ENGenious

ISSUE 16, 2019–20

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

of the California Institute of Technology

Caltech

ENGenious

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p. 1: Courtesy of Alireza Marandi; Vicki Chiu;
Alex Phillips (DC policy trip)
p. 2: Stevan Nadj-Perge
p. 3: Lance Hayashida
p. 4: Courtesy of Caltech
p. 5: Vicki Chiu
p. 6: Tom Bonner (lab);
Lance Hayashida (Bouman)
p. 7: Ian Brownstein (wind turbine);
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p. 8: Lance Hayashida
p. 9: Vicki Chiu
p. 11: Alireza Marandi
pp. 12-13: Vicki Chiu
p. 14: Robyn Javier
p. 18-19: Courtesy of Amnon Yariv
p. 21: Vicki Chiu
p. 22: Alex Phillips (Rise); Courtesy of the Caltech Y
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We invite you to learn more about the Division through our website, eas.caltech.edu.

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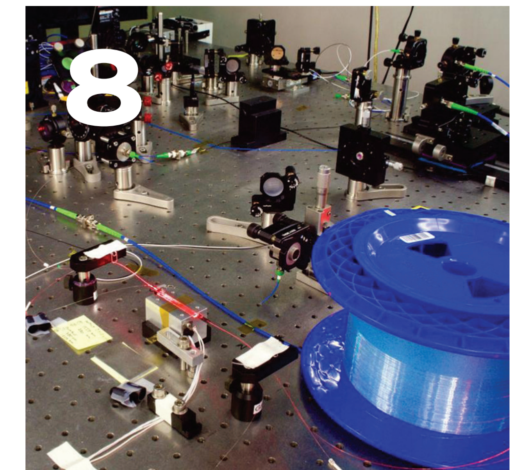
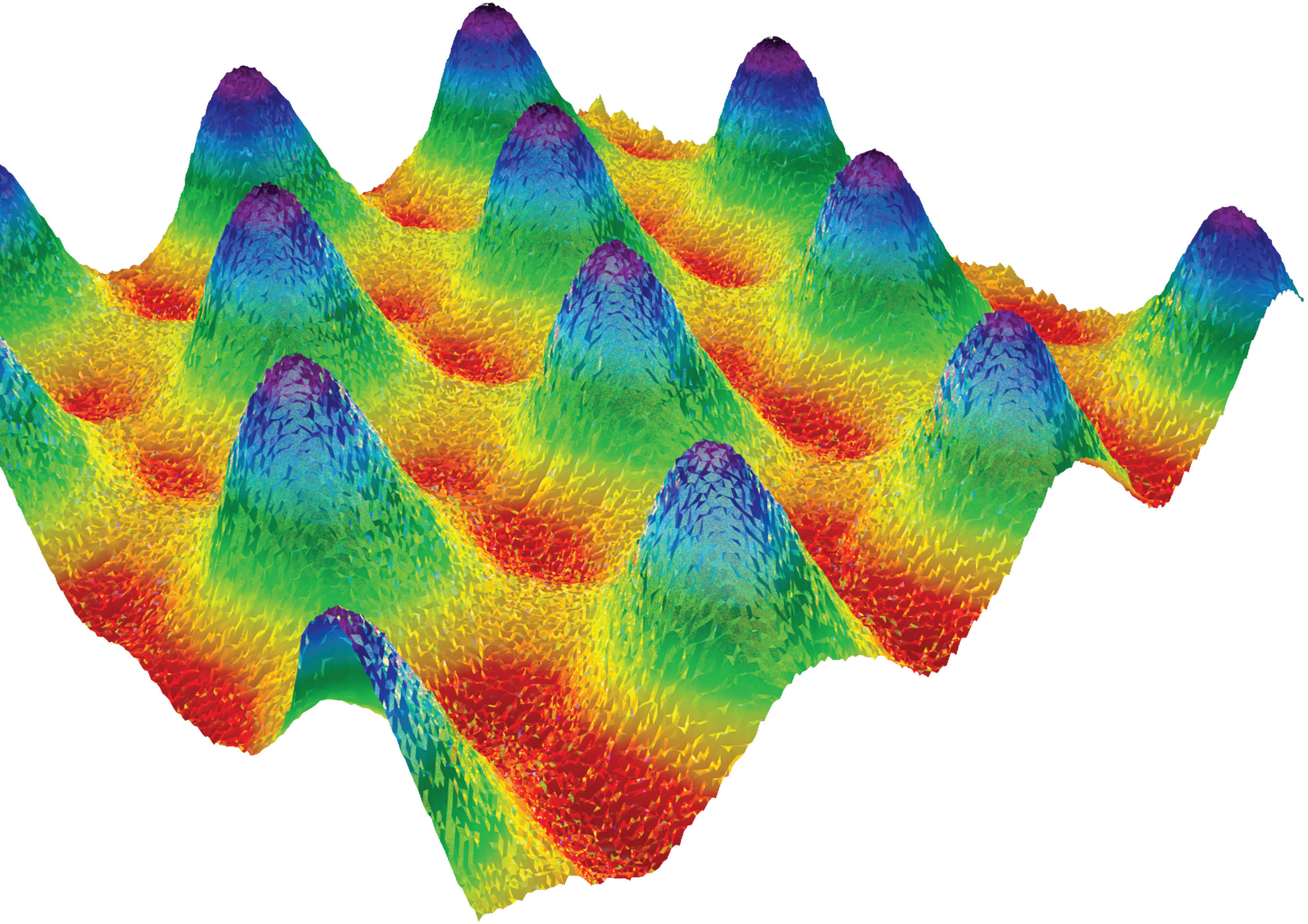
The Caltech Division of Engineering and Applied Science consists of seven departments and supports close to 90 faculty who are working at the leading edges of fundamental science to invent the technologies of the future.



Cover illustration: In EAS, we believe that there exists a significant opportunity to take a holistic approach toward co-design of Sensing and AI systems that will enable systems to perform optimally as well as to unlock wholly new applications. An intelligent, autonomous, and tightly connected world of the future will be enabled by a wide range of sensors and imagers that can measure a broad range of electromagnetic, mechanical, chemical, and biological signals. At the same time, the overwhelming amounts of data generated by future sensors will require complex computational approaches to quickly and efficiently distill and extract pertinent information, and to feed that information back to the sensor to enable autonomous decision-making. Caltech's **Sensing to Intelligence (s2i) Initiative** embodies this approach and seeks to develop a new generation of researchers whose skills span across the hardware-software divide. By developing seamless networks of sensors and intelligent systems we hope to build a more connected, more resilient, and healthier world.



Stevan Nadj-Perge, Assistant Professor of Applied Physics and Materials Science, and his colleagues have generated an image of the atomic structure and electronic properties of "magic angle-twisted" graphene. What is the magic angle? Say you take two sheets of graphene—single-atom thick lattices of carbon atoms—and lay one atop the other to create a bilayer material, then twist one of the sheets of graphene to shift their orientation to one another. As the orientation shifts, the electronic properties of the bilayer material will change with it. In early 2018, researchers at MIT discovered that, at a certain orientation (about 1.1 degrees of relative twist), the bilayer material, surprisingly, becomes superconducting and moreover, the superconducting properties can be controlled with the electric fields. Their discovery launched a new field of research into magic angle-oriented graphene, known as "twistronics." Nadj-Perge and his colleagues developed a new method of creating samples of magic angle-twisted graphene that can be used to align the two sheets of graphene very precisely while leaving it exposed for direct observation. Samples like this could help us to explain why the exotic electronic effects near the magic angle exist. Once we know that, we could help pave the way for useful applications, perhaps even leading to room-temperature superconductivity one day. (For more information, visit: www.caltech.edu/about/news/finding-magic-magic-angle)

Dear alumni and friends of the Division,

Entanglement, qubits, quantum computing: these concepts have moved decisively from the realm of theoretical physics into the lab, and specifically to our labs in the Division of Engineering and Applied Science. EAS is the home of a new effort to advance qubits from the lab to real world applications. To understand what this means, turn to page 12, where you can learn where we are placing our efforts, and what quantum computing holds in store for the advancement of computing. As we go to press with *ENGenious*, it was announced that the Amazon Web Services' AWS Center for Quantum Computing is being established at Caltech, led by Oskar Painter (MS '95, PhD '01), John G Braun Professor of Applied Physics and Physics, and Fernando Brandao, Bren Professor of Theoretical Physics. This center brings together researchers and engineers from Amazon, Caltech, and other leading academic institutions to develop more powerful quantum computing hardware and identify novel quantum applications.

The recent, historic gift from Stewart and Lynda Resnick to Caltech is the largest ever for environmental sustainability research, the largest in Caltech's history, and the second-largest gift to a U.S. academic institution. A multiplicity of fields—including solar science, climate science, energy, biofuels, water and environmental resources, and ecology and biosphere engineering—are supported by the Resnick's $750 million commitment to Caltech. The Resnicks have transformed Caltech, and their extraordinary gift will reach generations of students who will pursue new approaches to sustainability, climate science, and engineering—creating new schools of thought and novel technologies with the goal of establishing paths to a sustainable existence.

