the best engineering solutions given empirical knowledge and our developing fundamental understanding? “Addressing such engineering challenges to positively impact people’s lives is central to the purpose of engineering as a whole,” says Ares Rosakis, Theodore von Kármán Professor of Aeronautics and Professor of Mechanical Engineering.

ENGenious sat down with the three faculty members to jointly discuss their work and the ties that link them. Nadia Lapusta, Professor of Mechanical Engineering and Geophysics, who has been at Caltech since 2002 after a start at the National University of Kiev and Harvard, focuses on the complex dynamics of solid interfaces and their friction properties, both within the earth’s interior and in the lab. She develops friction laws and computational tools to analyze how confined materials and their interfaces behave under stress, some failing suddenly and violently and others moving more gradually and less destructively.

Domniki Asimaki, Professor of Mechanical and Civil Engineering, joined the EAS faculty last year, bringing from Athens and MIT a vision of understanding the reactions of surface features of the earth, ranging from hills and valleys to bridges and buildings, to the forces unleashed by subterranean players in the earth movement interactions analyzed by Lapusta.

José E. Andrade, Professor of Civil and Mechanical Engineering, who has been at Caltech since 2010, has been studying the properties of ground itself, of heterogeneous mixtures natural and artificial. Many materials—sand is one familiar example—are assemblies of particles of various shapes and sizes and chemical compositions with empty space between them. These do not have the neatly predictable behaviors of pieces of metal or crystal, but their behavior has to be understood both for industrial processes and for analysis of the natural world.

The methods of study overlap for the three EAS faculty members, and for each of them, that means using sophisticated modeling that combines scientific understanding and empirical data. Says Lapusta: “People have to build buildings and make decisions now mostly based on the empirical models they have. We are developing models that agree with the empirical observations but extend them to the situations and environments that have not or cannot be easily tested, using fundamental science. We are building models that will enable more science-based engineering solutions for tomorrow.”

Asimaki agrees, supplying her own formulation: “For science, we want to understand why and create predictive models about the events that we experience. But engineers are trained to find practical solutions to problems. Sometimes the solutions are not perfect, but they’re good enough to build a building. Lots of the holes that they lack in understanding, they fill with empirical models. They extrapolate without complete understanding. Our studies aim to develop more fundamental-science–based approaches to such extrapolations.”

“I think it’s a difference in the philosophy between the way that we see things at Caltech and the way that usually the engineering world perceives things,” adds Andrade. “Our approach here at Caltech is more of an engineering science approach. As Nadia and Domniki explain, let’s find a solution that relies on fundamental science while explaining empirical ideas.”

The three have succeeded in applying this approach to their different but related problems. Working on the smallest scale is Andrade, who explores granular particle mechanics (GEM) using an analytical path called the discrete element method. As an abstract of one of his recent papers explains, “It has been determined that lack of sphericity, sharper angularity and increased roughness all lead to increased mobilized strength in granular materials. For decades engineers have used very rough approximations of shape irregularities to make quite inaccurate predictions about behavior of such materials.” But Andrade’s group has found ways to statistically specify the various sizes and shapes of the disparate granules seen in high-resolution X-rays and other imaging technology. Their technique then allows them to use these detailed quantifications to predict precisely the properties to be expected in masses of granules.

“GEM bypasses one of the current bottlenecks in computational discrete mechanics of granular materials by allowing discrete elements [of modeling] to take realistic and complex granular shapes encountered in engineering and science (e.g., sand grains),” says Andrade. “It is expected that, with the rapid advancement of computational power, combining high-fidelity characterization with physics-based computations will lead to more predictive modeling approaches. The granular element method may help transition from characterization to modeling and could lead to more realistic predictions at the grain scale.”

Humans create and use huge amounts of granular materials. Concrete, a key example, is mixed by the gigaton yearly for construction projects from skyscrapers to backyard patios. A better understanding of particulate behavior, Andrade believes, may allow for the formulation of more precisely and optimally shaped concrete particles, which will mix more completely and efficiently and produce stronger walls and foundations—and do so in a more energy-efficient fashion.

“The CO_2 footprint of concrete has to do with all the energy that has to be harvested in order to make concrete, from breaking stone all the way to making the actual concrete that makes buildings,” Andrade says. “The cement component goes into conveyor belts. It goes into trucks. It gets mixed with water. It gets mixed with sand. Each time you undertake one of those processes, you spend energy. It has been calculated that in all of those processes, we waste about 60% of the energy we use.” The right model could improve this, says Andrade. It could “enable you to decide on a better mixing technique, for instance. Instead of being only 40% efficient, maybe it would be 50% efficient or 60% efficient, and therefore waste less energy. So all of a sudden, your mixer needs to use less fuel to mix.”

