ENGenious

ISSUE 14, 2017

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

Division

Guruswami (Ravi) Ravichandran, *John E. Goode, Jr., Professor of Aerospace and Mechanical Engineering; Otis Booth Leadership Chair, Division of Engineering and Applied Science*

Azita Emami
Andrew and Peggy Cherng Professor of Electrical Engineering and Medical Engineering; Deputy Chair, Division of Engineering and Applied Science

Marionne L. Epalle
Division Administrator

Departments

AEROSPACE (GALCIT)
Morteza Gharib, *Hans W. Liepmann Professor of Aeronautics and Bioinspired Engineering; Director, Graduate Aerospace Laboratories*
galcit.caltech.edu

ANDREW AND PEGGY CHERNG DEPARTMENT OF MEDICAL ENGINEERING (MEDE)
Yu-Chong Tai, *Anna L. Rosen Professor of Electrical Engineering and Mechanical Engineering; Executive Officer for Medical Engineering*
mede.caltech.edu

APPLIED PHYSICS AND MATERIALS SCIENCE (APHMS)
Kerry Vahala, *Ted and Ginger Jenkins Professor of Information Science and Technology and Applied Physics; Executive Officer for Applied Physics and Materials Science*
aphms.caltech.edu

COMPUTING AND MATHEMATICAL SCIENCES (CMS)
Adam Wierman, *Professor of Computing and Mathematical Sciences; Executive Officer for Computing and Mathematical Sciences*
cms.caltech.edu

ELECTRICAL ENGINEERING (EE)
Ali Hajimiri, *Bren Professor of Electrical Engineering and Medical Engineering; Executive Officer for Electrical Engineering*
ee.caltech.edu

ENVIRONMENTAL SCIENCE AND ENGINEERING (ESE)
Paul O. Wennberg, *R. Stanton Avery Professor of Atmospheric Chemistry and Environmental Science and Engineering; Executive Officer for Environmental Science and Engineering; Director, Ronald and Maxine Linde Center for Global Environmental Science*
ese.caltech.edu

MECHANICAL AND CIVIL ENGINEERING (MCE)
José Andrade, *George W. Housner Professor of Civil and Mechanical Engineering; Cecil and Sally Drinkward Leadership Chair, Department of Mechanical and Civil Engineering; Executive Officer for Mechanical and Civil Engineering*
mce.caltech.edu

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

ENGenious

EDITOR
Trity Pourbahrami

VISUAL DESIGNER
Vicki Chiu

CONTRIBUTING WRITERS
Eric Mankin
Jamie Meighen-Sei

COPY EDITOR
Sara Arnold

TRANSCRIBER
Leona Kershaw

SPECIAL THANKS
Whitney Clavin
Neil Fromer
Robert Perkins
Briana Ticehurst
Katarina Yang

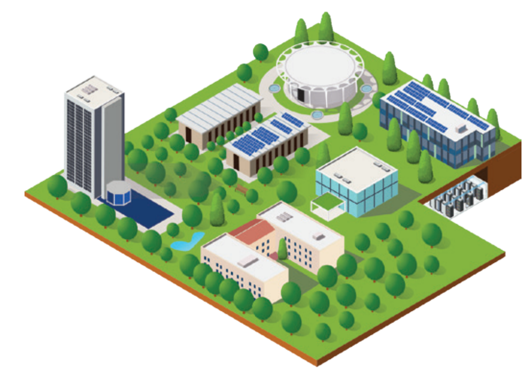
IMAGE CREDITS
Cover illustration: Vicki Chiu; Shutterstock (aurielaki, Adazhiy Dmytro, denisik11, elenabsl, Georgii Red, Golden Sikorka, Grimgram, Zern Liew, ksaverius, Macrovector, Oleh Markov, robuart, tele52, Vikpit)
p. 2: (top) Vicki Chiu; (middle, bottom) Briana Ticehurst
p. 3: Lance Hayashida
p. 4: (left) Trity Pourbahrami; (right) Tom Bonner, coarchitects.com
p. 5: (top) Courtesy of Ed Zschau; (bottom) Vicki Chiu
p. 6: Courtesy of Anima Anandkumar; Courtesy of Wei Gao
p. 7: Courtesy of Basile Audoly; Courtesy of Vahid Tarokh
pp. 8–10: Briana Ticehurst
p. 11: Google Earth
p. 14: Li Lin, Peng Hu, and Lihong V. Wang
pp. 16, 18: Vicki Chiu
p. 17: Courtesy of Yu-Chong Tai
p. 19: Chan et. al., Gradinaru Lab
p. 21: Vicki Chiu
p. 24: Courtesy of Richard Muller
p. 26: Dick White and staff of Berkeley Micro-laboratory
pp. 27–28, 31: Vicki Chiu
Inside back cover: Image courtesy of CO Architects

Contact
engenious@caltech.edu

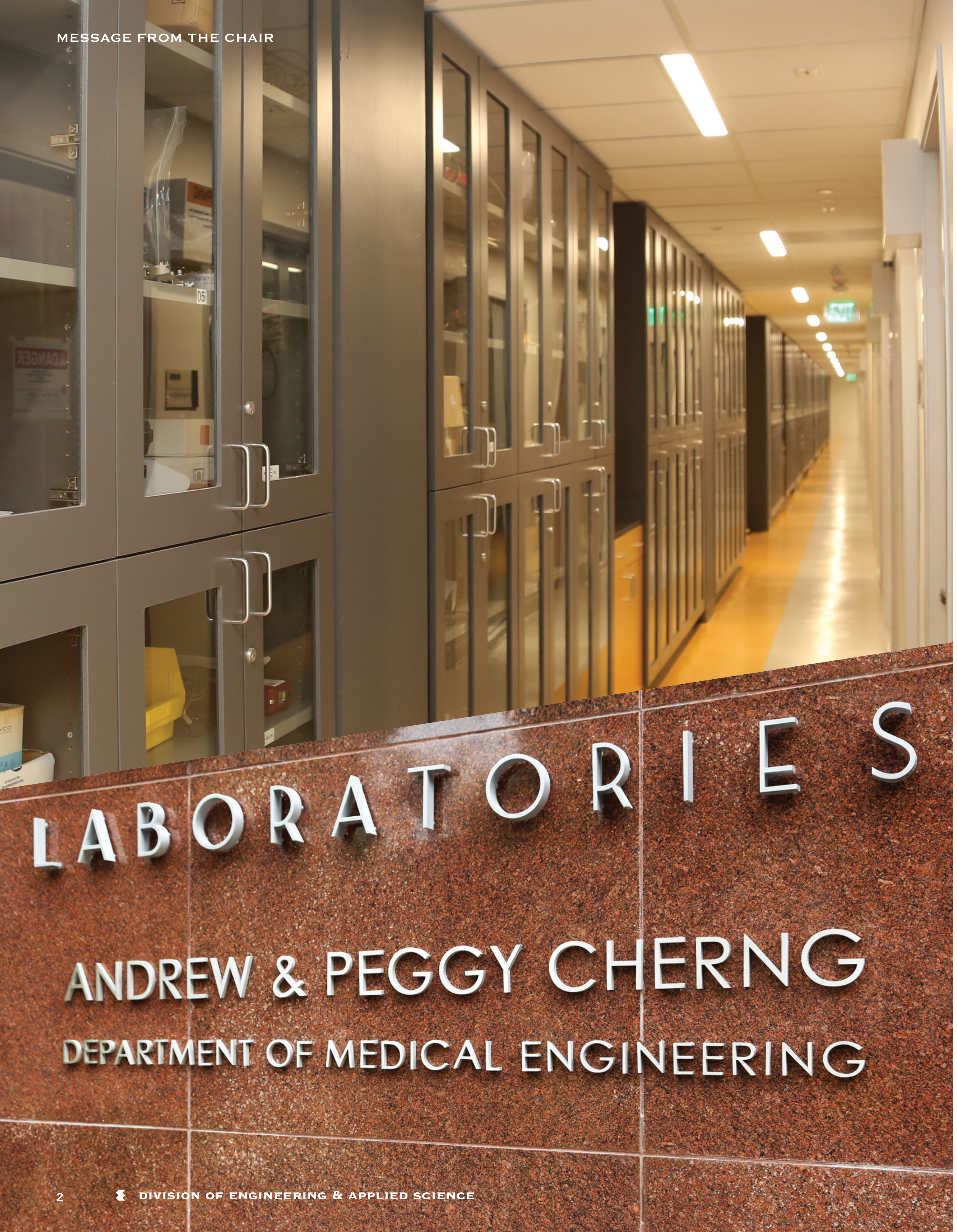
ENGenious

ISSUE 14, 2017

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.



The concept of resilient megacities is one of five current research thrusts identified by the Chair of Caltech's Division of Engineering and Applied Science. Caltech researchers featured in this issue of *ENGenious* are investigating the challenges that arise in the layered and interconnected systems of infrastructure, energy, and communications that characterize megacities such as Los Angeles. They are also working on interdisciplinary solutions to minimize disruptions during a disaster and to make megacities more sustainable overall.



MESSAGE FROM THE CHAIR

Dear alumni and friends of the Division,

Break Through, publicly launched just over a year ago, is already the most successful campaign in Caltech's history. In the first year of the public phase alone, gifts exceeded $400 million. And total contributions—over $1.4 billion—have surpassed the goal of Caltech's last campaign.

The support from our friends and alumni has been very strong and, as a consequence, the EAS Division has received several extraordinary gifts. Walter (MS '82) and Marcia Kortschak have established the Kortschak Scholars in Computing and Mathematical Sciences Fund, which endows up to 10 graduate fellowships annually. This fund is designed to support students during their first two years at Caltech and allow them the utmost flexibility to explore areas of research that are in the earliest stages of development. The Kortschaks' creative vision and generosity offers both a means of continuing to bring the brightest students to Caltech and a way to broaden research forays into high-risk, high-reward areas that do not always benefit from traditional funding sources.

Also sustaining the Division's continual venture into uncharted territory is the endowment of the Mechanical and Civil Engineering Leadership Chair by Cecil (BS '50) and Sally Drinkward. In an interview with *ENGenious* last year, Cecil Drinkward succinctly described his vision for the future of civil engineering: "We need to be able to—and willing to—think out of the box when training the next generation of civil engineers." And to this end, the leadership chair established by the Drinkwards will provide funds in perpetuity to support educational and research initiatives that push boundaries and build on new ideas. His legacy will reverberate through generations of faculty and students.

Finally, I am delighted and honored to announce that, for the first time, a department at Caltech has been endowed. The Division of Engineering and Applied Science has become home to the Andrew and Peggy Cherng Department of Medical Engineering. The Cherngs' gift is congruent with their commitment to "paying it forward" to improve the quality of life for people in their community and around the globe. As Peggy Cherng explained, "We are here to build the American dream, but not just for us." This gift allows EAS to build upon the transformational research and educational approaches already under way and seed future breakthroughs in medical technologies that will have worldwide impact. The Division's distinct advantage in this area is that we are able to apply our unique and deep-rooted strength in micro/nano-devices and optical imaging to address medical challenges. "From Bench to Bedside: New Paths, Sharper Resolution, Inventive Devices" reviews recent work in medical engineering by four faculty actively working in these fields.

The global perspective is driving research across the Division. Within the last few decades, we have seen and will continue to witness increasing urbanization worldwide and the formation of more megacities with populations exceeding 10 million: 31 as of 2016 and 41 projected by 2030. The complex challenges that these megacities face in the areas of physical and digital infrastructure, transportation, and recovery from disaster have inspired new research directions for many of our engineering faculty. "Making Megacities Resilient (Starting with Los Angeles)" describes some of these efforts.

The future of information and communications is explored in this issue of *ENGenious* by way of describing advances in quantum engineering, an emerging area in which our collaboration with exceptional quantum physicists gives us a distinct edge. EAS quantum engineers rely on the tools and campus-wide research community of the Kavli Nanoscience Institute, which provides state-of-the-art facilities for exploration of quantum phenomena in exquisite detail. "Quantum Engineering: A New Frontier" delves into the work of several leaders in this field—a field that is poised to entangle, reroute thinking, and deeply transform myriad technologies for future generations.