Our students are deeply embedded in their studies and research—but they are also embedded in the community through the Caltech Y. This is an organization which has touched the lives of almost everyone at Caltech for more than 100 years and is increasingly touching the lives of local middle and high school students who come for tutoring in math and science. Over 150 Caltech students per year participate in the Caltech Y's tutoring program—an astounding number given our combined graduate and undergraduate population of roughly 2,300. Learn about the evolution of the Y (see page 21)—and join them! There are myriad opportunities for alumni and friends of Caltech to participate in events and support the activities of the Y.

As always, I look forward to receiving your thoughts and comments. Please visit campus when you can—and stay in touch.

G. Ravichandran

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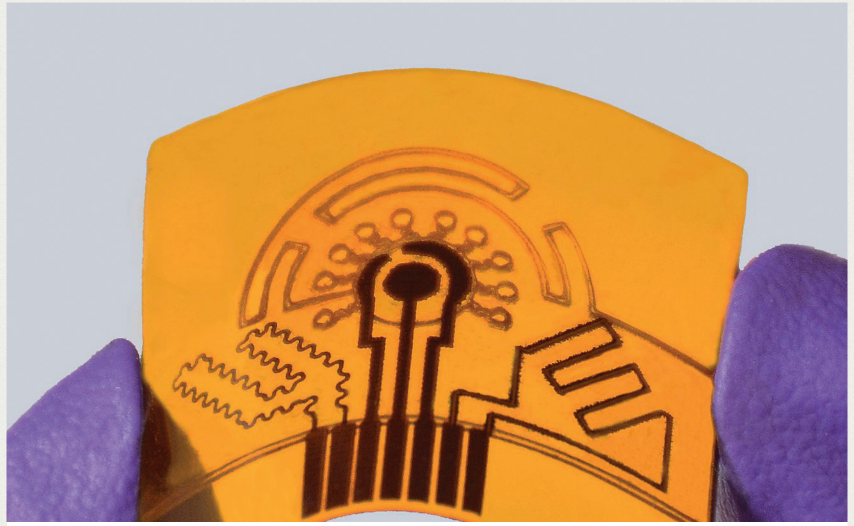


The Next Wave of Wearable Sensors: Sensitive, Low-Cost, and Flexible

Wei Gao, Assistant Professor of Medical Engineering, and his colleagues have developed a wearable sensor that can monitor levels of metabolites and nutrients in a person's blood by analyzing their sweat. Most previously developed sweat sensors targeted compounds that appear in high concentrations, such as electrolytes, glucose, and lactate. Gao's sensor is more sensitive than current devices and can detect sweat compounds in much lower concentrations, in addition to being mass producible. Previous microfluidic-based wearable sensors were mostly fabricated with a lithography-evaporation method, which requires complicated and expensive fabrication processes. His team makes their biosensors out of graphene, a sheet-like form of carbon. Both the graphene-based sensors and the tiny microfluidics channels are created by engraving plastic sheets with a carbon dioxide laser, a device that is now so common that it is available to home hobbyists. Gao's first sensor measures respiratory rate, heart rate, and levels of uric acid and tyrosine. Tyrosine is an indicator of metabolic disorders, liver disease, eating disorders, and neuropsychiatric conditions. Uric acid, at elevated levels, is associated with gout. Considering that abnormal circulating nutrients and metabolites are related to a number of health conditions, the information collected from such wearable sensors will be invaluable for both research and medical treatment.

Wei Gao, at right, monitors data from flexible sweat sensors worn by a volunteer.

Learn more at www.caltech.edu/about/news/wearable-sweat-sensor-detects-gout-causing-compounds.

Caltech Undergrads Build the Little Robot That Can

A robot designed and built by Caltech undergraduate students working with graduate students and JPLers made it to the field in the first phase of the Subterranean (SubT) Challenge, an international competition sponsored by the Defense Advanced Research Projects Agency (DARPA). Named after a famous rescue sled dog, Balto, the robot is built atop a commercial radio control car but with an entirely replaced electrical and control system. It is among the fleet of flying and tank-like robots that competed in the August 2019 tunnel-navigation competition in which the Caltech-JPL team took second place. Because of its light weight and small size, Balto is capable of rushing in and substituting as an *ad hoc* node in a wireless communications network. Initial work on Balto began in CS/EE/ME 75, Multidisciplinary Systems Engineering, a cross-discipline special projects undergraduate class, and continued through the Summer Undergraduate Research Fellowship (SURF) program.

Learn more at www.caltech.edu/about/news/caltech-undergrads-build-robot-darpa-challenge.

Through the SURF program, Caltech undergraduate Alexandra Bodrova fabricated custom parts for Balto (top).

The New Center of the Caltech Universe: Hameetman Center

The Hameetman Center, built with gifts from Fred (BS '62) and Joyce Hameetman and Steven and Mie Frautschi, was dedicated in February of 2019. It quickly became a hub of activity for the entire campus. Plenty of light-filled space, food and drinks provide by the Red Door Marketplace, and an expanded outdoor patio have drawn students, faculty and staff to Hameetman for casual meetings or individual study; it's a place to share a coffee with colleagues, grab a great avocado toast, and a venue to visit after an evening concert at Beckman Auditorium (or a long problem set)—the Red Door is open until 2 am! Upstairs are meeting rooms of various sizes, including the Steven and Mie Frautschi performance room. This is a state-of-the-art rehearsal room and recording studio for student performing arts groups and is used by the Caltech-Occidental Wind Orchestra, the Caltech Jazz Band, the Caltech Glee Club and Chamber Singers, Caltech Chamber Music and Guitar Ensembles, and The Caltech Orchestra, as well as Theater Arts at Caltech (TACIT).

Schmidt Academy for Software Engineering

In recognition of the fact that scientific advances often rely on the development of specialized software, Caltech has launched the Schmidt Academy for Software Engineering to train the next generation of science-savvy software engineers and set new standards in scientific software. The three-year pilot program, which is supported by Eric and Wendy Schmidt, is funding four Caltech Schmidt Scholars this year to work with research groups across campus; the cohort will grow to 12 scholars next year. For one to two years, the scholars will receive industry-competitive salaries while being mentored by a senior software engineer at Caltech and embedded in a research group. As they begin to work on their projects, scholars will attend a software "bootcamp" of relevant classes led by Schmidt Software Academy instructor Donnie Pinkston (BS '98), a familiar face to Caltech computer science students. Umesh Padia (BS '19), who is among the inaugural class of Caltech Schmidt Scholars, deferred enrollment as a graduate student at MIT to jump on what he describes as a way to build skills while simultaneously creating a tool that helps scientists who are at the forefront of their fields. "This is a way to work on a scientific project as a leader, which is uncommon at this stage of your career," Padia says. "If you go to work for a tech company, you're going to work on someone else's project and be a cog in a machine. Here, you're the project manager, you're the tester, you're the software engineer—you get to see everything. It makes you a better software engineer."

Left to right: Schmidt Academy instructor Donnie Pinkston, inaugural director Mike Gurnis, and administrative assistant Maria (Alicia) Creger

Learn more at www.caltech.edu/about/news/caltech-announces-schmidt-academy-software-engineering.

New Faculty

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

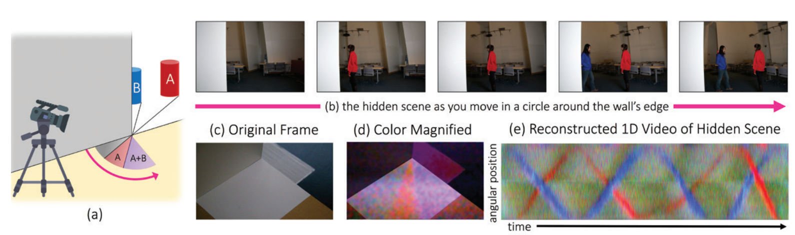
"I'm excited to start connecting with people across campus and help them use imaging to push the boundaries of their disciplines. I've already had the opportunity to speak with Zach Ross [Assistant Professor of Geophysics] about how new techniques could help in more precisely localizing the origin of collections of earthquakes. This work, perhaps surprisingly, contains many similarities to the work I've done in black hole imaging.

Katherine L. Bouman

Assistant Professor of Computing and Mathematical Sciences; Rosenberg Scholar

Katherine (Katie) L. Bouman's research focuses on computational imaging. She designs systems that tightly integrate novel sensor and algorithm design with the goal of developing a new generation of computational cameras that will allow us to observe phenomena that are difficult or impossible to measure with traditional approaches. This work led her to be a key member of the international Event Horizon Telescope team, which in April 2019 imaged the first-ever picture of the Messier 87 (M87) black hole 55 million light-years away. Bouman's new group at Caltech combines expertise from signal processing, computer vision, machine learning, and physics to find and exploit hidden signals for both scientific discovery and technological innovation.