The behavior of sand, earth, and other granules is also important for problems with larger spatial scales, such as in the assessment of the effects of geological forces. Asimaki explains: “At these scales, computational constraints prohibit us from using detailed models composed by individual grains. Instead, we combine the understanding from these models with empirical data from laboratory experiments and field studies of

Domniki Asimaki (left) and Nadia Lapusta

near-surface geology characterization to develop continuum mechanics models of soil behavior. These models are complex because the physics of the problem in hand are complex: deformation of soft sediments, liquefaction of saturated granular soils, slope stability failure, landslides, and the effects of all of these on the civil infrastructure of urban regions—buildings, transportation networks, and pipeline distribution systems.”

She emphasizes that “the challenge, however, is that, exactly because the models we are building are large—basins, hills, and ridges, to name a few—we cannot characterize the material properties as well as we could had the model been of a scale small enough to be tested in the lab. So while our models need to be complex to represent the complex behavior of geomaterials and how they affect the ground shaking during strong earthquakes, they at the same time need to be simple—that is, based on parameters that we estimate using simple field tests, satellite imagery, or empirical models. Of course, this abstraction introduces uncertainty that we also seek to quantify: uncertainty from the phenomena that our complex-simple models cannot capture, uncertainty from the errors involved in the parameter estimation, and uncertainty related to the fact that geomaterials are very heterogeneous—that is, their physical properties (stiffness, strength) can change dramatically over the distance of a few tens of meters, and the characterization of this variability also involves uncertainty.”

Asimaki is working to develop models that can improve the currently limited state of the art of evaluating vulnerabilities to phenomena such as liquefaction, landslides, and ground deformation, and also estimating the forces that these so-called earthquake effects impose on the buried and surficial infrastructure (e.g., pipelines, tunnels, and foundations) that can help to determine the risk of urban environments to earthquakes.

This is a critical area in cities all over the world, particularly in California. And now, Asimaki explains, there is a window of opportunity, in the wake of the release by the Los Angeles mayor’s office of the Resilience Assessment Overlay. “It’s basically an attempt,” she says, “to prioritize spending for public infrastructure (pipelines, buildings), so that in the occurrence of the next big earthquake, the amount of human losses and the economic loss will be minimized, and the city will improve its capability to pick up and start functioning again.”

But to do this, she adds, we have to fill in knowledge blanks. “Where exactly are the quake-prone areas, with what kind of buildings? What areas will be more prone than others? Where will the most deformation be induced on the pipelines?”

To get useful answers to these questions, according to Asimaki, we cannot just “rely on faith and our understanding of soils, beams, and pipelines from other cities and other earthquakes. We need to use new methods and mathematically model future scenarios in the specific fault system where they lie in the valley of Los Angeles as well as the buildings and pipelines.” We still need better modeling tools for the effects of earthquakes in general on soils and geological structures and buildings, Asimaki says. This is achievable, she adds, if we make the effort: “At least for the Los Angeles basin, we will be able to improve near-surface land deformation predictions on these large scales so that we can have physics-based assessments of the risks if an earthquake falls on the distributed system.”

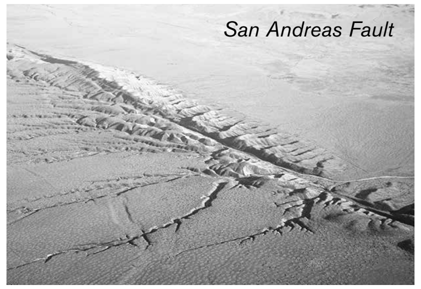
A crucial element in achieving such physics-based assessment is the work being done in her colleague Professor Lapusta’s computer simulation laboratory. Lapusta’s methods probe the detailed underground dynamics of the stresses induced by tectonic motion and create models that reveal how the materials and their interfaces behave in response. Under the large compressive forces in the earth’s interior, failure of solids that produces earthquakes is localized to extremely narrow zones, less than a tenth of an inch wide. Inside such zones, the resistance to motion is determined by micro- and nano-sized particles. Lapusta’s group includes in its models insights into how such materials behave from various sources, including micro-modeling from Andrade’s group and Lapusta’s own micro- and continuum modeling of localized shear.