EAS alumni have experienced firsthand the extraordinary community of scholars that defines Caltech: a collection of students and postdoctoral scholars who come from cities across the country and countries around the globe. No matter the path our scholars take to arrive, or what path they might forge after they leave, it is essential that in addition to their outstanding technical ability, they are able to effectively communicate their ideas, discoveries, and innovations. Communication is one of the essential skills possessed by leaders, as well as the ability to tolerate ambiguity and deal with crises. Our students are excellent problem solvers, and when they extend their problem-solving gifts to the areas of communication and interpersonal relationships, they are poised to become great leaders in their communities. Two such leaders in academia and industry, Richard Muller and Dan O'Dowd, are profiled in this issue.

I wish you the greatest success personally and professionally, and, as always, I look forward to receiving your thoughts and comments.

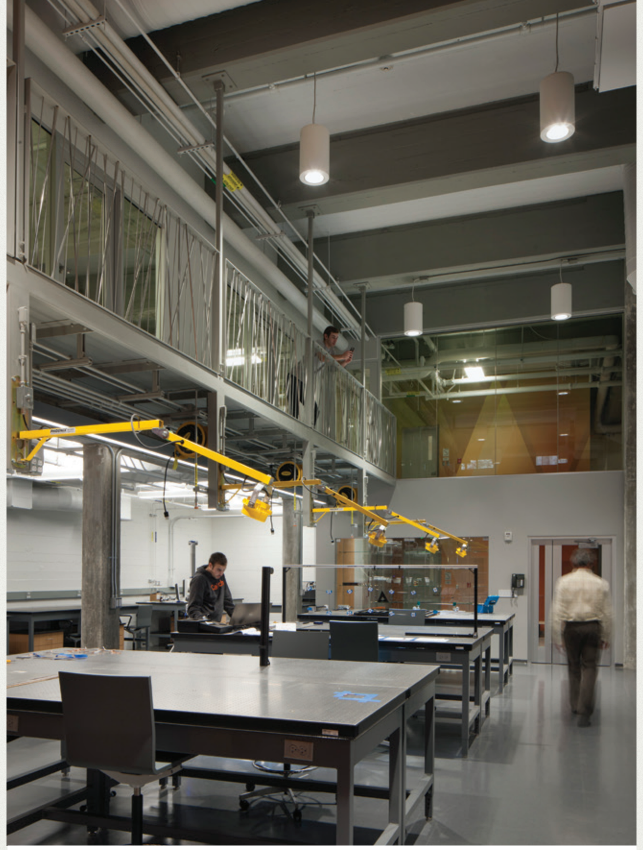
G. Ravichandran

Guruswami Ravichandran
Otis Booth Leadership Chair, Division of Engineering and Applied Science

Effective Communication Strategies for Engineers and Scientists

In response to graduate student need and with faculty support, the EAS Division Director of Communications, Trity Pourbahrami, and Christina Birch, STEM Writing Specialist in the Hixon Writing Center and Lecturer of Engineering, taught two pilot communication workshops for EAS graduate students in February and April of 2017. The workshops were designed to improve students' abilities to showcase their field expertise and to deepen their understanding of communication tools and techniques. The students learned how to align the message of their research with specific audiences and their strategic communication goals. They had the opportunity to create strong visual aids to communicate their core scientific and engineering messages. In addition, they gave presentations and received peer feedback, incorporated this feedback into their presentations, and set new personal goals. The responses of students and faculty to the workshops were very positive, and a new EAS course will be offered in the winter term (E111, Effective Communication Strategies for Engineers and Scientists). Students taking the course will explore scientific storytelling through the following communication genres: research manuscripts, abstracts, and proposals; figures, slide decks, and oral presentations; and traditional and social media channels.

EAS graduate students attending a communication workshop



New Space for Space Solar Power Project

The 22-foot-deep basement of the Kármán Laboratory, which originally contained two-story water tunnels, has been redesigned to meet the needs of the Space Solar Power Project (SSPP). The project was conceived by Professors Harry Atwater, Ali Hajimiri, and Sergio Pellegrino and is aimed at developing the scientific and technological innovations necessary to enable a space-based solar power system consisting of high-efficiency photovoltaics, an integrated power conversion system, and a phased-array system to distribute power dynamically, all mounted on ultralight deployable space structures. The new space was designed by CO Architects for the research team developing the deployable space structures. The two-story height of the space allows the team to assemble the various components created in the cleanroom and wet chemistry laboratory. Movable tables, light fixtures, and retractable electrical cord reels enable the space to be easily reconfigured for the construction of large test pieces. The structures integration area is organized around a sequence of activities transitioning from dirty to clean, and it contains the first three-wavelength laser cutter installed on the West Coast of the United States. The existing service mezzanine was repurposed to house new offices for graduate students that are accessed from a catwalk overlooking the integration area.

Former Congressman Mentors Future High-Tech Entrepreneurs

During the spring term, Ed Zschau, a former congressman who represented Silicon Valley in the 1980s, offered the Caltech course E102: Scientific & Technology Entrepreneurship for 26 Caltech students. This course was designed to introduce students to the analyses and actions required to launch a successful high-tech company. Specifically, it provided approaches for evaluating new technologies and business ideas for commercial feasibility, determining how best to implement those ideas, attracting the resources needed to start a new venture, selecting appropriate business models, refining products and plans based on prospective customer interactions, structuring and negotiating important business relationships, attracting customers or users, and managing early-stage companies toward "launch velocity." Professor Zschau brought to the course his 20 years of experience in heading startup companies (and a major IBM division in the 1990s) as well as his 20 years of offering similar courses at the Harvard Business School and in the engineering schools at Princeton University and the University of Nevada, Reno.

Former congressman Ed Zschau at his seat on the House Foreign Affairs Committee

Understanding the Brain on a Computational Basis

Thirty-five years ago, three Caltech professors joined forces to co-teach a new course called Physics of Computation, which aimed to identify and explore the fundamental laws of computation. Richard Feynman wanted to know, "Is it possible to build computers that use the laws of quantum mechanics to compute?" while Carver Mead was curious about "What's the 'right' way to implement computation in silicon?" and "Can we learn anything useful from biology?" John Hopfield posed the questions, "How does the brain compute? How does it remember? How does it learn from experience?" Their innovative approach gave rise to a vibrant community of scholars and a new field called Computation and Neural Systems (CNS). The Caltech PhD program in CNS began in 1986 and continues to challenge students to understand the brain on a computational basis and to draw inspiration from biology to design autonomous intelligent machines. Faculty, alumni, and friends of the CNS program came to Caltech in August 2017 to celebrate their 30-year history and consider the future. Professor Pietro Perona proposed that the CNS community's main future challenge is to investigate the interconnections between the scientific fields of brain and behavior and the engineering fields related to intelligent autonomous machines. To learn more about the CNS degree program, visit *cns.caltech.edu*.

Athanassios (Thanos) Siapas, Pietro Perona, Christof Koch, and Carver Mead at the 30-year celebration for CNS

New Faculty

To learn more about our new faculty's research and accomplishments, visit eas.caltech.edu/people.

Animashree (Anima) Anandkumar

Bren Professor of Computing and Mathematical Sciences

Anima Anandkumar's research interests are in the areas of large-scale machine learning, non-convex optimization, and high-dimensional statistics. She has spearheaded the development and analysis of tensor algorithms for machine learning. Tensors are multi-dimensional extensions of matrices and can encode higher-order relationships in data. More generally, she has investigated efficient techniques to speed up non-convex optimization in high dimensions. At Amazon, she has worked on the practical aspects of deploying machine learning at scale on the cloud infrastructure.

Anandkumar received her BTech in electrical engineering from Indian Institute of Technology Madras and her PhD from Cornell University. She was a postdoctoral researcher at the Massachusetts Institute of Technology, an assistant professor at the University of California, Irvine, a visiting researcher at Microsoft Research New England, and a principal scientist at Amazon Web Services.

Wei Gao

Assistant Professor of Medical Engineering

Wei Gao's primary research interest is in the development of novel bioelectronic devices for personalized and precision medicine. These devices include wearable and flexible biosensors that can analyze the various biomarkers in body fluids for real-time, continuous health monitoring and early diagnosis; wearable therapeutic devices for self-administered treatment through closed-loop sensing and therapeutic systems; and synthetic nanorobots for rapid drug delivery and precision surgery inside the human body. His research thrusts include fundamental materials innovations as well as practical device and system-level applications in translational medicine.

Gao received his BS in mechanical engineering from Huazhong University of Science and Technology and his MS in precision instruments from Tsinghua University, China. He obtained his PhD in chemical engineering from the University of California, San Diego. He was a postdoctoral fellow in the Department of Electrical Engineering and Computer Sciences at the University of California, Berkeley, before joining the Caltech medical engineering faculty.

Moore Scholars

The Moore Distinguished Scholar 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. Visit eas.caltech.edu/people/moorescholars.

Basile Audoly

Research Director at the French National Center for Scientific Research (CNRS) and Associate Professor at École Polytechnique

Basile Audoly's research focuses on non-linear mechanics—in particular, on the mathematical and numerical analysis of structures undergoing large displacement. Currently, he is developing one-dimensional models to analyze phenomena such as the buckling of viscous jets, pattern selection in biological structures, and the sudden collapse of thin elastic structures. For various systems, his mathematical analyses have offered original explanations for intriguing behaviors reported in experiments, and he has developed widely adopted efficient numerical methods for slender deformable objects.

He graduated in mathematics and physics from École Normale Supérieure in Paris and obtained his PhD from the statistical physics laboratory at École Normale. He holds a senior researcher position at CNRS and is a member of d'Alembert Institute of mechanics at the Université Pierre et Marie Curie and the laboratory of solid mechanics at École Polytechnique.

Vahid Tarokh

Perkins Professor of Applied Mathematics and Vinton Hayes Senior Research Fellow of Electrical Engineering, Harvard University

Vahid Tarokh's research focuses on statistical signal processing, pseudo-randomness, free probability, aspects of model matching, prediction of multi-regime processes, rare events prediction, and limits of learning. He also has interests in limited communications control, signal processing for biology, applications of extreme value theory to scheduling, radar, sequence design, and applications of number theory to the design of distributed interferometric arrays. He obtained his MS in mathematics from the University of Windsor in Canada and his PhD in electrical engineering from the University of Waterloo in Canada. He has worked at AT&T Labs–Research as a principal member of technical staff and as the head of the Department of Wireless Communications and Signal Processing. He was an associate professor of electrical engineering at the Massachusetts Institute of Technology before joining the Harvard University faculty.

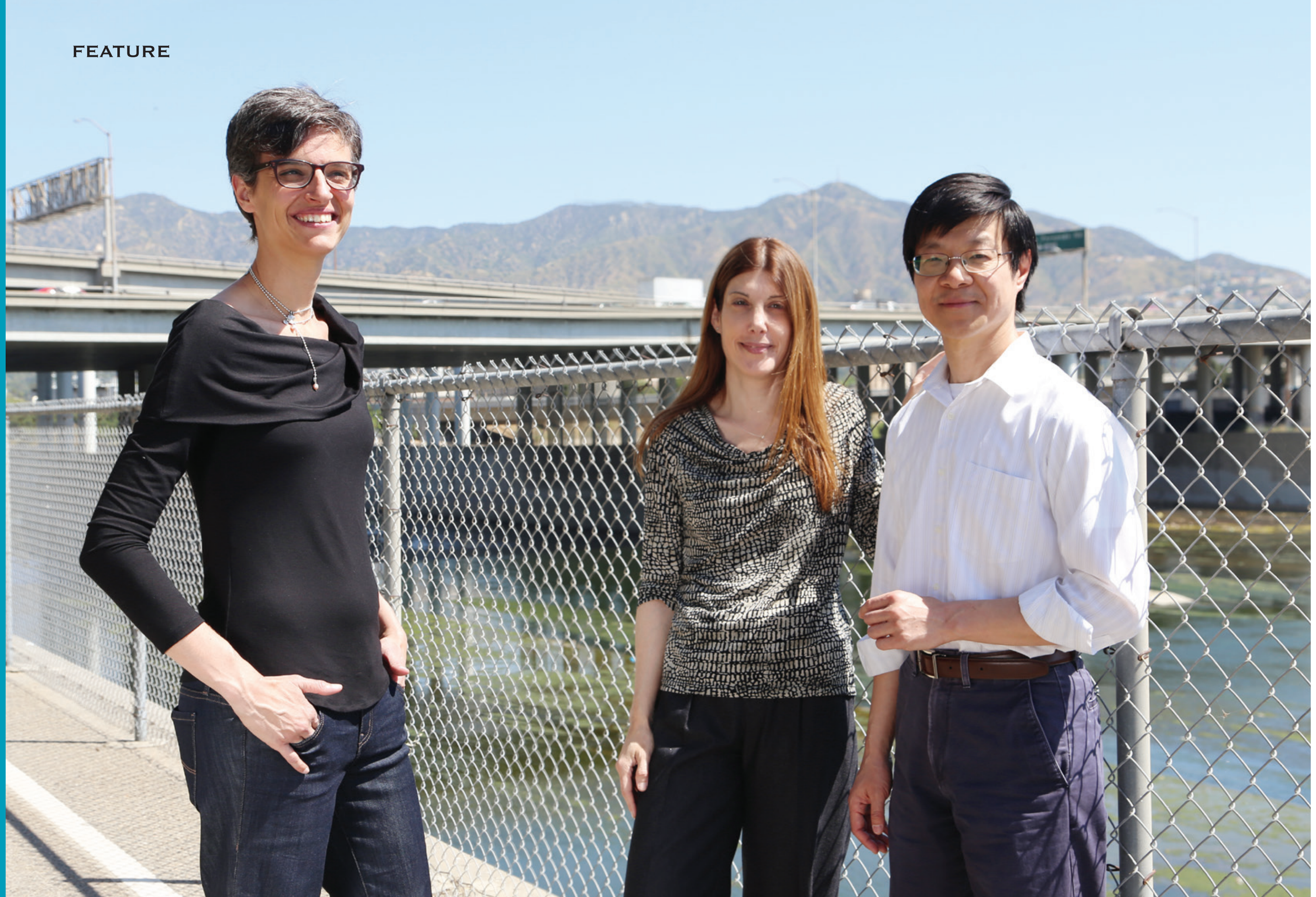
Making Megacities Resilient

(Starting with Los Angeles)