Bouman received her undergraduate degree from the University of Michigan and completed her master's and PhD at the Massachusetts Institute of Technology (MIT). She was formerly a Postdoctoral Fellow at the Harvard-Smithsonian Center for Astrophysics. Recently, she was a recipient of the Breakthrough Prize in fundamental physics as part of the Event Horizon Telescope team.



Seeing around corners: (a) Diagram shows two subjects (red and blue) hidden from a consumer camera's view by a wall. Only the yellow-shaded region is visible to the camera. (b) The hidden scene becomes visible as an observer walks around the occluding edge (magenta arrow). (c,d) Hidden scene information can be extracted and interpreted from the intensity and color of light reflected off the patch of ground near the corner. (e) Temporal frames of radiance variations on the ground are used to construct a one-dimensional video of motion evolution in the hidden scene.

John O. Dabiri

Centennial Professor of Aeronautics and Mechanical Engineering

John O. Dabiri's research focuses on unsteady fluid mechanics and flow physics, with particular emphasis on topics relevant to biology, energy, and the environment. His current interests include biological fluid dynamics in the ocean, next-generation wind energy, and development of new experimental methods. Dabiri is a MacArthur Fellow and Fellow of the American Physical Society. His other honors include the Presidential Early Career Award for Scientists and Engineers (PECASE), the Office of Naval Research Young Investigator Program award, and being named one of *MIT Technology Review*'s "35 Innovators Under 35" as well as one of *Popular Science*'s "Brilliant 10."

Dabiri received his BSE summa cum laude in Mechanical and Aerospace Engineering from Princeton University (2001); his MS in Aeronautics from Caltech (2003); and his PhD in Bioengineering with a minor in Aeronautics from Caltech (2005). He was a Professor of Aeronautics and Bioengineering at Caltech from 2005 to 2015. From 2015 to 2019 he served as Professor of Civil and Environmental Engineering and of Mechanical Engineering at Stanford University.

"Jellyfish seem simple at first glance, but having studied them for many years now (starting with a SURF project in my first summer at Caltech), I've come to appreciate how much they can teach us about everything from propulsion to evolution to climate change. I'm looking forward to developing some new ways to use robotics to learn even more from them in the lab and the ocean.

Long-exposure image of artificial snow released upwind of a vertical-axis wind turbine at the Caltech Field Laboratory for Optimized Wind Energy near Lancaster, California. Constructive aerodynamic interference between adjacent wind turbines significantly improves their performance.

Sensing to Intelligence

FEATURE

Professors Anima Anandkumar, Alireza Marandi, Azita Emami, Changhuei Yang, and Katie Bouman

When you think about sensing, you might imagine a fairly passive process in which information is picked up by a sensor and dutifully passed on to a centralized system. Examples abound: sensors in your home trigger an alarm when smoke is detected, an accelerometer provides movement data to your smartwatch which is then processed to indicate how many steps you've taken, and your car can sense and give warnings as you get too close to nearby objects.

In recent years, an exponential increase in sensors everywhere is generating massive amounts of data that will soon surpass what we can currently handle; yet artificial intelligence, machine learning, and algorithmic sophistication are accompanying this proliferation of sensors. For decades, sensors (hardware) and intelligence (software) have been treated as largely separate worlds, connected only by passive flow of information in one direction. This separation is endemic in the design of systems all around us, and in the organization of engineering research itself. Fortunately, a radically different approach is possible, and this is the goal of the EAS Division's newest research thrust: Sensing to Intelligence (S2I).

"Simultaneous advances in sensor technologies and artificial intelligence are converging to enable a fundamental shift away from centralized systems, toward distributed networks of sensors that are fully intelligent on their own," says Guruswami Ravichandran, Chair of the Division of Engineering and Applied Science. He notes this cannot be accomplished within the traditional constraints of single disciplines. "Only by taking a holistic approach that bridges the hardware-software divide can we truly harness the power of sensing to intelligence—to unlock a world that, in the words of Theodore von Kármán, has never been."

Given Caltech's deeply collaborative culture and leading expertise in both hardware and software, the Institute is an ideal incubator for advancing S2I. To learn more, *ENGenious* sat down with five EAS faculty working at the forefront of this emerging field: Azita Emami, Anima Anandkumar, Alireza Marandi, Changhuei Yang, and Katie Bouman.

"The goal is to bring two isolated fields together—the field of sensing and imaging, and the field of computation and algorithms—in order to develop new systems that are more efficient and intelligent. This will help create a world that is more connected, resilient, and healthier," says Azita Emami, Andrew and Peggy Cherng Professor of Electrical Engineering and Medical Engineering. The key is not just that software and hardware are closely connected but that the flow of information goes both ways. As Changhuei Yang, Thomas G. Myers Professor of Electrical Engineering, Bioengineering, and Medical Engineering, explains, "Traditionally, data is just taken from sensors and processed. But now we're trying to send data back in the other direction to optimize the sensors themselves."

"Closing the loop" in this way is critical because it allows a system to adapt and learn. Katie Bouman, Assistant Professor of Computing and Mathematical Sciences and Electrical Engineering, observes, "Often, when people build these systems, they just sit down with a piece of paper and think, 'Ideally this is how the world works.' But that can only get you so far, because the real world is messy and imperfect." An S2I approach, on the other hand, could more efficiently deal with the realities of a physical environment.

Emami has been working closely with Anima Anandkumar, Bren Professor of Computing and Mathematical Sciences, on optimal 'hardware plus software' co-design. This can be a daunting task, explains Anandkumar, "but if we consider our strong hardware expertise, then ask what noise models for hardware are reasonable and which machine learning approaches would mesh well, it's a great starting point—and we can grow the complexity from there."

How far to grow that complexity depends on the type of problem researchers are trying to solve. There is theoretically no limit to the number of sensors that might operate together as a vast, intelligent system with powerful emergent properties. "Each sensor has only a limited field of view, but by coordinating, they can build a much bigger picture and potentially solve extremely complex tasks," says Anandkumar. "This is just the tip of the iceberg," she adds.

Alireza Marandi, Assistant Professor of Electrical Engineering and Applied Physics, encourages us to reimagine what's possible. "When we think about sensors," he says, "we have to ask: What things are we not able to sense efficiently with existing methods? Similarly, on the information-processing side, what types of processes are not easy to do with standard computer hardware?" His research group is using photonic technologies to enable entirely new types of hardware for capturing and processing information.

Yang's group, on the other hand, seeks to combine multiple types of sensor information (optical, electrical, and ultrasound, for example). The catch, he notes, is that such "multimodal" systems are very complicated to design. "It actually may not be possible for us as humans to design systems that optimally integrate multimodal data, but a machine learning approach could be used to find a solution—and ultimately give us better information."

Anandkumar is especially drawn to machine learning challenges in S2I. "The systems we're interested in operate at the boundaries of our knowledge, which means we have to invent completely new algorithms," she says. Bouman, who played a key role in producing the first-ever image of a black hole earlier this year, agrees and observed, "We had to develop entirely new techniques to generate an image from the data. With these novel techniques, we were able to make the black hole image within minutes—but we still went through months of additional tests and developed new methods to gain confidence in the results."

With the right sensor technologies and machine learning algorithms combined, potential applications are truly limitless. Medicine is a "perfect fit," according to Emami, in part because S2I can deal with the limited energy capacity of biomedical devices that "often need to be wearable or implantable and sometimes don't even have batteries." S2I can also help avoid information overload for patients and doctors, she says. "Intelligent sensor systems could process and make sense of the data, do a better job of avoiding false positives, and decrease cost."

Noise is another major challenge in biomedical data, particularly neural recordings. Emami is collaborating with Caltech neuroscientists to apply S2I to brain-machine interfaces. "Neural data is extremely messy, and there are lots of day-to-day variations as well as gradual changes as electrodes move and some become less efficient over time," she explains. Machine learning algorithms optimized for noisy environments could enable long-term recording of neural data, which, for example, could be used to predict desired movements of people with spinal cord injury.

Yang is also interested in neuroscience applications, specifically improving the efficiency of functional imaging techniques. As he explains, neural activity has sparsity characteristics—that is, groups of neurons tend to fire in a coordinated way for any particular task or process. Therefore, he points out, "if we're clever in our approach and optimize sensors to capture just the relevant subsets of neurons, we should be able to efficiently capture data in low resolution and make good sense of it."

> "The goal is to bring two isolated fields together—the field of sensing and imaging, and the field of computation and algorithms—in order to develop new systems that are more efficient and intelligent. This will help create a world that is more connected, resilient, and healthier."
>
> **Azita Emami**
> *Executive Officer for the Department of Electrical Engineering*

Marandi sees broad potential for S2I medical applications, which he likens to the evolution of cameras. "Years ago, cameras were a luxury item. Now they're everywhere—including the phone in your pocket—and everyone has access to this powerful tool." He envisions a future where new sensor technologies in your smartphone could provide early warnings of disease based on your breath or other simple tests. "Being able to process sensor information in a more efficient way could allow us to bring these technologies out of the lab and into day-to-day life."