In some cases, Lapusta notes, “as loading increases, the material resists until it experiences a catastrophic failure, a high-magnitude earthquake. But sometimes it accommodates the loading by gradually sliding and releasing the stored energy less violently. This understanding, as it increases, opens intriguing possibilities of both forecasting different types of behaviors and new action alternatives.”

There are limits, of course, but Lapusta also sees great potential. “To predict that there is going to be an earthquake on Tuesday at 2 p.m. will not be possible,” she says. “But what else can we do about it? Our models are realistic enough at this point that we can start using our modeling and the increasing array of observations to understand the potential future earthquake scenarios and their effects. It may also be feasible to find a way to avoid a large earthquake altogether. Might we find a way to modify the behavior of the fault so that, instead of one large event, we get much smaller events or slow slip that does not generate shaking? This is quite futuristic and far-fetched but conceivable. But we first need to understand in detail what the physics of the process is, and then we can ask if we can modify it.”

The beginnings of this striking vision took the form of a graphic portrait of a segment of the San Andreas Fault, imaged from an array of instruments on the surface. A range of motion of the segment was reproduced in the simulation, from almost none in some parts of the fault to active slippage corresponding to the known movement—a stop-action movie of the earth in motion. Then Lapusta and colleagues modeled in detail earthquakes in Taiwan and Japan, trying to find the subterranean differences leading to massive, violent slips, as opposed to gentler, more gradual slides. In these studies, the researchers combined all known fault behaviors—earthquake nucleation, dynamic rupture, post-seismic slip, interseismic deformation, and patterns of large earthquakes—in a single dynamic model. The construction of such a model was facilitated by extensive collaborations and consultations across campus with a number of EAS and GPS (Geological and Planetary Sciences) faculty.

One message that came out of this work has disturbing consequences for California: creeping segments can participate in large earthquakes, and hence much larger events than seismologists currently anticipate in many areas of the world are possible. That means, Lapusta says, that the seismic hazard in those areas need to be reevaluated—including around the San Andreas Fault.



San Andreas Fault

A creeping segment separates the southern and northern parts of California’s San Andreas Fault. Seismic hazard assessments assume that this segment would stop an earthquake from propagating from one part to the other, limiting the scope of a San Andreas quake. However, Lapusta’s models suggest that a much larger event may be possible than is now anticipated—one that might involve both the Los Angeles and San Francisco metropolitan areas.

Lapusta and Asimaki say we still need to have a much deeper understanding of exactly what we have along our faults in California, both to make estimates of possible damage and perhaps—not tomorrow, but someday—to take action to create prophylactic miniquakes or slow slip to relieve accumulating stress, such as by manipulating fluid effects. But to do this, much better information is required.

In the meantime, the hope of these researchers is more modest but still ambitious: a research valley. They visualize an area along an active fault zone that can be minutely, meticulously instrumented, with boreholes extending to various depths, in order to obtain unique and currently unavailable data on actual fault structure and properties at various depths, factors that are currently incorporated in models mostly based on materials science theories. “Not today,” says Lapusta, and “maybe not even in 20 years. But eventually we may learn enough to understand and modify the behavior of these faults.”

She adds that Caltech is the ideal place to try. “It has the best solid mechanics faculty in the world and also the best geophysics faculty in the world,” she says. “Hence it is the best place in the world for my work, which uses solid mechanics to understand earthquakes and their effects.”

Andrade finds Caltech’s relative smallness to be a particular benefit: “The energy barrier to communicate across campus is essentially zero. So at Caltech my group has been able to do things and to think of things that were not possible somewhere else.” He notes, too, that “the JPL connection would never have happened somewhere else. JPL is like a great playground for us engineers!”

“It’s an inspiring place to work,” Asimaki agrees. “Scientific discoveries across campus motivate you to keep asking questions.” Plus, as she noted when she first arrived, “It’s gorgeous! I’ve never had the opportunity to live in a place that reminds me so much of Greece.”

José Andrade is Professor of Civil and Mechanical Engineering. Domniki Asimaki is Professor of Mechanical and Civil Engineering. Nadia Lapusta is Professor of Mechanical Engineering and Geophysics.