Resilience is the capacity to endure and recover from stress, to bend and not break. Caltech engineers and scientists have a long track record of studying the resilience of materials and structures, from geological strata to material alloys. The Division of Engineering and Applied Science (EAS) has decided to further build on this body of research by identifying "resilient megacities" as one of five future research thrusts.

ENGenious brought three faculty members from different EAS disciplines together for a discussion about attempts to quantify and improve the resilience of megacities and to create—specifically in the context of Los Angeles—design strategies and tools that can make megacities more resilient without ignoring other important factors, such as sustainability.

Megacities are a trademark of the twenty-first century, as more and more activities, structures, and people concentrate in relatively few spots around the world. Over 30 cities worldwide now have populations that



Chiara Daraio, Domniki Asimaki, and Steven Low by the Los Angeles River

surpass 10 million people, including Greater Los Angeles, with more than 18 million.

Even in the developed world, however, these concentrated urban areas are plagued with problems of infrastructure arising from their original planning, which was intended to cover the needs of a city population 100 years ago and did not include strategic plans for expansion, monitoring, retrofit, or repairs to the network infrastructure. Deeper problems thus loom for the future. This is particularly true for megacities located in active earthquake zones, like Los Angeles, but nearby oceans and mountain and rivers can also be threats. Such places may be plagued with problems of infrastructure—critical systems of transportation, communication, power, and water, oil, and gas distribution are prone to interruption, and more major disruption would have serious consequences.

"Despite the advancements in construction methods and materials," says Professor of Mechanical and Civil Engineering Domniki Asimaki, "people are more vulnerable to hazards today than they were before because of population concentration, reliance on data and electricity, as well as the coupling of all infrastructure systems that comprise modern urban centers."

In Los Angeles, the realization has been dawning that with new engineering and communication tools, at least some of these worries can be abated. This dialogue, focused on making Los Angeles not just a megacity but a smarter megacity, is beginning to broaden in important ways. The city of Los Angeles has a resilience task force, headed by a chief resilience officer, urban planner Marissa Aho. Aho is at work developing a Resilience Assessment Overlay, seeking to reduce the vulnerability of the entire immense Los Angeles complex—underground, offshore, electrical and digital, structures and systems—and make it both more resilient and more sustainable, in the context of public planning and expenditure.

"The Overlay," according to Asimaki, "is an effort to prioritize spending for public infrastructure (pipelines, buildings, communication network components) so that in the occurrence of the next big earthquake, human and economic loss will be minimized, and the city will have improved its capability to pick up and start functioning again." Her definition of resilience, in terms of megacity planning and growth, is ambitious but vital: "A resilient system is a system of systems of people and infrastructure and administrations that responds fast during extreme events and recovers rapidly, economically, health-wise and with minimal loss of life."

Asimaki has long been working on a critical area of megacity stress. Her field is geotechnical engineering, computational mechanics, and engineering seismology, dealing with complicated problems involved in estimating the impact of potential earthquakes. The geological formations subject to quakes are very heterogeneous. Even within quite short distances—tens of meters—their physical properties, such as stiffness and strength, can be different. And

Downtown Los Angeles

"We cannot stop the growth of cities, so we have to think about the problem in a completely different way."

Domniki Asimaki, *Professor of Mechanical and Civil Engineering*

> "Los Angeles is a city that embodies all the factors of resilience that we would like to study, from catastrophic contingencies to sustainability requirements. We have earthquakes. We have drought. Los Angeles is also a major port, air travel center, and data hub."
>
> Steven H. Low, *Professor of Computer Science and Electrical Engineering*

consequently, the force transmitted from a quake varies significantly according to the specific composition of material at its focus, the stiffness and strength of the material, and whether it yields gradually to the forces or suddenly breaks. Asimaki has been using her techniques for probing earthquake effects on shallow geologic features, and the impact of these effects on the built environment, to create a resilience atlas of Greater Los Angeles.

Asimaki's work has been part of the evolution of the field of earthquake engineering, which, she says, "was born here at Caltech, out of seismology." It then grew into an independent field with an emphasis on the study of buildings and bridges and tunnels, and the two fields uncoupled. "Over the years, we lost the common vocabulary," she explains, "and now we're at a point of coming back together and looking at expanding from the individual structure to systems. We're back working together out of necessity to define the hazards and quantify the risks and the impact on the infrastructure systems on the scale of entire cities."

Professor of Mechanical Engineering and Applied Physics Chiara Daraio is also involved in this reunification of the fields. She teaches about resilience of materials in her undergraduate mechanics class (ME 12c). "There's a quantitative definition for modulus of resilience in materials, which is the energy absorbed by a material upon elastic deformation," she says. "The higher the resilience of a material, the more it can recover from large deformations without permanent damage." Similarly, a resilient megacity should be able to recover from increasing stresses, like population growth, environmental or climate changes, and unexpected events, without permanently fracturing the city's infrastructure or damaging its quality of living.

Daraio and her research group study the response of materials to external stimuli, like stresses and temperature, and apply these findings to create new, optimally resilient materials and sensing devices that could be used to monitor infrastructures.

Other members of the EAS faculty are at work on such problems, as well. Professor of Computer Science and Electrical Engineering Steven Low specializes in management of networks, both power systems distributing electricity and the Internet and other communication services. These networks are vulnerable to disruption, from hardware destruction to cyber-physical attacks or simple congestion, even in the absence of earthquakes or other major stress events.

"A city comprises interacting systems of critical infrastructures, organizations, communities, and people," says Low. "A resilient megacity not only minimizes the impact of a disruption to human life, the economy, and the infrastructures but must also heal itself. Our current infrastructures are often developed organically without such foresight, and, as a result, a failure in one infrastructure can cascade into another. For instance, an earthquake can bring down part of the power grid, which may cause a disruption of the water distribution system, shutting down pumped hydro energy storage and potentially causing a blackout or brownout. Failures can be quickly amplified throughout the megacity."

The earthquake situation applies, almost by definition, to events compressed into a narrow time scale. But the researchers say that resilience can be a valuable goal even at much, much longer time scales—over the life of cities.

Therefore, as Daraio explains, aging infrastructure such as crumbling roads, collapsing bridges, leaking pipelines, and failing water systems must be part of resilience planning. "There must be either redundancy or some alternative plan ready—a flexible emergency response–type plan that effectively reacts to local failures in these systems," she says.

Low notes that one key to developing this type of resiliency is an evolving understanding of how to coordinate or unify the disparate elements involved. "In the past, different components were more separated," he says, but "today the connectivity among data, operations, controls, and optimization is more developed. So not immediately but conceivably, the whole complex system can act like one when it is needed." He is not talking about a city that is all centrally controlled or centrally managed: "The resiliency structure can be distributed yet coordinated so that the entire system can react as a coherent whole."

Creating such a distributed response system requires consideration of elements that are not strictly engineering concerns, says Daraio. "Engineering can improve the building technology and controls of infrastructures, for example, by introducing new materials and distributed sensor networks that actively monitor performances," she explains. "But acquiring data alone is not enough, as the data must be used to coordinate a response to the events monitored. To be able to properly respond, a combination of engineering and social sciences is necessary. Translating the infrastructure performance of a system delivering a service involves policy and community well-being, which go hand in hand with economic and social factors. Along with concerns for sustainability."

Asimaki provides an example of how different kinds of vulnerabilities demand different resilience postures. "Let's say an earthquake happens," she says. "There's debris and then reconstruction, so there will be an additional carbon footprint to build new buildings, which harms the environment." But this is partly due to poor preparation: "If the performance of the structure were better and there wasn't catastrophic collapse, we would not have to do so much to disrupt the natural environment following the disaster."

The reality of developing resilience can be much more complicated, as is now being seen in the Sacramento delta and on the coast. "We are trying to protect the waterfront and its human inhabitants from floods or sea-level rise, so we create additional manmade structures to protect the coastal cities from hurricanes or floods or from sea level rise," Asimaki says. "But by doing this, we increase the hazard of floods, and we harm the wetlands, all of which have potential negative impacts."

It's a very complex problem. She goes on: "We can't just increase the number of performance sensors or just make the control systems more efficient. There is a dependency on constructing and over-densifying population into megacities. This is further complicated because we cannot stop the growth of cities, so we have to think about the problem in a completely different way. Making individual structures resilient to earthquakes is not adequate if it's not followed by a resilience plan of infrastructure systems that impact the performance of groups of such structures, a resilience plan that accounts for the interdependency of these systems, a mitigation and emergency response plan that spans entire urban centers, and an education and outreach plan to teach the public how to prepare and respond when the Big One happens."

Low's specialty, power and networks, involves somewhat different tradeoffs on resilience and sustainability, including cases where the two goals coincide—when an emphasis on resilience can also be beneficial for sustainability. Giant centralized power plants, either fossil fueled or nuclear or hydro, that still generate about two-thirds of our electricity, are almost by definition barriers to resilience. If one plant is knocked out, the whole system is disturbed, and if two are knocked out, stability of the whole system will be threatened. "But new systems of distributed wind and solar power with backed-up batteries can distribute the vulnerability," he points out, "creating both a more sustainable and a more resilient generation infrastructure." For instance, Low says, "with local generation and storage, blackouts can be avoided in many places for weeks and months," even after severe damages. "There may be areas where resilience and sustainability conflict, but this is where I think we can achieve both." By understanding such conflicts in advance, he adds, adjustments can be made: "If we connect all sorts of data, then we can understand a lot more about the city as a whole and how the different pieces interact."