Beyond the field of medicine are countless industrial applications. For example, smart networks of molecular sensors could monitor for the presence of hazardous materials in a factory or plant. To accomplish this, Emami states that efficiency is crucial. "The devices need to operate continuously with almost zero energy, and then 'wake up' when something happens," she says. "The network of sensors needs to be distributed and needs to have some level of intelligence to be able to operate efficiently." Such systems could significantly improve safety for industrial workers in agriculture, chemical plants, and other settings.

Researchers are also looking to use S2I beyond our own terrestrial boundaries. For example, Bouman is already starting to collaborate with researchers at the Jet Propulsion Laboratory (JPL) and elsewhere to use S2I for optimization of satellite arrays. As Emami remarks, "S2I systems are very promising for space because they can deal with extreme conditions and optimize themselves to find things that we don't even know we're looking for." She describes "smart instruments" that could design experiments on their own—an invaluable capability in unfamiliar worlds.

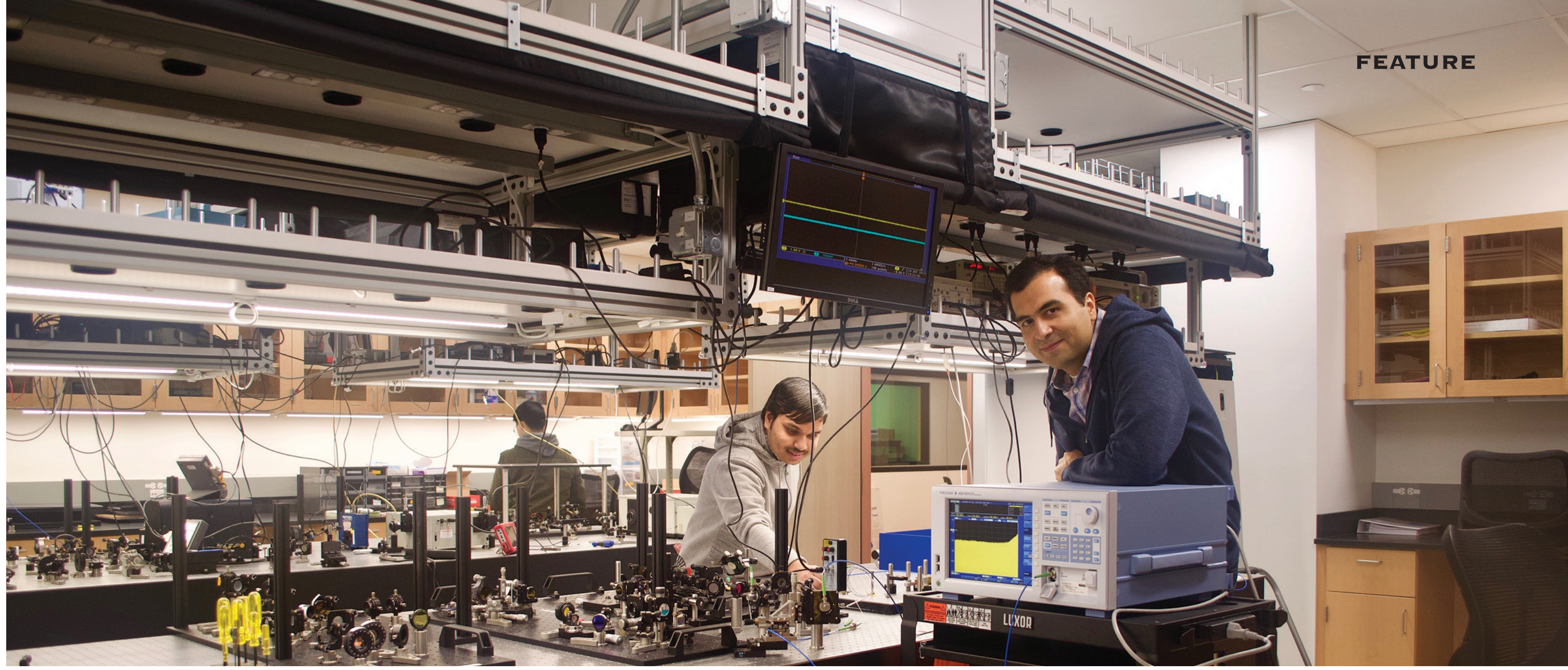
S2I will change the way we explore alien and unmapped terrain. "When we're using machines like a Mars rover to explore new regions, they can't go everywhere," explains Anandkumar. "So we need a way to optimize this process of exploration—where to go, what types of measurements to take, etc." Such approaches might be used back on Earth as well—for instance, in mapping inhospitable regions like networks of caves or the ocean floor.

While S2I has great potential to improve our lives, it is not without hazards. Anandkumar points to the example of monitoring and surveillance. "We need to wield these tools responsibly and balance the technology with individual rights and privacy," she says. "These are hard questions, and it shouldn't just be scientists making the decisions. This is where policymakers and people from all communities should come together to ask how we as a society will deal with these new capabilities."

She also describes facial recognition algorithms that perform in troubling ways when analyzing people with darker skin. "We know these systems aren't perfect, so we need to understand the errors they make and have mechanisms to deal with those errors." Anandkumar isn't the only one concerned—she and several dozen other researchers recently signed a letter asking law enforcement to stop using facial recognition software until it can be certified to meet agreed-upon standards.

In pursuing the potential and also addressing the challenges of S2I, Caltech will undoubtedly play a leading role in shaping the future. "This work requires collaborations across computation, algorithms, and hardware, as well as other areas of science and engineering," says Emami. "Caltech is the perfect place to do this because it's a highly collaborative environment and we're very used to multidisciplinary research."

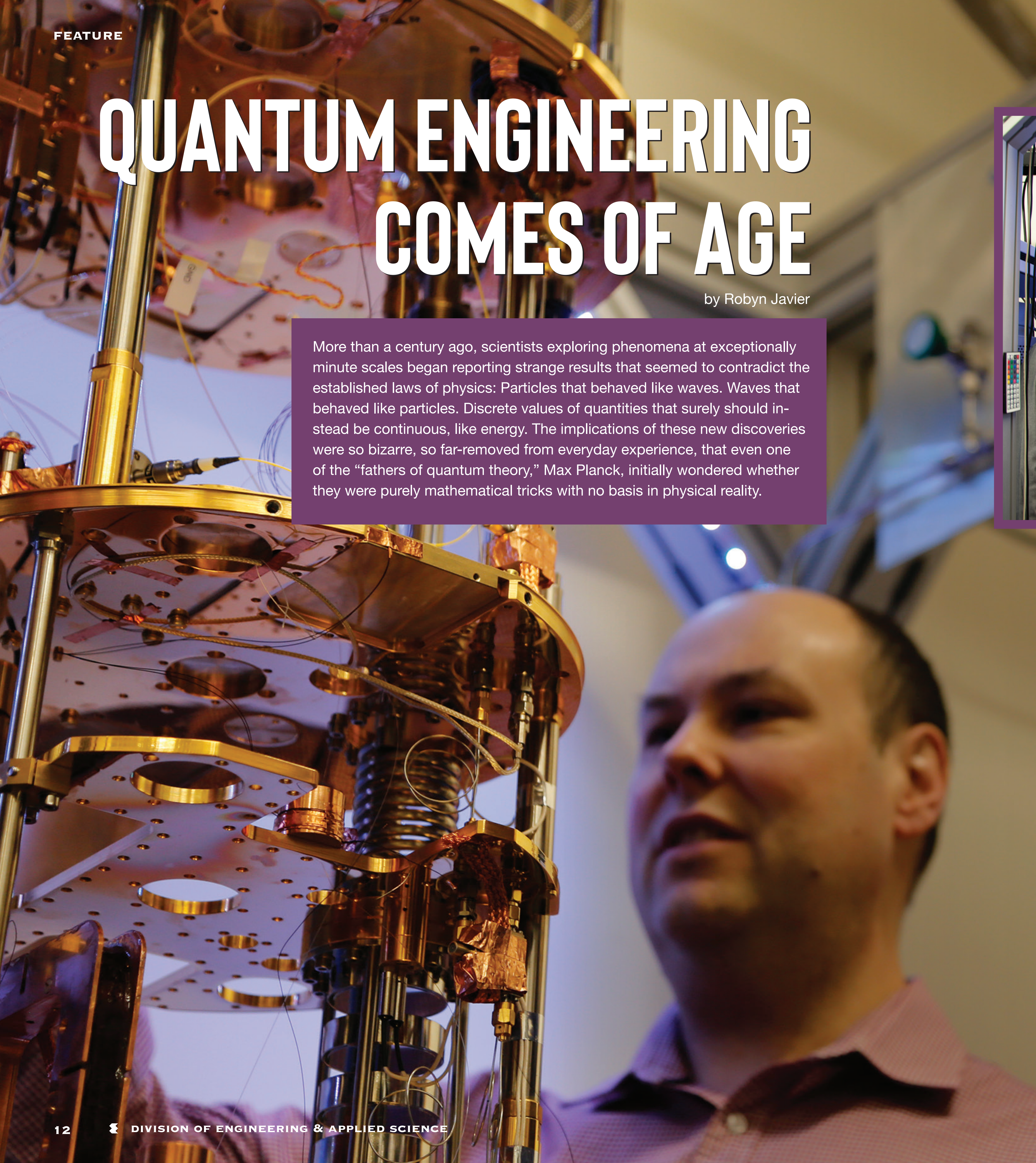
The Institute's collaborative culture permeates not only the faculty level but the student level as well, Yang explains. "We have really good students who think in creative and unconventional ways. And because the barriers to working together are so low here, the students are generating new ideas and fostering new collaborations." Anandkumar adds, "As long as we equip students with the fundamentals, they can connect the dots." She teaches a class in which students across disciplines work together to apply machine learning to real projects. Her group also hosts AI4Science open office hours in which anybody can drop by with machine learning questions. She notes that some students have already put what they've learned into practice, resulting in publishable discoveries.