Bringing the Right People Together

Keck Institute for Space Studies

The Keck Institute for Space Studies (KISS) was established at Caltech in January 2008 with an eight-year grant from the W. M. Keck Foundation totaling $24 million. The institute is a "think and do tank" whose primary purpose is to bring together a broad spectrum of scientists and engineers for sustained technical interaction aimed at developing new space-mission concepts and technology. *ENGenious* sat down with the two leaders of this unique institute to understand the secrets of their great success. The KISS director is Thomas A. Prince, who is also a Caltech physics professor, and the managing director is Michele Judd.

ENGenious: **What has been the primary purpose of the Keck Institute for Space Studies?**

Judd: Our goal is to have a positive impact on future space missions. We do this in three very different ways. The first and foremost is holding small and intense studies/workshops and then following up on any great ideas generated; this follow-up takes the form of investing technical development funds that can flesh out the idea to a point where it can be picked up by NASA or some another agency. The second way is identifying and supporting the development of the future leaders (grad students and postdocs) in the field. Finally, we want to keep the public engaged and excited about space exploration, such as through our lecture series and symposia.

Prince: In addition to space missions, we want to come up with new concepts for broad areas of space science and engineering. This includes looking down from space at Earth and looking out into space from the ground. As one example, we've funded the development of telescopes and observations on the ground of small near-Earth asteroids. Another example is supporting measurements of greenhouse gases in the Los Angeles basin. Space exploration means both going out there and doing observations from the ground. Critically important in all of this is bringing the right people together to investigate the concepts. If you have the right team, it's just magic. We try to bring together people who wouldn't normally be in the same room together. Again and again, we have seen that by engaging people from different backgrounds in the creative process, we get totally new results that would not have happened any other way.

Judd: We work really hard to create this collaborative environment. For example, each study or workshop starts off with a short course where each discipline presents its fundamentals, so there's an early sharing and establishment of a common vocabulary. The problem we are investigating needs to be framed specifically enough that we can get something out of it, but broadly enough that we can have different ideas to solve it. Then we encourage highly interactive discussions with the group as a whole, small subgroups, and between individuals.

ENGenious: **What makes KISS unique?**

Prince: All our studies involve people from campus, JPL, and the external research communities. Therefore, if a new idea arises out of one of our studies or workshops, it's jointly owned by all of those people, and that's very powerful. That mix of people allows new ideas to come out but also to be followed up on. One of my criteria as director is that I want to see a path forward after our study ends. For example, we did a study of the advantages of using a high-altitude airship to do science that would normally go on a satellite. One such advantage is that you can retrieve it, and these are airships that can maneuver. The workshop participants took the ideas from the study and went on to make a successful NASA Centennial Challenge proposal for a demonstration of high-altitude airship observations.

ENGenious: **How do you know that you've been successful?**

Prince: Number one is if the group of people that we brought together feels like they've had an excellent experience in investigating the topic. The next level of success is if a plan emerges for how to implement the ideas that came up in the study. Lastly, although we don't require it, we are extremely happy when an entirely new idea comes out of the study, an idea that would not have happened without KISS.

Judd: The most common comment that we get back on our study evaluations is, "You brought together people that would never have spoken to each other." People are very happy they had that opportunity.

Prince: Quite a few people also have said that they were thoroughly spoiled by going to a KISS workshop because it's so different from most other conventional workshops.

Judd: Our job is to make it the most pleasant experience with the least burden logistically for the study participants. We've put so many processes in place to enable the collaborative effort. A KISS workshop is a workshop, not a conference. You're not shopping your idea around. You are leading discussions. You are asking provocative questions that challenge the people in the room and the person leading the discussion, and then somebody stands up and says, "I think you're wrong." And it's that ensuing debate, that collegial yet pointed debate, that really gets to the heart of the issues.

Thomas Prince and Michele Judd

Prince: We have tried to think through in detail how to encourage deep and substantive interactions, so that in four or five days you can go from not knowing each other and being from diverse fields to having a brilliant new idea that's going to change the future of space exploration. This requires different approaches, such as setting 50% of the workshop time for talks—but even those are supposed to be people leading discussions—and 50% for unstructured discussions, to the dinners and lunches we have where people mix in different ways, to having a poster session where the more junior researchers present their results. Every single person in that room should be comfortable with saying what they want to say at any time during the workshop.

Judd: Tom comes into the end of every session and silently observes from the back of the room. If 50% of the people are not fully engaged in the summary of the workshop and the findings, we do not feel very good about the workshop. That rarely happens.