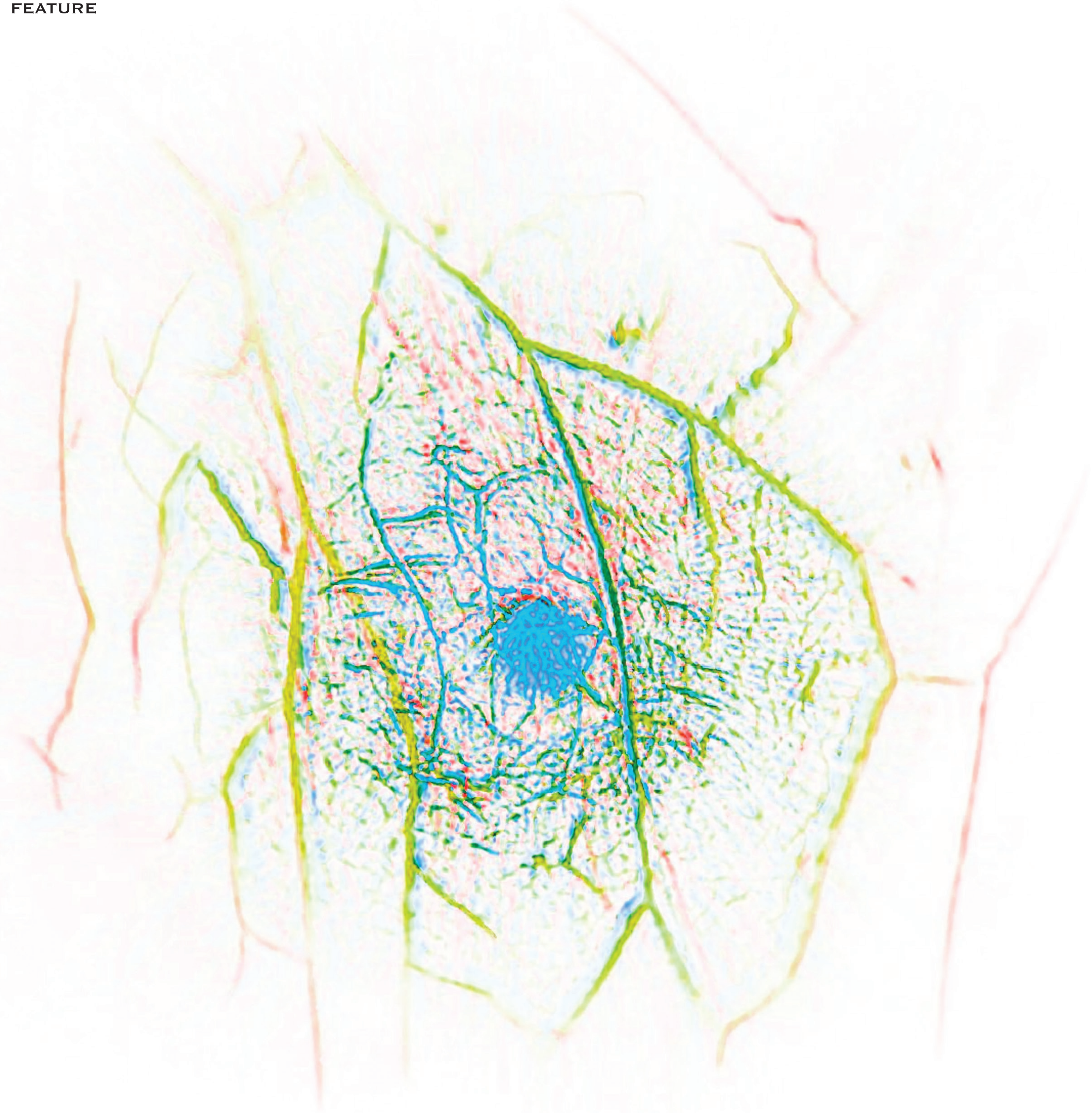
It's key, the researchers say, that the government of Los Angeles and its surroundings now seem aware of the critical need to grow in a better way. The establishment of an office of resilience and a resilience officer may not seem revolutionary, but these are steps in the right direction, integrating social science and engineering planning in essential ways.

Moving forward, the engineering faculty agree that Caltech is uniquely equipped to help make Southern California a prototype of smart urban planning. Caltech's interdisciplinary environment and its low barriers to collaboration allow them to be innovative and disruptive in their approaches. Their focus on fundamentals and insistence on rigor will allow these researchers to help tackle the most complex challenges that the planners of resilient megacities of the future must overcome.

"Los Angeles is a city that embodies all the factors of resilience that we would like to study, from catastrophic contingencies to sustainability requirements," says Low. "We have earthquakes. We have drought. Los Angeles is also a major port, air travel center, and data hub."

It's critical, then, that "Los Angeles, with its resilience task force and other initiatives, is the first city in the U.S. that's making resilience a design goal," adds Asimaki. This, combined with the strategic decision of the EAS Division to focus on this area of research, has made this the perfect time and place to explore our city's capacity to endure and recover from stress—to bend and not break. E N G

Domniki Asimaki is Professor of Mechanical and Civil Engineering. Chiara Daraio is Professor of Mechanical Engineering and Applied Physics. Steven H. Low is Professor of Computer Science and Electrical Engineering.



Photoacoustic computed tomography of a healthy human breast acquired *in vivo* within a single-breath hold without using any harmful ionizing radiation or contrast agent. This new technology can image blood vessels as small as a few times the diameter of a human hair, outperforming all other imaging technologies. The initial clinical testing has successfully identified all breast tumors imaged. Color here encodes depth.

FEATURE

From Bench to Bedside

New Paths, Sharper Resolution, Inventive Devices

The interwoven, interdisciplinary culture of Caltech has inspired two significant gifts that are elevating and intensifying biological and medical engineering research across campus. Andrew and Peggy Cherng have endowed the medical engineering department in the Division of Engineering and Applied Science, and Tianqiao and Chrissy Chen have endowed the Chen Institute for Neuroscience, which finds its home in the Division of Biology and Biological Engineering. The prescience and generosity of these donors is matched only by the insight and creativity of Caltech's faculty—and here we explore several connections and horizons that mark a new period of research at Caltech that brings together biologists, engineers, chemists, computer scientists, social scientists, and physicists in pursuit of revolutionary advances in health and human welfare.

Involving faculty from across the university's six academic divisions, the Chen Institute for Neuroscience at Caltech will catalyze a campus-wide interdisciplinary community with the shared goal of understanding the fundamental principles that underlie brain function. "Everything that we are as human beings—our ability to see the world and ask questions about our universe—is rooted in the structure and function of our brains," remarked Steve Mayo (PhD '87), the Bren Professor of Biology and Chemistry and the William K. Bowes Jr. Leadership Chair of the Division of Biology and Biological Engineering, upon the establishment of the Tianqiao and Chrissy Chen Institute for Neuroscience. "One of the greatest challenges and opportunities of our time is to be able to unlock that structure and how it relates to function, which will have an enormous impact on the lives of real people." Similarly, "the endowment of the Andrew and Peggy Cherng Department of Medical Engineering draws upon the expertise of faculty members across all engineering and science disciplines to bring innovative, non-invasive, and smarter medical devices to patients," says Guruswami Ravichandran, Caltech's Otis Booth Leadership Chair in EAS and the John E. Goode, Jr., Professor of Aerospace and Mechanical Engineering.

ENGenious spoke with four Caltech faculty members to learn about the passions and forces that are enhancing their work and driving them forward. Each anticipates that the combination of an unprecedented inventory of intellectual and technological resources, the excellence of Caltech students and postdoctoral scholars, and the academic freedom afforded by the Chen and Cherng infusions will yield exponential growth for their research.

Morteza Gharib, Viviana Gradinaru, and Lihong Wang

Viviana Gradinaru (BS ’05), Assistant Professor of Biology and Biological Engineering, Heritage Medical Research Institute Investigator, and Director of the Center for Molecular and Cellular Neuroscience in the Chen Institute for Neuroscience, investigates mechanisms underlying neurodegeneration and develops tools and methods for use in neuroscience. “We live in an unprecedented time, where the speed of basic discoveries has been accelerated,” she says. “We are sitting on fundamental knowledge and have a duty to transfer it to benefit human health in terms of sensing diseases, monitoring progression, and eventually coping with the symptoms or even treating the disorders.”

Gradinaru’s lab exemplifies this approach. “As part of our neuroscience work in trying to understand how deep brain stimulation works, we found that detailed maps of neural paths were lacking,” she explains. “Brain circuits are comprised of very fine projections that are severed in the standard process of sectioning tissue into paper-thin slices to gain optical access. To bypass this problem, we worked on a method of tissue clearing by removing the lipids that scatter light within the tissue. The result is a transparent organ that becomes a tool to solve problems that have to do with disease, drug screening, and the effect of therapies on tissue. Thus, the techniques that we developed to figure out challenges in basic neuroscience are now a technology that can help with tissue pathology and screening for medical engineering purposes.”

There is a recognition among Caltech’s faculty that progress in human health requires scientists and engineers from a wide spectrum of disciplines to attack complex challenges and cross-pollinate ideas. The Cherng Department of Medical Engineering and the Chen Institute for Neuroscience are both dedicated to this approach. Morteza Gharib, Hans W. Liepmann Professor of Aeronautics and Bioinspired Engineering, puts it this way: “What medical and biological engineering provide are venues for researchers from biology, engineering, and information science to work on areas that can go from the lab to the bedside.” For example, Gharib’s research on the cardiovascular system is applied to new generations of heart valves and monitoring devices that unify multiple vital indices in a single blood-pressure reading in real time. When combined with the expertise of his colleagues in electrical engineering and materials science who share his interest in miniaturizing devices, there emerges the possibility of new monitoring and imaging accessories that can increase both the quality and accessibility of valuable metrics for patients and clinicians.

Medical problems present profound challenges that are ideal for Caltech biologists, chemists, and engineers to tackle together. Gharib is a case in point. “I am a rocket scientist with a PhD in aerospace, and I’m very interested in fluid dynamics,” he explains. “I see life as aquatic, and therefore fluid dynamics plays a big role in it. We are small enough to be a real interdisciplinary institution. This approach provides us a significant cushion in the face of being afraid to fail. I can be bold, to the point of taking on what others consider too risky, because I know I can get there with my colleagues, our students and postdocs, and the Caltech level of excellence and resources.”

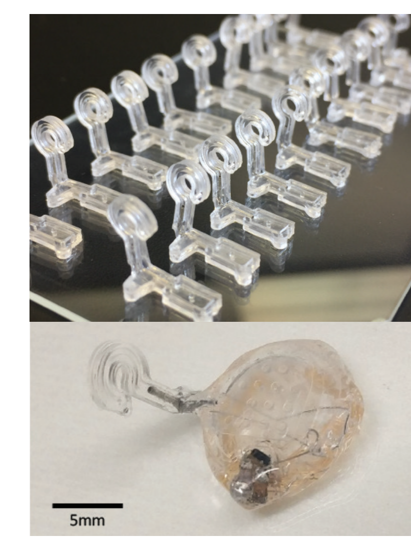
“We are small enough to be a real interdisciplinary institution. This approach provides us a significant cushion in the face of being afraid to fail. I can be bold, to the point of taking on what others consider too risky, because I know I can get there with my colleagues, our students and postdocs, and the Caltech level of excellence and resources.”

Morteza Gharib, *Hans W. Liepmann Professor of Aeronautics and Bioinspired Engineering; Director, Graduate Aerospace Laboratories; Director, Center for Autonomous Systems and Technologies*

Lihong Wang, Bren Professor of Medical Engineering and Electrical Engineering, adds that Caltech’s stature attracts the best students and postdocs, drawing talent from all over the world to help push this kind of leading-edge work forward. “When we combine the strength of our world-class lab members with the number of nearby first-rate medical institutions, we have no shortage of research ideas or clinical collaboration. This combination presents a tremendous opportunity for biological and medical engineering at Caltech.”

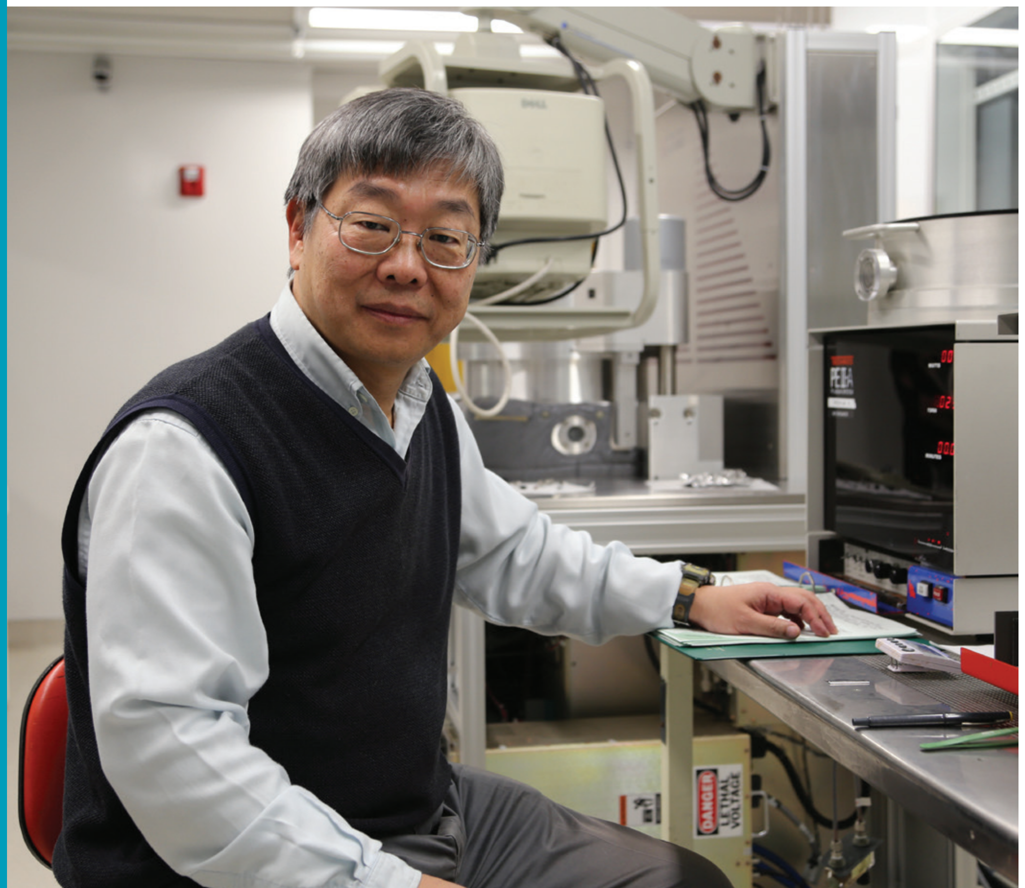
“We are earning our name based on the successful approaches we already have in place that solve really difficult problems and incorporate new technology,” says Yu-Chong Tai, Anna L. Rosen Professor of Electrical Engineering and Mechanical Engineering and the Executive Officer of the Cherng Department of Medical Engineering. “Chronic diseases are costly; Caltech engineers can help by making the future of medical technology smaller, cheaper, and better.”