Optical Ising machine utilizes light pulses in a long spool of fiber to solve computational problems that are challenging for digital computers. Such special-purpose computers that the Marandi Group is developing could enable new paths for intelligent systems.

Asked to sum up the potential of S2I, Bouman says, "This new research area has the potential to make what you *can* do cheaper, and to make what you *can't* do possible." Emami agrees, adding that we can take great strides if we "truly take a holistic approach instead of the isolated approaches we've seen so far."

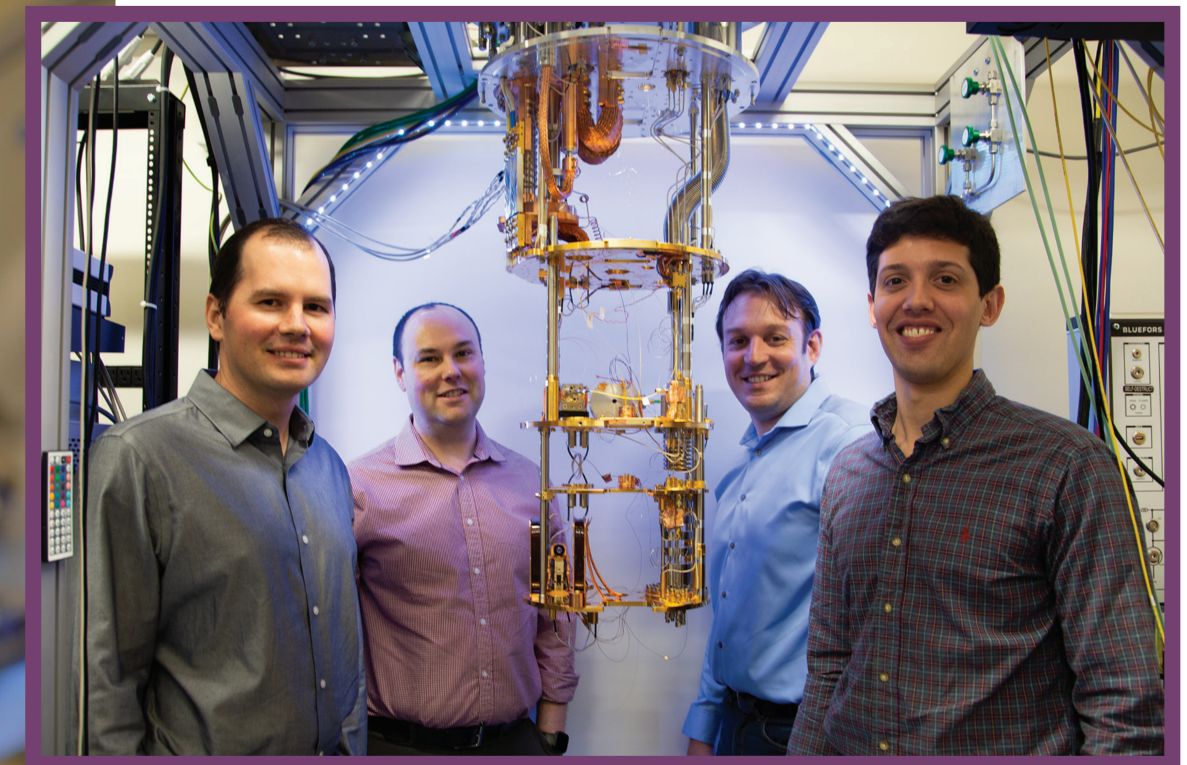
Azita Emami is Andrew and Peggy Cherng Professor of Electrical Engineering and Medical Engineering; Executive Officer for the Department of Electrical Engineering. Alireza Marandi is Assistant Professor of Electrical Engineering and Applied Physics. Changhuei Yang is Thomas G. Myers Professor of Electrical Engineering, Bioengineering, and Medical Engineering. Animashree (Anima) Anandkumar is Bren Professor of Computing and Mathematical Sciences. Katherine (Katie) L. Bouman is Assistant Professor of Computing and Mathematical Sciences and Electrical Engineering, as well as a Rosenberg Scholar.



QUANTUM ENGINEERING COMES OF AGE

by Robyn Javier

More than a century ago, scientists exploring phenomena at exceptionally minute scales began reporting strange results that seemed to contradict the established laws of physics: Particles that behaved like waves. Waves that behaved like particles. Discrete values of quantities that surely should instead be continuous, like energy. The implications of these new discoveries were so bizarre, so far-removed from everyday experience, that even one of the "fathers of quantum theory," Max Planck, initially wondered whether they were purely mathematical tricks with no basis in physical reality.



Above: Professors Andrei Faraon, Oskar Painter, Stevan Nadj-Perge, and Austin Minnich

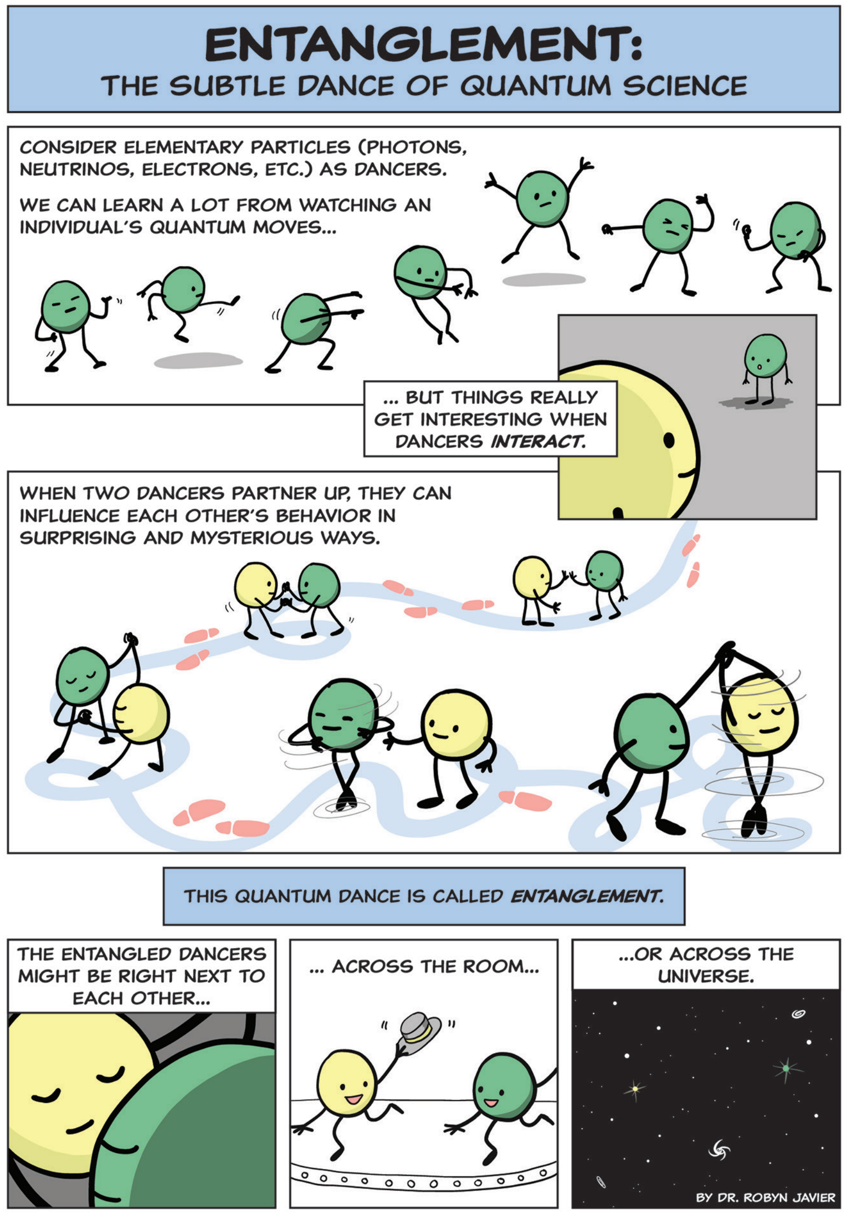
Today, we accept these ideas as fundamental principles of quantum science—the study of nature at its smallest scale. As our knowledge of the quantum world has advanced in recent years, Caltech engineers and applied scientists are increasingly asking what we can do with this new information. In other words, explains Oskar Painter (MS '95, PhD '01), John G Braun Professor of Applied Physics, "what started out as a physics mystery has now moved into the field of engineering." To further explore this frontier of engineering, *ENGenious* sat down with Painter and three of his Engineering and Applied Science colleagues. The roundtable discussion with Painter, Stevan Nadj-Perge, Andrei Faraon, and Austin Minnich, inspired this article.