ENGenious: **What are the elements of this success?**

Judd: I think a hallmark of our success is that we try new things all the time. We find out not only what doesn't work, but also what works better than we could have ever expected.

Prince: If you are afraid to fail, it means that everything you're doing will be fairly mundane, and you pretty much know it's going to work. But the really new advances come when you risk trying something that you don't know is going to work. Picking topics that are high risk and high return is a critical but challenging part of what we do. A very important aspect of our approach is that we have a steering committee that's composed roughly half of campus faculty and half of researchers, scientists and engineers at JPL. It's that group that will say, "Yes, that's the right concept at the right time." The technology and the science are such that there's a definite possibility of something really new and interesting developing out of the program.

Judd: When we send out proposals for review, my favorite reviewer remark is, "This is crazy, but if you could do it, it would fundamentally change the field." That's what we want to be doing.

ENGenious: **How do your very distinct roles complement each other?**

Judd: I like to joke that if we had a Venn diagram of our various skills, the only overlap we would have is respect for each other's opinions. Tom's a scientist. I'm an engineer. But we're such a great team. You have to treasure those rare moments when you love and respect the people you work with and you feel like you've built something together that you honestly don't think would have happened had the other person not been part of the equation. Tom handles the large-scale strategy of KISS, continually challenging the institute and the steering committee to move in new and creative directions. Once I have the broad scope of the direction we need to go in, I'm really good about finding ways to make what Tom has envisioned happen.

Prince: Michele and I sit down together and map everything from the very detailed aspects of how we do things to the strategy and how we best get concepts. We approach it from very different directions, but Michele is absolutely on-target about our big-picture objectives and how we get to them. While we have definite ways of carrying out our programs, I often say we have guidelines but no rules. And guidelines can always be changed or ignored if you have a good reason or a new idea.

ENGenious: **How is KISS serving the JPL community and the Caltech community?**

Prince: We've been very successful in establishing substantive collaborations that would not have happened otherwise between campus and JPL. We're almost like a retreat center for our JPL colleagues. It's a different place, a different atmosphere, where they can be away from their everyday work and just be blue-sky about things. Also, we can provide a forum for JPL people to interact with their colleagues and especially foreign nationals. ITAR (International Traffic in Arms Regulations) must be respected at all levels, but the interaction between individuals on things that are not ITAR-controlled allows that. From the campus perspective, as director, I want to help campus investigators achieve their research goals by providing opportunities for new collaborations and by providing seed funding for new research directions. We've certainly seen it happen where a campus investigator has come into a workshop and said, "How about this idea?" And all of a sudden, the group, including JPL and Caltech participants, is off and running and investigating it and then developing plans to make it happen.

Judd: One example that ties both campus and JPL together is the first Mars study that we did in 2008, focused on understanding the history of Mars through rocks. Professor Ken Farley had not been involved with Mars at all, but he was in that study and got excited about the possibilities of actually age-dating a rock on another planet. He was able to convince the Mars Science Laboratory, which is now called Curiosity, to try to do the first age-dating of a rock on another planet, and they succeeded. This fundamentally changed the direction of his research, also impacting both campus and JPL and the wider scientific community.

***ENGenious:* What have been some of the pivotal or magical moments for KISS so far?**

Prince: Space missions take a decade or more to develop, so I had no expectation when the Keck Institute started that we would be having the kind of real-time impact we've had so far, with things like the first in-situ dating of a rock on another planet, having an impact on the selection of the 2016 Mars lander, and NASA adopting a version of the asteroid redirect mission. We are thus already achieving our goal of significant impact on the US space program. On a completely different scale, we are investing in the next generation of leaders in space exploration by involving students and postdocs in all of our programs, and we are reaching out to the public through our programs at Beckman Auditorium and other venues in which we have brought prominent current leaders of space exploration to Caltech, including leading scientists, policy makers, entrepreneurs, and astronauts.

Judd: Tom and I were walking down the Olive Walk one day soon after KISS was up and running. We were finally hitting our stride, and he wanted to mix it up. He said, "We've just spent two years setting up all the right processes for the faculty and JPL and the external people to hold studies. We should allow students to propose their own studies." And the very first of those was the 2011 Caltech Space Challenge, which continues today and is probably one of the most representative examples of how KISS works. If we start something and it's good, somebody else will pick it up. In this case the Engineering and Applied Science Division's Graduate Aerospace Laboratories (GALCIT) picked up the Space Challenge, and its impact continues today.