Trained in electrical and mechanical engineering, Tai is a self-described electromechanical engineer who makes small gadgets that target the four major causes of blindness: cataracts, glaucoma, macular disease, and diabetic retinopathy. He is also working on catheter-tip-sized diagnostic devices that can probe the heart to analyze plaque. Continuing to push boundaries, he is aiming to develop “non-invasive diagnostics and sensors that draw on electrical engineering and electromagnetism to develop approaches for assessing edema and both ischemic and hemorrhagic strokes. I am also interested



Implantable devices for the treatment of diabetic retinopathy: passive oxytransporters (top) developed by graduate students Nick Scianmarello and Colin Cook (2016) and an active oxygenator (bottom) developed by Nick Scianmarello (2017).

FEATURE



Yu-Chong Tai

in developing drug delivery systems that are wireless and smart." Tai notes that the young researchers he mentors are a critical part of these efforts: "We continue to recruit students and postdocs who are interested in artificial intelligence as it could apply to medicine. I think their influence on devices will change the way we do medicine."

Even the labs themselves, with their impressive infrastructure, contribute to Caltech's frontier status. "There were items that were only on my wish list that are now doable thanks to the setup of Lihong's lab," says Gradinaru. "I can now see the route that is established as blood flows through the brain. Currently we do this postmortem. If we can know how and where blood enters the living brain, then we can get a handle on region specificity, which could be very meaningful to noninvasive delivery of brain therapies." Add to that easy interdisciplinary collaboration, and what you get is potentially global reach. According to Gradinaru, "We're also going to see a huge influence on hardware and software as a result of solving our data problems in medical engineering and engaging our colleagues in data processing."

Caltech's creative interplay of disciplines also reflects the democratization of medicine. Caltech doesn't have a medical school, so it forms partnerships with medical institutions in the region for access to physicians and patients. Gradinaru points to the Caltech–City of Hope collaboration, in particular: "We brought the quantitative engineering excellence of Caltech. They brought the real-world medical applications and the great physicians and scientists of City of Hope. Jointly, we can better influence clinical practice for patients' benefit."

These collaborations are part of Caltech's overall strategy of incorporating the broadest possible range of technical approaches to improving health. "Our mission to improve human health allows for full inclusion. You might not necessarily need to change any biology to do that. Mining behavioral data and developing effective feedback systems can go a long way in guiding patient behavior to a healthier outcome," Gradinaru explains.

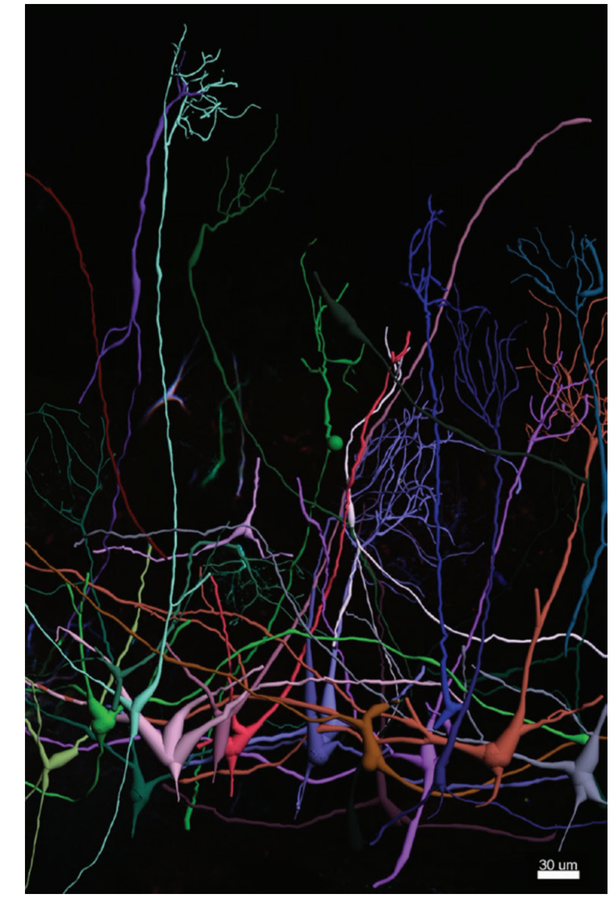
One of the researchers' overarching aims is to make medical technology more affordable and accessible. "Some machines range in cost from 30 to 50 thousand dollars, but all the physician wants to measure is actually something simple, to see if they even need to escalate diagnostics," says Gharib, by way of example. There is a great need for devices that can inexpensively triage patients and do pre-screening. Gharib's research has shown that the flow coming out of the heart can be measured with a $10 device he has prototyped, rather than a $30,000 device currently used in hospitals. This is the kind of progress that Caltech aims to deliver: "It means working smarter, not harder, with our resources, both on the patient side and the delivery side."

Wang sees great potential in such application of new engineering approaches in medicine. "Traditional medicine is really not that quantitative," he says. "With technology, it is becoming more quantitative and therefore more effective. We can hasten the efficacy by injecting the lessons of physics, chemistry, biology, and quantitative science to solve medical problems more fundamentally." In Wang's research, this data-based approach has expanded the range of what doctors can observe happening in the body, from the smallest systems to the largest. "Right now, we are the only lab in the world that provides multiscale *in-vivo* imaging from organelles all the way to whole-body organisms using the same contrast mechanism," says Wang.

Integrated science and first-rate research are hallmark strengths of Caltech, but the exceptional funding from Tianqiao and Chrissy Chen and Andrew and Peggy Cherng provides the essential, stabilizing force that has enabled Caltech to carve out this important niche. "In order to thrive, we need collaborative ecosystems with clear missions," Gradinaru says. "Rather than each lab doing this on the side as peripheral outcomes of our research, what the Chen and Cherng gifts have done is allow us to be explicit. We can identify, assess, target, and work together deliberately to move along faster and smarter. These gifts are catalysts of exponential growth for research already happening across campus."

Gharib believes this to be something these donors recognized instinctively. "They saw that this faculty, these excellent students and postdocs, all they needed was a venue and a start," he says. "Once this free flow of research is started, progress happens—and our students today, and future Caltech students for a long time to come, will be solving medical problems as a result of this momentum."

These gifts are particularly timely, given the current anxiety about continued government funding. Wang stresses that maintaining the Caltech standard, especially with respect to problems that involve such complex systems, is dependent on consistent, significant support. "Our main challenge is having enough resources, which include people, time, and money," he says. "We are all singularities here. We all stand out in our own fields. If we are limited by resources, the synergies weaken and the system starts to underperform. We are not an average institution; we cannot be limited to average resources. The outstanding quality of each individual is maximized by the abundant support of research here. To keep that model alive, we need support."



Neuron morphology in mitral cells of an adult mouse olfactory bulb, shown reconstructed using vector-assisted spectral tracing (VAST), developed in the Gradinaru lab. Neurons are labeled with multiple colors to facilitate morphology tracing.

Gradinaru offers a personal framing of the necessity and impact of funding these efforts. She recalls a trip with her young sons to see the dentist, who told them, "Take good care of these molars, because they're permanent, and you're going to live to be 110." She was struck by the comment. "It hit me. Lifespan has been increasing because of medical advancements, and along the way, this created new needs and opportunities for medical and biological engineering. We're soon going to need better molars." It's the kind of reflection that makes the big picture that much clearer. "One thing is for sure: contributions to the Andrew and Peggy Cherng Department of Medical Engineering and to the Chen Institute for Neuroscience are contributions to our loved ones and ourselves. We are all recipients of these gifts, and we should all participate." ENG

Morteza Gharib is the Hans W. Liepmann Professor of Aeronautics and Bioinspired Engineering, Director of the Graduate Aerospace Laboratories, and Director of the Center for Autonomous Systems and Technologies. Viviana Gradinaru is Assistant Professor of Biology and Biological Engineering, a Heritage Medical Research Institute Investigator, and Director of the Center for Molecular and Cellular Neuroscience. Yu-Chong Tai is the Anna L. Rosen Professor of Electrical Engineering and Mechanical Engineering, the Andrew and Peggy Cherng Medical Engineering Leadership Chair, and the Executive Officer for Medical Engineering. Lihong Wang is the Bren Professor of Medical Engineering and Electrical Engineering.

Visit mede.caltech.edu.

Quantum Engineering

A New Frontier

The evolving field of quantum science, especially as incubated at Caltech, is a defining example of the Institute's commitment to innovation through deep exploration and understanding across disciplines. When Guruswami Ravichandran, Chair of the Division of Engineering and Applied Science, is asked about the future of science and engineering, he focuses on frontier fields such as quantum engineering, where Caltech is a unique catalyst. "The science of things is getting smaller," he says. "We are also seeing a societal need for things to get smaller—and it doesn't get smaller than the quantum scale, which is an area of historic expertise for Caltech." According to Ravichandran, "the marriage of quantum science and engineering has the potential to result in technologies that can revolutionize all aspects of science."

ENGenious sat down with four EAS faculty members who Ravichandran identifies as part of a select group focused on studying the quantum phenomena "in exquisite detail, with an eye to bringing that detail to usefulness. The group spans the whole spectrum, from the most basic science to information theory and quantum information theory to the reality of devices." These four are Oskar Painter, John G Braun Professor of Applied Physics and Fletcher Jones Foundation Co-Director of the Kavli Nanoscience Institute (KNI); Keith Schwab, Professor of Applied Physics; Andrei Faraon, Assistant Professor of Applied Physics and Materials Science; and Thomas Vidick, Associate Professor of Computing and Mathematical Sciences.

These researchers are exploring the root concept of quanta on a scale both vast and minute, enabling and limiting. "What we're really thinking about is fully using all the subtlety that is in nature, as described with quantum mechanics, and trying to extract all the functionality and utility out of that model. This full use of nature—it's what we're after," says Keith Schwab. "We ask ourselves: How does the full quantumness of nature help us do things in the world? How does the physics of these things limit what we can do? Nature doesn't always provide capability. The best-known example is probably the sensitivity of LIGO (the Laser Interferometer Gravitational-Wave Observatory). It is limited by the quantum fluctuations of light. We do this dance with nature, working within all of its capabilities and limitations."

Andrei Faraon goes on to explain that the history of quantum engineering is an evolution from ensemble systems to single quantum states. "In the past, quantum mechanics was used to make devices like lasers, which are an ensemble of quantum objects described in a quantum way," he says. "Now we are entering a new era where we are working with quantumness that is fundamental and singular: single atoms, single photons, or single electrons. We are only now trying to develop devices that use these single quantum objects and single quantum states." This trajectory, with the generation of photonics and laser applications giving rise to the more theoretical frontiers of single quantum states, is evident in the range of the respective disciplines of the researchers brought together in this emerging field.