Quantum engineering—as this nascent field is now known—is a rapidly evolving area "in which quantum properties are essential to how a device or technology operates," says Stevan Nadj-Perge, Assistant Professor of Applied Physics and Materials Science. It's a relatively new term, but the field itself has deep roots in disciplines such as computer science, electrical engineering, materials science, and applied physics. Quantum engineering is now finally coming into its own. "In the same way that electrical engineering split from physics more than a hundred years ago, I think soon quantum engineering will split from more-classical engineering and physics," says Andrei Faraon (BS '04), Professor of Applied Physics and Electrical Engineering.

From quantum computers, currently quite specialized, but posited to eventually outshine today's general-purpose supercomputers, to novel devices for probing tough cosmological mysteries, the potential applications of quantum engineering are groundbreaking and far-reaching. But, as Austin Minnich, Professor of Mechanical Engineering and Applied Physics, notes, "it's not just about industrial and technological applications. It's really about doing science in a completely different way."

A Quantum Leap Forward

In many ways, quantum engineering has already had a tremendous impact on the world, even before the term quantum engineering was coined. Technologies like lasers, transistors, electron microscopy, and magnetic-resonance imaging were all developed based on concepts of quantum science. However, previous work does not



depend on complex quantum interactions between particles that can result in even more bizarre emergent properties. Researchers have long known about these behaviors, but only recently have the science and technology advanced to a point where it's conceivable to *harness* such behaviors.

"The grand challenge of quantum engineering in the 21st century is how to make use of the more subtle aspects of quantum theory—concepts like entanglement—which people like Bohr, Einstein, Heisenberg, and Schrödinger really struggled with," says Painter. Successful utilization of quantum properties such as entanglement (the way particles influence one another's states) and superposition (the ability of individual particles to exist in two states at once) is what is enabling a giant leap forward in quantum engineering today.

Innovative and groundbreaking work is happening at Caltech, thanks to the Institute's unique strengths across the engineering and applied science disciplines and the EAS faculty's deep connections to the sciences. Caltech has a rich history of breakthroughs in quantum science (consider the Nobel-winning work of Richard Feynman on quantum electrodynamics and Linus Pauling on quantum chemistry), and now it has become a leading incubator for quantum engineering as well.

Nadj-Perge is one of several faculty members working at the leading edge of quantum engineering. His research group is particularly interested in new materials for quantum computers. "One of the bottlenecks of doing quantum computation is that the exotic materials needed to push the field further have basically not yet been invented," he explains. "All the practical materials that we have around have some limitations—and we don't even fully understand those limitations." Determining what the ideal materials would look like, and how to develop them, is therefore a major focus of his research. The results could greatly improve quantum devices and underlie the design of future quantum computers.

Another challenge in developing quantum systems is the need to take extremely quiet quantum signals and amplify them to the everyday scale. That is, we need to produce an output that "we can lay our grubby, classical hands on," to borrow a phrase from renowned physicist and Caltech alumnus Carlton Caves (PhD '79). Minnich's group is addressing this challenge by improving the semiconductor-based microwave amplifiers often used in quantum systems. "We think we have a way to reduce the noise of those amplifiers to the lowest level physically possible," says Minnich. "If we're successful, it would greatly enhance our ability to probe nature at its very fundamental quantum limits."

Minnich is also exploring quantum engineering from a theoretical perspective, using classical computers to simulate quantum phenomena. Whereas experimental approaches can produce data that might be interpreted in multiple ways, simulation can provide a more precise way of refining the predictions of a theory. Consider a difficult problem like the Schrödinger equation, which can't be solved exactly. "Numerical tools go beyond what we can do with pen and paper by taking this equation and solving it under certain approximations," explains Minnich. "This essentially provides a simulation of an experiment." Such an approach can be useful, for example, when interpreting the emergent "quasiparticles" that result from the interactions of elementary particles in a material.

Light is another commonly used tool in quantum engineering, and it is the primary workhorse in Faraon's laboratory. Operating near the fundamental limit of light-matter interactions, his group uses photons traveling through optical fibers to probe single atoms. The insights gleaned from his research could have major implications for quantum computing. Faraon notes an additional benefit of working with light: "It allows you to control quantum systems that are actually spaced quite far apart. Once a photon is in an optical fiber, the distance it travels—whether a meter or many kilometers—doesn't really matter." That means it may be possible to create interconnected quantum systems that are delocalized over a very large area.

Painter's research interests cover a broad swath of quantum engineering, from optical materials and devices to superconducting quantum circuits. One particular area of focus, however, is exploring what so-called "early-stage quantum computers" can do. "Quantum systems today still make too many errors to be fully useful," says Painter, "but we can already start to build complex circuits capable of doing fairly mature computations." Understanding how to best use quantum computers as they currently exist will undoubtedly facilitate important applications of this powerful technology in the near term. Looking further ahead, such insights will lay a critical foundation for the future as quantum computers continue to evolve.

Bringing It All Together

Quantum engineering is a field driven by convergence—the convergence of disciplines that initially led to its creation, and now the convergence of engineering and technological advances that is ushering in a new era of devices. Thanks to the intensely collaborative and interdisciplinary environment at Caltech, faculty like Nadj-Perge, Minnich, Faraon, and Painter can explore synergistic connections among their areas of expertise.

For example, Minnich's efforts to improve microwave amplifiers are directly relevant to researchers like Painter whose experiments rely on microwave-based quantum systems. Microwave systems can, in turn, be connected with other types of quantum systems. In particular, Painter and Faraon are interested in connecting their microwave systems and light systems to enable quantum communication across modalities. The instantaneous transmission of quantum information from one location to another is known as quantum teleportation. This phenomenon was first observed 20 years ago at Caltech using a purely optical system, but achieving quantum teleportation between two completely different types of quantum systems is an intriguing possibility.

A convergence of solutions will also likely be required to overcome the problem of "parasitic entanglement," a term referring to the way experimental systems can become entangled with other objects in the environment, thus leaching away the subtle information researchers are trying to observe. Painter points to research developing new types of computational algorithms that can accommodate more imperfections, allowing for the reality of parasitic connections while salvaging enough quantum information to be useful. Meanwhile, Nadj-Perge seeks to overcome the problem altogether by exploring materials with so-called topological protection that intrinsically "hides" information from the environment.

Critical contributions to this emerging field are not limited to academia. Progress in quantum engineering to date has been greatly facilitated by work in industry. Google, for example, has become heavily involved in quantum computer research and development, recently announcing a 53-qubit system that performed a sampling calculation in under 4 minutes that would have taken the fastest super-computers an estimated 10,000 years to perform. Revised estimates are still being made that show this time can be substantially reduced with specialized memory-usage algorithms, but the writing is on the

> It's not just about industrial and technological applications. It's really about doing science in a completely different way.

Austin Minnich
Professor of Mechanical Engineering and Applied Physics

wall regarding the challenges faced by classical computers in keeping up with new quantum computing hardware. Painter notes that each of the academic and industrial worlds brings its unique strengths—flexibility and freedom to do basic exploration on the academic side, and the capacity for sustained investment and large-scale efforts on the industry side. "Quantum engineering is such a hard thing that we're going to need new breakthroughs at every level," he says. "And so that tandem force of industrial investment along with academic investment is key."

Quantum Engineering in Action

Perhaps the most tangible evidence of recent progress in quantum engineering is the increased size and complexity of quantum devices. Just a couple years ago, the most advanced quantum systems contained about 5 qubits (a qubit, short for "quantum bit," is the fundamental building block of quantum systems). Today, researchers have successfully engineered systems with 50 qubits or more. "That might not sound like much—going from 5 to 50—but every time we add a single qubit, we double the complexity of the system," explains Painter. "So, it's really exponential improvement, and it's an enormous breakthrough."

With these advances, researchers have established a new era that is punctuated by various feats of "quantum supremacy." Quantum supremacy, a term coined by John Preskill, Richard P. Feynman Professor of Theoretical Physics, refers to the first use of a quantum computer to solve a problem that is effectively impossible to solve using classical computers. Achievement of quantum supremacy by various devices will result in a string of unique milestones in quantum engineering, parallel to other 'firsts' such as the first flight or the first earth-orbiting satellite. These events heralded tipping points that led to vast technological and societal changes.