Prince: Our greatest impact, period, could be bringing together the best and brightest students from around the world for their first experience in designing a space mission. A fairly large fraction of those people will be the international leaders in space exploration 20, 30 years from now.

***ENGenious:* What do Caltech alumni need to know about KISS?**

Prince: We strive to continue the best traditions of Caltech by doing absolutely cutting-edge science and engineering. Another is that we require students and postdocs to be part of every single one of our studies. We want to solve problems now, but we also focus on the social and human nature of research, not just the content.

***ENGenious:* What's next for KISS?**

Prince: There's been a new space innovation council formed, and one of its goals is to support KISS in its way forward. We are very grateful for the eight years of generous support from the W. M. Keck Foundation, who were willing themselves to take a risk and allow our institute to thrive. We will now take KISS forward, building on our past success with a new base of support. I also see this transition as an opportunity to pursue new approaches and directions. As an example, we will certainly want to be substantively engaged in encouraging the rapidly developing private/commercial/public partnership in space exploration. At the same time, we have an opportunity to explore other dimensions. One is the evolving relationship between media, science, and engineering. The basic way that science is being communicated to the public is changing. I don't think that's going to be a core focus of ours, but it's an area that we can play in and be creative about making a contribution to.

Judd: I want KISS to continue changing space exploration, finding the emerging leaders, and keeping the public excited about opportunities to explore space. That's what we do best.

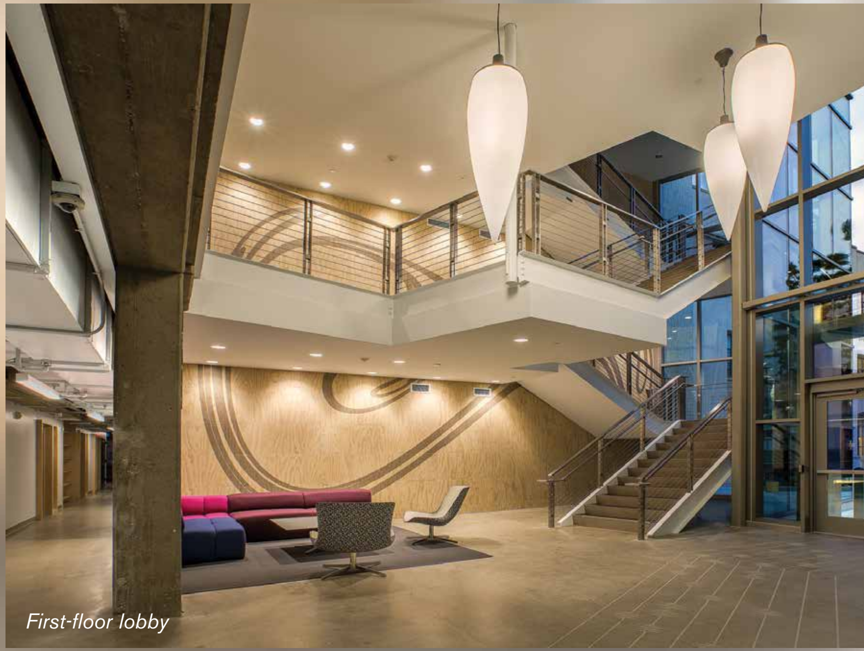
Thomas Prince is Professor of Physics, Jet Propulsion Laboratory Senior Research Scientist, Director of the W. M. Keck Institute for Space Studies, and Deputy Executive Officer for Astronomy. Michele Judd is Managing Director of the W. M. Keck Institute.

Visit kiss.caltech.edu.


Housner Lounge

Charles C. Gates Jr.–Franklin Thomas Laboratory

The renovation of the former Franklin Thomas Laboratory of Engineering has thoroughly modernized the facility while honoring the building's storied past and the people who helped advance mechanical engineering, civil engineering, and applied mechanics at Caltech. The original structure was completed at the close of World War II, when human space flight was still years in the future and the idea of nanotechnology had not yet been conceived. The updated Gates–Thomas Laboratory of Engineering provides new, bright open spaces where scholars and students can better collaborate and engage in experimental and computational work undreamed of when the building first opened its doors. The laboratory is named after two devoted stewards of the Institute: Charles C. Gates Jr. (1921–2005), businessman, philanthropist, and longtime Caltech trustee, and Franklin Thomas (1885–1952), civil engineering professor, division chair, and dean of students.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