Oskar Painter, like Faraon, comes from the more traditional area historically referred to as quantum electronics or laser physics. He is excited by the potential that such newcomers as Thomas Vidick have brought to the work as the field has expanded into information science. "Thomas works on the boundary of quantum information science," says Painter. "His work broadens the scope of how we can think about the information of quantum physics. His field has huge potential for communications and the

Clockwise from top left: Oskar Painter, Thomas Vidick, Keith Schwab, and Andrei Faraon way we compute and process information." Then there is the important question of measurement, where Painter sees Keith Schwab's contribution as essential: "Keith represents the key in-between and has worked his whole career to develop new types of measurement techniques and sensors that can rely on some of these very subtle properties of quantum physics that are not represented in the more historical work. This idea of precision measurement and the limitations of measurements helps us do things in a better way."

Discussion of applications in the emerging quantum field requires a long view and a respect for the inherent nature of research in general, according to Painter. "Quantumness is by definition at the forefront of science," he says. "It is the fascinating aspect of the physical world that is completely surprising. It is what we are passionate about. The necessity for an application, however, is cultural and gradual. 'What is it good for? What can you DO with it?' are always the first questions we are asked about our work. One good answer I can offer is, 'When the researchers who developed quantum mechanics in the 1920s and 1930s were posed such questions, they didn't know it would lead to a trillion-dollar industry 70 years in the future.' It is a good example of how long it can take the underlying science of a technological revolution to emerge." Schwab agrees that there is a unique set of challenges to working in a field where the "short term" is defined by a period of about 20 years, and this complicates the question of applications. "What makes it hard is that the fundamental science evolves so rapidly that we are always on shifting ground as to where applications might end up, but it is inherent in our nature as researchers to ask, 'How can I use this thing so I can engineer a solution or provide some function?' Applications come, but often not in any direction we can anticipate or any fixed timeline."

> "If you look at the history of humankind, you have to wait until about 1850 for electricity, cities, and cars to define the first really big evolution for human productivity. Then there were electronics, but since then we haven't had much in the way of advancement in productivity. Quantum engineering could provide that next leap in the productivity of mankind."
>
> Andrei Faraon, *Assistant Professor of Applied Physics and Materials Science*

One can already point to such specific applications and aims as advanced cryptography, ever more precise navigation, and atomic clocks, but Ravichandran and Faraon see the future of quantum studies and quantum engineering as being about enhancing productivity across the board. "If you look at the history of humankind, you have to wait until about 1850 for electricity, cities, and cars to define the first really big evolution for human productivity," says Faraon. "Then there were electronics, but since then we haven't had much in the way of advancement in productivity. Quantum engineering could provide that next leap in the productivity of mankind. There is a lot of physical worth we will extract that will lead to better computing, better understanding of chemistry and materials." Getting to this new practical paradigm in a field so deep in theoretical territory is an exercise in layering—of disciplines and processes.

This is where Schwab predicts the real return on the current quantum computing push will be. He explains, "Money flows to cryptography for strong cultural and political reasons, but the real utility of quantum engineering for computation is going to be small-scale quantum computers that do calculations that classical computation can't do, like simulations of Hamiltonians for material science." Faraon points out that at a deeper level, this idea becomes triage for research and can lead to huge efficiency. "Quantum engineers aim to simulate chemical reactions and capture all the subtleties of their interactions on a relatively fast time scale. Having indications of which reactions are most likely to work on the front end of testing could really narrow down the space and provide excellent focus and rapid progress for research."

On the educational side, says Painter, the emergence of the field of quantum engineering has created a need to expose his students to the many overlapping disciplines that guide the research. "There is a recognition I share with my students that if we're going to understand and build new devices that really take advantage of all the aspects of the quantum world, we need to understand information theory in a way I never understood it. We need to understand measurement in a way I never fully appreciated. My own training would be insufficient for their preparation in the field. More and more, I have to teach specialized classes to get the students the depth and interconnection they need across disciplines to be able to perform cutting-edge quantum research."

The future of quantum research and its application at Caltech is strongly linked to its past, in large part through the history and impact of scientific instrumentation. According to the researchers, LIGO's recent detection and observation of gravitational waves not only increases our understanding of the universe but also demonstrates and advances quantum instrumentation, which has a long history at Caltech. That history very much matters to future generations of students and professors, notes Schwab. "Quantum engineering was happening here before the name existed," he says. "Precision measurements, sensitive instruments, and applied new detection make Caltech unique in the field, and this groundwork lives here. Future scientists can use this foundation to go forward to improve and develop the foundation with singular recognized focus."

> "Quantum engineering was happening here before the name existed. Precision measurements, sensitive instruments, and applied new detection make Caltech unique in the field, and this groundwork lives here."
>
> Keith C. Schwab, *Professor of Applied Physics*

Faraon further underscores Caltech's prominence in many areas of quantum science: "Basically every time I go to write or engage in some collaboration with other people, no matter where it starts, I always end up right back here at Caltech by way of a mutual connection," he says. "And I do mean always." The Kavli Nanoscience Institute (KNI) has enabled much of this prominence in quantum research and instrumentation. According to Faraon, "KNI is a place that can be tailored to the individual needs of the research. It's not a generic cleanroom hoping to cater to everyone. It can be shaped to accommodate the very specific needs of the faculty. It is one of the ways that your voice is truly heard as a Caltech faculty member. That combination of facility and autonomous direction is as good as it gets."

Theorists come to Caltech for that kind of access, says Vidick. "I am a computer scientist, and I'm here because this place is very small and very strong," he explains. "I sit in a computer science department alongside quantum information researchers. There are all kinds of strong physicists around for me to learn from. Caltech is unique in this way. I will bump into people a lot, and these valuable conversations would never happen if I were in a larger institution." Painter adds creativity to the list of Caltech's essential attributes, along with scale and size, saying, "Caltech is unique in its nurturing of creativity in that it gives faculty a lot of room to play. As a result, there is a tendency for our research to spin off and suddenly sprout up elsewhere in some new area for the next generation of engineers."

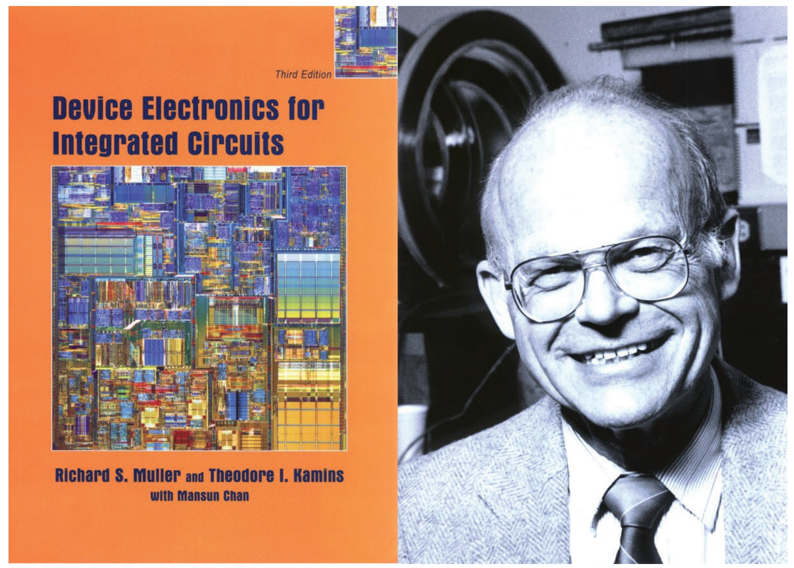
Schwab sees great value in that kind of creativity, as well, pointing to the essential ability of creative scientists to identify the kind of research that is most valuable. "I fully believe that the experiments and theories that are being done at Caltech today are exactly the ones that should be done," he says. "I don't know what will be the most interesting outcome, but the experiments of today in manipulating single quantum elements and working with them is absolutely the right trajectory for the field. If you are the kind of person who wants to strike out into blue sky in quantum science, Caltech is the place for you. It has the financial strength, vision, creativity, and people to meet the challenges unique to frontier science." And Vidick, like Ravichandran, frames that work as vital and necessary because of its potential for societal impact, even if some of that remains theoretical for now, offering a reminder that he and his colleagues "are guided by usefulness all the time. Not in the sense of selling a product, but in the sense that the understanding we build by exploring today's questions positions us to formulate and address tomorrow's challenges. Quantum engineering is a deeply integrated field, and it is in the making at Caltech." ENG

Andrei Faraon is Assistant Professor of Applied Physics and Materials Science. Oskar J. Painter is the John G. Braun Professor of Applied Physics and Physics and Fletcher Jones Foundation Co-Director of the Kavli Nanoscience Institute. Keith C. Schwab is Professor of Applied Physics. Thomas G. Vidick is Associate Professor of Computing and Mathematical Sciences.

ALUMNI PROFILE

A Pioneer and Gifted Teacher

Richard Muller (MS '57 EE, PhD '62 EE) found himself in the midst of the revolution of solid-state electronics in the mid-twentieth century. *ENGenious* sat down with him to find out who at Caltech inspired him to engage with electronics, among all of the possible engineering paths, and how he has shaped the education and lives of generations of engineers.



ENGenious: Who inspired you to become an electrical engineer?

Muller: Many of the Caltech faculty were inspirational role models. Most influential to me was my advisor, Dave Middlebrook. When I began studies for my master's degree at Caltech in 1955, the sources of information about my interest area, solid-state electronics, typically had their origins in research papers written by pioneers in the field. Many of the research papers reported Bell Labs advances and were difficult to place into meaningful context. Through questions and suggestions, Professor Middlebrook helped me to clearly identify what the previous work had shown and, more importantly, what favorable research path might lead to further advances in the area.

Richard Feynman in the physics department was also a big influence. He was a captivating and outgoing man whose intelligence and depth of understanding were inspirational. He was a truly gifted teacher. His teaching helped me see the ways in which electrical engineering rests on strong foundations from physics and mathematics.

Imagine my pleasure in the fortunate pairing of these two role models decades later, when Dave Middlebrook received Caltech's Richard Feynman award for teaching. I am profoundly thankful that I have been taught by these two talented professors.

ENGenious: How has your Caltech education influenced your career?

Muller: Caltech was excellent at cultivating independence in scholarship. In retrospect, I see now that encouraging papers with sole authorship, which was the standard at the time, put candidates in the very important position of finding their own profitable on-target research paths. We had to prove that we could establish relevant research on our own, an approach that is essential to pursuing results that have impact.

This is not to say that Caltech graduate research in the 1950s was a solitary endeavor. Libraries were the socio-academic hubs of campus. You had to know where all of the libraries were, because these were the sites to seek out well-written documents that can serve as role models for budding researchers. Library work might sound like an individual act, but there was a lot of talking and sharing at libraries about who wrote the best solutions and what articles could be of interest.

In my career as a teacher, this practice of collegiate reading and sharing has developed as a lasting influence of my experience at Caltech. It also influenced how I went about writing the teaching text that I co-authored with Ted Kamins, *Device Electronics for Integrated Circuits*, published in 1977. In its third edition and with five translations, *Device Electronics* is still used in teaching today.

ENGenious: Can you give a specific example of that shared book knowledge at Caltech?

Muller: There was the Bone Book, as in "bone up on your studies." Once you went through your qualifying exam, which every graduate student approached as a necessary crisis, you were obligated to write it all down. You wrote about the professors in the room, what the problems were, and how you solved the problems. You then passed the Bone Book on to whomever was most likely to be the next student facing the qualifying exam. These actions were all done in good faith, and the book was a great resource and morale builder. Before your exam, you could look in the Bone Book (in which there were entries dating as far back as the 1930s) and read about the exams taken by dozens of doctoral candidates, some of whom later earned Nobel and other distinguished prizes as well as their Caltech doctorates.

ENGenious: Why and how did you choose an academic career?

Muller: Necessity and then satisfaction, really. In 1957, the University of Southern California (USC) had a teaching emergency. There was an electrical engineering professor who left his post just a few weeks before he was to start teaching a fully enrolled course in solid-state electronics. I had recently finished my master's degree at Caltech while working part-time at Hughes Aircraft in a joint program they had at the time. Hughes was contacted by USC to find a suitable stand-in for their vacancy, and my name was brought up as someone who might be both interested and able to teach the course. I still recall the lengthy evening discussions with Joyce, my new wife, about the pros and cons of taking on the new obligation. She understood better than I that embracing the experience would make it clear to us whether or not we were prepared for a full academic life at a research university. I decided to take the challenge, and within a few weeks I became convinced that an academic life would indeed be appealing for both of us. The course went well, and I was invited to teach it again in the spring. By that time, I had applied for and been awarded a National Science Foundation (NSF) graduate fellowship in support of a doctoral program. I returned to Dave Middlebrook, who enthusiastically agreed to be my advisor and supported my view that laboratory research on the electronic properties of solid materials would provide fruitful paths to advance the field of electronics. In teaching at USC in 1957–58, I had sensed the joy that there is in teaching at the university level, and I became convinced of how right is that age-old saying that "if you become a teacher, by your pupils you'll be taught."