Tackling impossibly difficult problems via quantum computing may open the floodgates of insight across many scientific fields. "Being able to solve these very difficult quantum simulation problems can actually help us understand our universe better," says Minnich. Take black holes, for example. The question of what happens to information that falls through a black hole's event horizon has vexed physicists for years. According to Minnich, answers may come from measuring how reliably information can be retrieved via "quantum teleportation" across a network of qubits—which provides a window into the type of information scrambling that may occur within a black hole. Cracking this cosmic mystery is just one potential example of the power of quantum computation, and quantum computation is just one area of quantum engineering.

Another major area of quantum engineering is quantum metrology—the development of sensors and measurement devices that use quantum properties to deliver unprecedented precision and sensitivity. Consider the Laser Interferometer Gravitational-Wave Observatory (LIGO), which used extremely sensitive equipment to achieve the first-ever detection of gravitational waves (signals so faint that Einstein thought they would never be possible to observe). Yet even this incomparably precise undertaking was ultimately limited by quantum mechanical properties of the massive mirrors used to measure displacement. Quantum engineering, on the other hand, can push beyond the so-called standard quantum limits of measurement, surpassing LIGO's current capabilities and enabling fundamentally new types of astronomy.

Quantum measurement devices may provide a path forward in high-energy physics, where many current experiments require particle accelerators with a footprint the size of a small city. "We can't just keep making larger and larger energy colliders," observes Painter, "but rather we can make increasingly precise measurements in a laboratory setting." Imagine experiments currently conducted in massive particle accelerators like the Large Hadron Collider (LHC) but carried out in a standard laboratory setting.

Other major areas of quantum engineering include development of quantum materials and communication. The possibilities touch literally every area of science and technology.

Nadj-Perge sums it up this way: "Quantum engineering is definitely where the next revolution in science and engineering will happen."

Training for the New Frontier

In industry, demand for quantum engineers is already surging. "Companies like IBM and Google are telling us they need quantum engineers *now*, but the workforce largely doesn't exist yet," says Minnich. Fortunately, Caltech has long been at the forefront of education in quantum science and is now leading the way in development of rigorous training for quantum engineers.

For example, Caltech is launching a minor in quantum science and engineering for graduate students. The program expands upon previously developed curriculum, and will offer courses on quantum hardware, devices, and techniques, as well as near-term quantum computing. Its formal structure ensures students receive the comprehensive education needed for a career in quantum engineering, and the degree itself provides clear recognition of the students' specialized training—a key advantage when applying for jobs. Faraon sees the minor as an important first step, adding that "as the field continues to grow, we will likely offer master's and PhD degrees in the future."

Naturally, research opportunities in quantum engineering at Caltech are not limited to graduate students. Undergraduate students have access to specialized courses and the Summer Undergraduate Research Fellowship in Experimental Quantum Science and Technology (QuantumSURF). About a dozen faculty members participate in QuantumSURF, including Minnich, Painter, Nadj-Perge, and Faraon.

In the coming years, the true impact of all these efforts will unfold as Caltech's students and postdoctoral scholars move on to careers in quantum engineering. Whether that means blazing new intellectual trails in academia, tackling the toughest problems at leading tech companies, or creating start-ups that define entirely new quantum engineering-based industries, Caltech students are uniquely equipped for success. "Despite Caltech's small size, its students tend to have an outsized impact because they're the people who go on to create new ideas and become leaders in the field," says Painter. In this new age of quantum engineering, he predicts that "Caltech will again be very influential as our students grow." ENG

> Quantum engineering is definitely where the next revolution in science and engineering will happen.

Stevan Nadj-Perge
Assistant Professor of Applied Physics and Materials Science

Andrei Faraon is Professor of Applied Physics and Electrical Engineering. Austin Minnich is Professor of Mechanical Engineering and Applied Physics. Stevan Nadj-Perge is Assistant Professor of Applied Physics and Materials Science. Oskar Painter is the John G Braun Professor of Applied Physics.

Robyn Javier is a STEM Communication Specialist and Lecturer in the Caltech Division of Engineering and Applied Science.

Lasers, Fiber Optics, and Endless Opportunities

Caltech's groundbreaking research has given rise to countless companies over the years. One remarkable success story is Ortel Corporation, which was founded in 1980 by Amnon Yariv, Martin and Eileen Summerfield Professor of Applied Physics and Electrical Engineering, and his group members Nadav Bar-Chaim and Israel Ury. The company was a pioneer in the development of semiconductor lasers for fiber-optic communication and was eventually acquired by Lucent Technologies. It subsequently spun off to become a division of Emcore Corporation and remains a prominent supplier of high-performance microwave optoelectronics components and fiber systems for the cable, wireless, and satellite communication industries.

ENGenious recently sat down with former Caltech postdoctoral scholar Nadav Bar-Chaim and two of his Ortel colleagues who are also Caltech alumni—Kam Lau (BS '78, MS '78, PhD '81, electrical engineering) and Henry (Hank) Blauvelt (PhD '83, applied physics)—to learn more about their training at Caltech and how it taught them to adapt to changes in technology and its applications.

***ENGenious*: What inspired you to become engineers?**

Hank: I was always intrigued with trying to make things. Figuring out how to use technology to solve problems is challenging, interesting, and rewarding.

Nadav: I actually wanted to become a physicist. But when I went to do my PhD, the school of engineering was new and had sort of an unlimited budget.

Nadav Bar-Chaim

So, I got my degree in electrical engineering, but I was able to do everything I wanted to do—keeping one leg in physics and one leg in engineering.

Kam: I can trace my interest in engineering back to when I was a kid. My father didn't get past first grade in elementary school, but he was extremely good with his hands. He used to buy model battleships for me that we glued together piece by piece, put in a motor and gears, and took to sail in a pond. That was a great inspiration for me, and I got interested in how to build things and how to improvise solutions when things don't work.

***ENGenious*: How did you come to join Professor Amnon Yariv's group at Caltech?**

Kam: I actually came to Caltech fully intending to major in aeronautics. In high school, I had read a biography of Qian Xuesen, the father of Chinese rocketry and a Caltech alum, and I was inspired to follow in his footsteps. But I was coming from Hong Kong, and I soon learned how difficult it would be to get an aeronautics job in the U.S. as a foreign student. So I decided to do something more practical. And that's how I ended up in electrical engineering. Right away I was impressed by the off-the-scale caliber of the faculty. Early on, I connected with Professor John Pierce (BS '33, MS '34, PhD '36), a Caltech alum who had been an executive director at Bell Labs, famed for leading the first satellite transmission demonstration in the 1960s. He came back to teach at Caltech in the 1970s, and it was through him that I got a chance to do research at Bell Labs during the summers of my junior and senior years. It gave me a taste for research and hooked me into the field of optical communication. Coming back to Caltech in the fall, I showed Amnon my work at Bell, and he was impressed enough to invite me to join his group to work for a PhD.

Hank: I was primarily attracted by the work they were doing on lasers. This research would be useful for fiber-optic communication, and it was a topic of particular interest to me. In addition, Amnon was able to put together a tremendous group of graduate students and postdocs, which made it a great environment to learn and develop your skills.

***ENGenious*: Tell us the story of Ortel.**

Kam: Back in the 1970s, there were already a couple of companies building semiconductor lasers. To make them practical, we had to make them lase continuously at room temperature. So this was the main goal of our work in Amnon's group at that time. Nadav filled the important role of making the first continuously operating laser in our lab. Then Amnon asked me to look into how fast we could modulate it; that is, how to make a laser that could be modulated faster than anyone else could do it. At the time, the fastest speed anyone could modulate semiconductor lasers directly was stuck at about 1 to 2 gigahertz. Together with other visiting researchers from Amnon's group, we salvaged some World War II era microwave equipment from campus surplus and were eventually able to push the speed up to 3, 4 gigahertz. Around the time I graduated in 1981, Amnon and Nadav and another student in the group, Israel Ury, had the idea to start a company building and selling these lasers—and that was of course Ortel. They asked me to join with the intention to differentiate the company as a supplier of high-speed lasers. Within a few years, we were able to push our lasers first to 8 gigahertz and then 10 gigahertz. No other company at the time came close.

Nadav: I believe the idea came up at a lunch. Amnon said we're making lasers as good if not better than anyone else, so we should commercialize them. At first, I thought he was joking. But I discussed it with my wife and figured, well, we have nothing to lose. If it works, great. If not, there are other opportunities. We'd try it for a couple of years and see. In those early days, each of us had our own territory. I was really into designing lasers and fabricating them. Israel was more of the packaging guy. Kam's area was testing, modeling, and designing high-speed lasers. And Hank joined later but eventually got involved in almost everything.