ENGenious: What are the hallmarks of a gifted teacher?

Muller: At the top of the list are clarity in explanation and strong rapport with students. Once students are well known and understood by their professors, the best professors—the ones who have a sincere interest in the research field and who understand the boundaries that constrain its development—can align these boundaries with the goals and motivations of individual students and help further the research. A good advisor will also discern and help remedy shortcomings in performance. For instance, there are many students for whom English is a second language. Good professors will help with language and any remediation that improves the communication of the research.

ENGenious: As a young professor at Berkeley just after Silicon Valley emerged on the map, how did your research and the industry start to interplay?

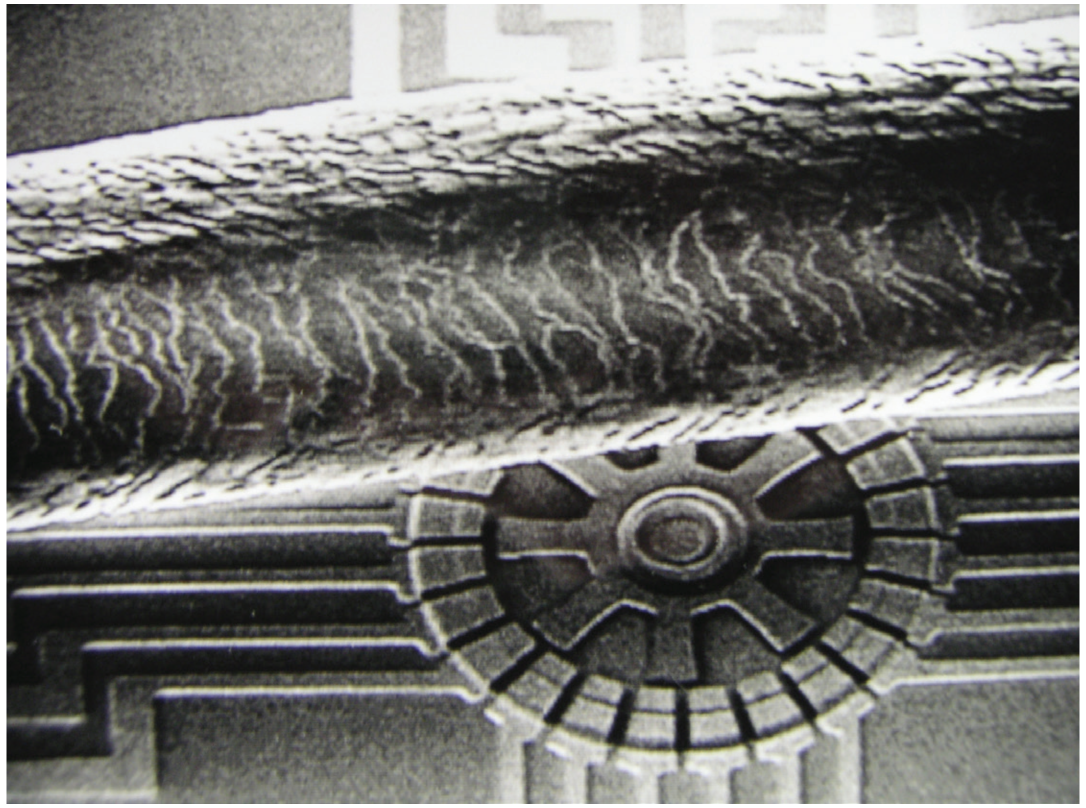
Muller: My mentor at Berkeley, the late Don Pederson, had built up a strong research program in solid-state electronics. My interest in research on the properties of thin films was a welcome addition right at the time that industrial focus on silicon devices and processes had shown strong advantages over deposited thin films. I revised the solid-state course at Berkeley to reflect that shift and made it entirely focus on the physics of device operation and the design of integrated circuits. By the end of the 1960s, it had become apparent that integrated circuits made possible such useful micro-systems that they would force the redesign of many systems in many fields. The link to industries was direct, immediate, and broad.

ENGenious: Was there a pivotal moment in your academic career that related to this revolution to come?

Muller: Yes, and it involves a former student who is now a professor at Caltech. The moment was from the startup phase in our looking at building non-electronic as well as electronic devices using integrated circuit (IC) processes at Berkeley. We fabricated a gas-sensing device in which a ribbon of polycrystalline silicon was formed into a doubly supported beam, coated with an absorbent thick film, and resonated after being actuated by an IC-controlled electric field. This project was Roger Howe's research, and it was followed by a design and demonstration of the first operating micro-motor by Yu-Chong Tai, presently Executive Officer of Medical Engineering at Caltech.

ENGenious: How did that translation start to happen at the practical level, moving from academic lab to industry?

Muller: From Don Pederson, I learned the art of pruning. Strongly supporting the enlightened adaptation of concepts, materials, and new ideas is what brings progress to research, but creative engineering is also about retiring less-rewarding ideas and projects in order to spearhead progress.



MEMS motor and hair

Realizing the impact of the developments of integrated circuits, my research group shifted focus from developing better electronic devices to designing micro-devices that could sense and interact with nonelectric variables such as force, pressure, and photons. That first micro-motor and other devices like it called out for a place to house the partnerships and entrepreneurial applications of the lab work. To fill this need, a colleague, Dick White, and I founded the Berkeley Sensor & Actuator Center (BSAC) in 1986, with the support of NSF and five industrial sponsors.

A breakthrough achievement occurred in the early years of BSAC when an industrial sponsor (Analog Devices, which had joined while Analog was solely an IC manufacturer) applied the BSAC-invented poly-Si mechanical-device processing to produce a breakthrough accelerometer for automobile airbags. Over the 30-plus ensuing years, scores of advances were carried out at BSAC as the MEMS/NEMS industry grew from negligible size to its present tens-of-billion-dollar worldwide product size. BSAC itself has likewise grown, until today it is directed by 13 research faculty, who typically supervise more than 100 graduate students in programs associated with roughly 35 industrial sponsors. In 2013, the impact of BSAC was honored by the presentation of the IEEE/Royal Society of Edinburgh (RSE) James Clerk Maxwell Medal to BSAC—Dick and myself, as the founders.

ENGenious: For a scientist, you have had a heavy focus on communication and language skills throughout your roles in teaching and research. Why is that?

Muller: I discovered this passion early, when I founded the first newspaper at my grammar school. I went on to run the newspaper in high school. I was the editor-in-chief of the Stevens newspaper at my undergraduate college. In those early years, I had a strong inclination toward a career in journalism—but the appeal of engineering caused me to decide on study at an institute of technology. An important part of my research career has been service as editor-in-chief of the IEEE/ASME *Journal of Microelectromechanical Systems* from 1997 to 2012. These years of editing were valuable in learning to evaluate ideas and to express them with clarity and impact. With these perspectives, the researcher is equipped to recognize frontiers in a problem area and to decide on ways to push back these frontiers. Charting frontiers is the skill of pioneers. E N G

Richard S. Muller is Professor Emeritus in the Department of Electrical Engineering at the University of California, Berkeley, and Co-Founding Director of the Berkeley Sensor & Actuator Center.

Dan O'Dowd

Richard O'Dowd

From Debugging to Integrity in Coding

ENGenious sat down with Dan O'Dowd (BS '76, engineering) and his son Richard O'Dowd (BS '13, computer science) to discuss their Caltech journeys, their dedication to computer science, and the field's impact on the world.

Dan O'Dowd discovered his passion for fixing bugs in code as a Caltech undergraduate student. Less than 10 years later, he founded Green Hills Software, and he is still serving as its president and chief executive officer. Before founding Green Hills Software, he was manager of compiler and operating system development at National Semiconductor, where he designed the architecture for the NS32000 32-bit microprocessor. Prior to that, he was at APh Technological Consulting, developing some of the first embedded development tools for microprocessors. These were used for developing the first handheld electronic games for Mattel and Mattel's line of home video games. O'Dowd has crossed paths with many luminaries in computer science, including Steve Jobs, and his mathematically proven secure software, called INTEGRITY, has been essential to the aerospace industry. His son Richard works at Green Hills Software as a senior software engineer, developing the next generation of real-time operating systems.

ENGenious: How did you both come to choose computer science and Caltech?

Dan: Caltech is the top school for science—it was then and it is now. I actually started out in mathematics, but I took some computer courses along the way, which I liked. Knowing that programming would mean guaranteed employment, I switched to computer science, which is still sort of math, just a more practical application. Of course, there was no computer science department at the time. That didn't start until the year after I left, so I got an engineering degree, but with a focus in computer science.

Richard: I was steeped in my dad's interests. I was always a math and science guy, so Caltech was a natural fit. My dad did computer science, so I dabbled in it and in programming. But when I came to Caltech I gave myself two choices, biology or computer science, since they seemed like the two emerging fields going forward. I did try biology, but computer science proved much more interesting to me.

ENGenious: Was it a coincidence that you both ended up at Dabney House?

Richard: My dad didn't talk much about his time at Caltech. He did share some, but more of it was after I came to campus and we realized I was his legacy in Dabney. I wasn't even certain which house he was in when I got here. I had an inkling it was Dabney, but I didn't know for sure. As it turns out, we are both keepers of the Dabney jai alai tradition and were both avid players of the "ball against the wall."

Dan: I came to Caltech to visit Richard at Dabney shortly after Richard got here, and I had this weird déjà vu where I felt it was 37 years earlier.

It was at the same time familiar and unfamiliar, and I had the feeling of being a freshman coming in for the first time. I felt he had to come to that himself; that he ended up in Dabney was by way of his own path that happened to intersect with mine.

ENGenious: What Caltech experiences do you still carry with you?

Dan: I found a memory recently. I stumbled on a manila envelope in an old box marked "September 1976." Inside were my student records of fixing bugs for one month. I recorded everything I did, every bug I had, the mistakes I made, and how long it took to fix them. I was studying my own process even then. Fixing bugs has been my professional career, but the original notion started at Caltech.

Richard: Caltech students are a lively bunch, up to all sorts of random shenanigans. Everyone is smart and coming to new ideas and new conclusions. Your mind is changed and you change minds in routine conversation about interesting topics. And then there is jai alai, of course.

ENGenious: Why is your collaboration with the aerospace industry unique?

Dan: What we do, for the most part, at Green Hills Software is solve the basic problems of software. Following traditional methodologies, software invariably has bugs and security vulnerabilities, which are simply not acceptable when you're building something that people's lives are dependent upon. And yet software is still being created the traditional way, so how do you fix it? The aerospace industry is a place where they take this question seriously. It's the one industry where they really go to the trouble to do it well, because planes do crash, and hundreds of people die when they crash. There is major incentive to study and fix problems. I was interested in the problem of fixing software, the aerospace industry needed that problem solved, and we were equally dedicated to the solutions. That combination created opportunity, and now most modern aircraft use our INTEGRITY software and our tools for debugging the software.

Dan and Richard O'Dowd explore their former dorm, Dabney House.

ENGenious: You also have worked on space technology with JPL . . . ?

Dan: Yes, in late 1970s I designed the microprocessor that was used in the camera onboard the Mars Global Surveyor. The Jet Propulsion Laboratory calls it a camera, but it's really a telescope that photographs the surface of Mars, which is why we now have a complete high-resolution map of the planet. It was also used by the Mars rover for communication to Earth.

ENGenious: How did you come to collaborate with Steve Jobs?

Dan: In the early days of Green Hills, we developed our C compiler. I got a call one day from a friend of mine who worked at Apple, telling me they needed a C compiler for the Macintosh. So I went to meet Steve Jobs. I made my presentation and told him, "Yes, I can do this thing." A C compiler is what you need to develop all of the application software. We worked on this project together, maintained a friendship, and shared knowledge for a long time. He left Apple shortly thereafter, but I continued to interact with him for some years after that. I developed a product for him to use by the happenstance of a single overlapping connection.

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

Dan: I think you should do something you like, something you're good at and you really like, because that makes it fun and then you accomplish things. I went from math to computer science because I liked math, but I liked computer science better. It felt like a big decision to make that switch, but it was the right one for me, and all of these years later I still know it was right.

Richard: I would say dabble some in computer science. Actually, almost everybody at Caltech now does, because CS 1 is taken by every incoming student. Caltech gives you a good foundation in programming, which is in high demand and rapidly turning into a core skill of science and engineering. Many of my Caltech friends are now coding in addition to being engineers. We are the coding experts among our working peers, and it makes us very valuable.

ENGenious: Why do you equate some software with weapons of mass destruction?

Dan: Soon every car will be internet connected. Researchers have recently demonstrated that by hacking the internet connection, they can control the brakes, throttle, and steering of several popular models of cars. Every security bug in the millions of lines of code that run a car is also in millions of other identical cars. A hacker can exploit one of those bugs to seize control of millions of cars at the same time, accelerating them all to 100 miles per hour and turning them into oncoming traffic, causing millions of high-speed head-on collisions in a matter of minutes.

One bug can be more devastating than a nuclear weapon. Internet-connected cars are weapons of mass destruction. In dangerous disciplines like nuclear weapons, infectious diseases, and deadly chemicals, there exist strict safeguards and regulations. There are no similar restrictions for software, which can now be as deadly. Engineers must own up to this and acknowledge that we're building things which are extraordinarily dangerous and need to be fixed before they go to market. We cannot design the means of our own destruction. We have a lot of control as the designers, because they can't build something until we design it. We must be able to say, "No. This device can kill people. We will not connect it to the internet," even when that could mean the loss of a job. If something can't be built safely, it shouldn't be built at all.

ENGenious: How are you encouraging engineers of your generation to put this notion of safety into practice?

Richard: You can lead by example. I feel like some engineers have a problem with constrained thinking. They often receive constraints, mainly from management, of time and money. So the engineer says, "Okay, I'll do the best that I can do." And then management will say, "Well, now you have even less time and less money." And the engineer will say, "I'll do the best I can. I mean, it's not going to be good, but it'll be the best that I can do." What they don't say is, "No. We can't do the right job with that much money and that much time." The engineers need to push back in these cases, because this culture can be dangerous. It can kill lots of people. We have to think it all the way through and push back.

ENGenious: How did Caltech help you integrate this base layer of safety?

Dan: I work on technology, but I also have to get people to understand the fundamental ethical problem so that the decision makers will make the right decisions. When I was a student at Caltech, there was a course on engineering ethics, which taught us that we could design a product that wasn't very good, or of low quality, but that we must say no at the point when we realize a device is an outright danger to humanity. To refuse to make a bad product is an acceptable moral choice but a potentially insufficient one. At some point you have to call it out, become the whistleblower, and foster support from other people if you believe there is a tragedy or catastrophe in process.

ENGenious: Are design integrity and logic having their meta-battle moment?

Dan: We need to ask why it is that we think we need the things we're building. What is their value? If the answer is convenience, cost savings, or entertainment, then follow that question with another: Is it worth it if that thing can kill millions of people? A prime example is the internet-connected home. Once you come to this concept and you identify cost savings or convenience opportunities, then you suddenly think everything in the home should be connected as the next logical conclusion: "The stove is in the house, so it must be connected." You can't just push a high-level concept down to the lower levels without thought. At the point where you get to the stove, it becomes too dangerous. If someone can hack into your stove and cause an explosion in your home, that is unacceptable risk. We need to get the engineering back on track one device at a time and figure this out. We cannot start with a big idea and build a reality without thinking it through device by device. And if a device cannot be fixed, then it shouldn't be connected to the internet, despite market forces, competitors, or bottom lines.

ENGenious: How do you make code reliable and safe?

Dan: We need to start by separating the critical code from the non-critical code, which greatly reduces the debugging task. Often code serves to optimize, improve, or entertain, all of which takes a lot of code but doesn't control the actual device. It's okay if the non-critical part of software doesn't work. It might be annoying, but it is not critical. We can't make all code reliable—it's just too much. We find a way to get it down to the few percent that is critical and make sure we do that part correctly. This can cost $1,000 per line of code. And before anyone even thinks about cost, consider this: If your device is such that it has the ability to kill lots of people, it almost by definition is a big enough business to support this level of software scrutiny and safety. Cars are a trillion-dollar business. Trains are a hundred-billion-dollar business. Our exploding stove? Tens of billions of dollars are spent on stoves annually. Guaranteeing the safety of critical software in these products is a small reinvestment of profit that provides huge payoffs in the overall health of the consumer and the company. ENG

Dan O'Dowd is founder, president, and chief executive officer at Green Hills Software. Richard O'Dowd is a senior software engineer at Green Hills Software.

CAMPUS RESOURCE

Center for Diversity

When *ENGenious* profiled the Caltech Center for Diversity six years ago, it was housed in the Student Affairs department and had crystalized around a common notion of diversity to maximize impact, having historically been organized according to the separate needs of specific interest groups. Today that common notion of an inclusive community continues to advance and evolve, and the center's home is now the Provost's Office. As Cindy Weinstein, Vice Provost and Chief Diversity Officer, explains, "The Center for Diversity has become an instrumental part of the Caltech academic program by facilitating an environment where everyone can flourish socially and academically."

Taso Dimitriadis, Hanna Song, Marlene Moncada, Erin-Kate Escobar, and Monique Thomas

ENGenious sat down with the people behind these efforts, who are building on the foundations of the center to offer practical and meaningful skills-delivery programs. The team includes Hanna Song, the Senior Director for Diversity, and two assistant directors: Taso Dimitriadis and Erin-Kate Escobar.

***ENGenious*: How is the Caltech diversity effort unique?**

Song: We make diversity a science, in a way. We translate our work into terms Caltech already understands and engages with regularly. Issues of social justice can really be academic in that there is good research and lots of data to support the importance and relevance of diversity and inclusion in everyday life. We also keep it topical and relevant. We have established many structured spaces that are facilitated and moderated by experts who can engage intellectually with our community on current questions and flashpoint issues in the culture. This information–lecture–debrief model works well at Caltech. It also engages people emotionally. The growing attendance at our topical programming is great evidence that we are helping when people need it most. Some of our largest gatherings this past year included processing the Pulse nightclub shooting and a post-election debrief. We filled our space and had people outside our doors wanting to find a space to discuss current events. We speak in a language specific to Caltech, but we do it in a way that blurs the lines between Caltech and the rest of the world.

***ENGenious*: What challenges do you encounter at Caltech?**

Escobar: Our job is to manage challenges in this unique Caltech environment. It is really important to acknowledge that the act of unpacking emotions in our fact-based reality has value and importance. This reality is a two-way street of empathy and emotional intelligence. We cannot continue to work in spaces where we're not allowed to have emotions about what is going on in the larger world. We also must create spaces where scientists can process how their work intersects with the communities it affects. Closing the door on emotions trickling in or trying to get out doesn't work. We have to be thoughtful about taking care of the people who are the brilliance of Caltech.

***ENGenious*: Why does Caltech need a diversity center?**

Song: As soon as respect is deemed important to a community, you need a place where members can cultivate basic skills for understanding one another. Caltech is driven by outcomes. People here care deeply about their work. The best work can only happen when communication and productivity are beneficial for everyone.

Dimitriadis: We help lay the groundwork for collaboration and engagement, which are important to success in our global STEM village. Caltech is a collection of unique, singular, stellar individuals, and, especially for that reason, the Center for Diversity strives to cultivate an environment where everyone wins.

Escobar: This means meeting every need for every community member and creating spaces where every member can be their whole self at Caltech. No one should have to leave any part of their identity at the lab door or the office door.

***ENGenious*: How have the center and its activities changed?**

Song: The move from Student Affairs to the Provost's Office was a recognition that addressing diversity issues isn't just important for students but for every member of the Caltech community. We are now broader and more strategic in our programming. With working groups and conversations at the macro level, with administration and faculty all the way to the more immediate needs expressed by students, faculty, and staff at Caltech, we now have a structure that allows us to drill down and scale up depending on the audience and the need. This also broadens the effect of our work.

Dimitriadis: We advise faculty on searches and big statistical realities, but we also are equipped to help every member develop their voice and empower themselves to do their best work. With the shift to the Provost's Office, there can be no question as to who, how, or why integrating every identity is important: the answer is everyone, in every context, all the time.

ENGenious: Why is it important that members of underrepresented groups enter established networks when they first come to Caltech?

Song: Caltech is small and it is excellent. When students come here, they can struggle with a baseline buzz of anxiety over the rigor and brilliance surrounding them. Many wonder if they even belong here. They'll ask themselves, "How did I get in?" Now layer on the fact that they are in a subpopulation. Not only are they questioning their self-worth as a student at Caltech, but they're suddenly the sole representative of their cultural group or sexual orientation group, or they're the first-generation student from the smallest town on the map.

Dimitriadis: That implies a lot of identity development. When we provide students with an affinity group and physical space to meet, it grants them important validation of their individual experience and the realization that they are not alone. That kind of framework can make all the difference to their experience. We also value the intersectionality of all identities and how that is so important in developing our perspectives and values as scientists and unique human beings.

ENGenious: How do you help members of the Caltech community who aren't underrepresented?

Song: No matter what you do, either as a current student or employee of Caltech or after you leave here, you will be interacting with people who are not like you. If you don't have experience working with people who aren't like you, if you have no skills to manage the challenges that come with what happens when people rub up against the majority culture, you will only go so far. We offer training that will have real-world impact on your career. If you want to achieve in a global economy, navigating space with someone who is nothing like you isn't an optional skill. Our workshops and programs raise basic cultural competency for all constituents across the campus, which in turn improves the campus climate for everyone, including those in the majority. There is no "us versus them" in developing a person or belonging to a community.

Escobar: On a practical level, this can mean unlearning. We help people develop the ability to take one extra moment for that first reaction to people who are different from themselves to pass. We teach people to ask themselves how they can allow people to be who they are, without asserting what is their "normal."

Dimitriadis: Our goal is to offer the skills and the benefits of cultivating interactions for every member of the Caltech community. This is why we have allyship training. For example, the second day of our safe-zone training lays out how you, as a member of the majority population, can provide support and lead with your inherent status to make sure everyone is included. These are real-world skills in managing harassment, ensuring physical safety, managing poor humor, and learning how to diffuse conflict. Mastering these simple but activating skills is of value to companies and will make you more attractive for employment.

ENGenious: How can alumni get involved?

Song: Come back and play a part! There is great power in engaging with our current students. The most important thing we can do is show our current students that resources like mentorship, sponsorship, and role modeling exist. There is a tendency for students to think that there is a straight line from A to B. In fact, we all know that there are many roads to success, and the more exposure they have to all of the ways people move forward in their lives, the better. We have all levels of engagement opportunities, from committee work to CV reviews to conducting mock interviews to speaking opportunities.

Dimitriadis: We would love to hear from our Caltech alums about how their identity and their expertise combined and unfolded in the world. This speaks to the last little-known fact about diversity: it breeds creativity. Caltech is brilliantly unique, but it doesn't have a lot of philosophy majors or film students roaming around and interacting with the science-minded. Communities that engage people who inherently see problems from different angles because of their experience are a real-world benefit to the science at Caltech. We would love to hear how they've been able to contribute to science, communities, and the world.

Escobar: Alums can help serve as examples as to how their experiences have launched their professional scientific ship. That is a powerful and rewarding gift to give back to Caltech. ENG

Hanna Song is Senior Director for Diversity. Taso Dimitriadis is Assistant Director. Erin-Kate Escobar is Assistant Director.

Visit diversitycenter.caltech.edu.

The Center for Autonomous Systems Technologies (CAST) was established by Caltech to promote interdisciplinary research and the exchange of ideas in the exploding area of autonomous systems. The soon-to-be-completed 5,056-square-foot home of the Center will be a living experiment that promotes a synergic environment where machines and humans share the workplace. The centerpiece of the facility is the three-story-tall, enclosed, 75,064-cubic-foot aerodrome to test flying drones—the largest of its kind. The aerodrome will include a 100-square-foot wall of 2,000 fans that can be individually controlled to create a nearly infinite variety of wind conditions for drones to learn to react to—everything from a light gust of wind to the vortex of a tornado.

Rendering created by CO Architects.

For information, visit cast.caltech.edu.

Division of Engineering and Applied Science
CALIFORNIA INSTITUTE OF TECHNOLOGY
1200 East California Boulevard, Mail Code 155-44, Pasadena, California 91125