Hank: I joined in 1985. At that time, I was working on lasers with longer wavelengths—1.3 or 1.5 microns—which are outside the visible spectrum but work very well for transmitting signals through optical fibers. These signals can travel much longer distances than shorter wavelengths. I was still a graduate student when Ortel started. I was aware that starting a company was being explored, but I was not involved in the founding of Ortel.

***ENGenious*: Can you tell us a little more about the impact of Ortel's technology?**

Hank: Ortel's main niche was making lasers that could reproduce signals with extremely high quality. The applications we were working with involved complicated signals that correspond to what comes into your home through a cable TV network. There are lots of video channels and they all have modulation, so you have to reproduce that signal with the best accuracy possible. We had a very good

Kam Lau

reputation for making lasers that accomplished this goal, and the technology persisted even after Ortel was acquired by Lucent and no longer existed as an independent company.

Nadav: We were actually the first to show the cable companies that you can use semiconductor lasers to bring the signal to the home. It allows for much better quality, longer distance transmission, and more channels. About 60 percent of homes with cable TV get their signal via Ortel's technology. Interestingly, our main market before that had been defense. But in the late 1980s, when the Cold War ended, a lot of the defense work dried up. So we adapted and found a new opportunity in cable TV. Now of course the focus is on providing high-speed internet rather than supplying TV channels, but Ortel's laser technology has remained crucial.

ENGenious: **What are your favorite memories of your time with Amnon and the group?**

Hank: My best memories from my time at Caltech are about the collaborative environment that existed in Amnon's group. There was a large group of graduate students and postdocs working to better understand the emerging field of semiconductor lasers, but for the most part we were working on independent projects. This resulted in a very high level of constructive interactions and discussions with minimal competition for credit for the results. I found it to be very favorable for learning.

Kam: I remember being extremely protective of my experimental setup. I used to plaster threatening signs all over my microwave measurement equipment: "DO NOT TOUCH!" "DO NOT MOVE!" "DO NOT LOOK!" "DO NOT THINK!" "DO NOT EVEN BREATHE!"

ENGenious: **How is a Caltech education viewed in your industry?**

Hank: Caltech is small, but in every area where it's heavily involved, its researchers are viewed as leaders. Especially people like Amnon who have such high standing in the scientific and engineering world. That affords Caltech students a lot of freedom. We would get these open-ended research projects where we could do almost anything we wanted. Being able to follow the science wherever it leads is a tremendous opportunity.

Nadav: Between the professors, students, and research fellows, you have a lot of good brainpower here. So the ability to translate ideas into reality is natural for Caltech trainees. At Ortel, our strength as a technology leader was based on our close connection to academic research. That's how we gained advantage over the competition—we were always a step ahead.

Kam: Training with the world-class faculty at Caltech really sets you apart. Amnon, for example, is extremely well known and well respected in the field of fiber optics and optoelectronics. When I was working in his lab, we constantly had recruiters from industry visiting our group. His students were hotly pursued as soon as—or even before—they graduated, and each of us got multiple job offers. This is a testament to how valuable a training in Amnon's group was regarded in industry, and still is today.

ENGenious: **What advice do you have for current Caltech students?**

Nadav: Keep an open mind in what you do. Don't get married to a specific idea—if it doesn't work out, just go around the corner and try something else. And be a team player. For practical work, it's much easier to accomplish things in teams.

Hank: Learn as much of the conventional wisdom and theory as possible, but realize it's always incomplete. Progress comes from finding what's wrong with or missing from the conventional wisdom. When things don't go as expected, those surprises often lead to whole new areas of study.

Henry (Hank) Blauvelt

Kam: As a student, it can be easy to focus just on coursework, exams, and your own narrow research topic. But you should take advantage of the world-class resources available to you through Caltech, the connections to industries, and faculty like Amnon. And take advantage of mission-oriented facilities like JPL, big optical telescopes like Palomar and Keck, and radio telescopes at Owens Valley. Those are major engineering undertakings that present tremendous real-life experience for EAS students. Especially JPL, since it is within daily commute distance of the campus. Don't be shy—knock on doors and ask for opportunities.

Nadav Bar-Chaim was vice president of Ortel Corporation. Kam Lau is Professor Emeritus in the Department of Electrical Engineering and Computer Sciences at the University of California, Berkeley and was a founding staff scientist and then the chief scientist at Ortel Corporation. Henry (Hank) Blauvelt is the Chief Technology Officer at Emcore.

The Caltech Y: Learn by Doing

For more than 100 years, the Caltech Y has engaged Caltech students in a wide variety of programs and services that create opportunities for adventure, leadership, and service. The activities and events offered are student-driven, and remarkable programs have emerged over the years. One shining example is the Rise Program, a low-cost after-school tutoring program in math and science in which Caltech undergraduate and graduate students tutor public-school students between grades 8 and 12. Another is the Student Activism Speaker Series (SASS), the student-run lecture series. And, last but not least, the Y is still the place to go to rent camping equipment!

ENGenious interviewed the Caltech Y team that includes executive director Athena Castro, staff members Greg Fletcher, Liz Jackman, and Agnes Tong, and board chair Peter Hung (BS '08, PhD '16). Working out of the Tyson House on Wilson Avenue (the Y moved there in 2011), the team helps facilitate programs centered on the five pillars of leadership, service, adventure, civic engagement, and perspective—and, along with Caltech students and many friends (some of them four-legged), continues to provide profound experiences for Caltech and its surrounding community.

Top row: Camila Fernandez, Maria Johnson Kriechbaum, Liz Jackman, Greg Fletcher, Miranda Maxwell; bottom row: Marta Lopez Viseras, Athena Castro, JJ the dog, and Agnes Tong at the Tyson House

ENGenious: **What is the role of the Caltech Y?**

Athena: The Y's mission complements Caltech's mission—we help to create citizen scientists. Part of what we do is present current issues to students and challenge them to become involved. By inviting speakers to campus

Top: Rise tutoring with current graduate student Haley Bauser (left)

Right: SASS committee with Bernie Sanders in 2004

Bottom: Caltech Y Board Chair Peter Hung (BS '08, PhD '16) in front of the White House on the 2013 DC Science Policy trip with Student Activities Director Greg Fletcher (middle) and Josie Kishi (BS '14) (left).

to talk about what's happening in the world—locally, nationally, and globally—students learn what those issues are. We saw that recently with the March for Science and the way students got involved. We want to develop compassionate leaders. We want them to think about the issues that affect the wider community and how they themselves will contribute as they become leaders in their companies, in industry, or in their research labs. That's why leadership and perspective are the bookends of the Y's pillars.

Peter: Leadership is one of the things that we, the students, can learn through our involvement with the Y.

Greg: Athena once said, "Where else other than a college campus can you get this kind of experience where you can engage with different perspectives and hear from the other side?" And, I would add, be challenged in a respectful way. You can disagree or not like certain things. It's not always going to be easy. But it's still good to hear and respond to other perspectives. You still gain from the experience. Providing these types of opportunities is certainly one of the roles of the Caltech Y.

***ENGenious*: Tell us about some of your programs.**

Greg: We have 70 or so programs going on during the year, not including the weekly and monthly service projects or the Rise tutoring program—including those pushes us to well over 100 events each year.

Liz: And the Rise program just keeps growing. In 2018, we had 150 tutors—with a small place like Caltech, that's a really high participant rate. Student tutors have to commit to at least two terms, but most of them commit to at least a year. One of the tutors had the idea to start an SAT/ACT tutoring program, so we expanded Rise and started that program this past year.

Greg: Our Washington, DC Science Policy Trip is going on 14 years now. This program was initiated by Patricia Neil [PhD '06], who was then a grad student serving on ExComm, our student executive committee. We've seen hundreds of students participate in this program—and we get some pretty impressive access. We've seen the director of DARPA, the director of the NSF, a director at the NIH. We've been to the White House Office of Science and Technology Policy, seen former science advisors to Secretaries of State and to Vice President Al Gore, talked with the former director of the Office of Technology Assessment, and that is just scratching the surface. In all of these places, we have the opportunity to ask questions and to have real dialogues.

Agnes: Union Station is a program that has a lot of impact. Students buy the food, pick out the menu, cook, serve, and clean up. They talk to the residents and hear their stories—how they got to where they are, how they plan to move forward. Our students see how homelessness is affecting our community, and they come to realize how privileged they are studying at Caltech.

Athena: There are the outdoor-adventure programs: hiking, backpacking—all opportunities for students to get back to nature. It's a great decompressor, a great way to mitigate the stress that you're feeling and get in touch with yourself. There's nothing like being out in the backcountry hauling 30 pounds on your back.

***ENGenious*: What has been the impact of Caltech Y programs?**

Peter: My first exposure to the Y was as an undergrad, going to Union Station and learning how to cook for 60 people. I personally grew up in a low-income family. Going to Union Station and seeing people in need was not out of the ordinary. But by the time I was a grad student, I had gotten so used to going to the Athenaeum, the faculty club at Caltech, that I forgot there was a real world outside of Caltech, where people didn't have a place to stay and weren't getting enough food. Caltech was just so academically demanding that often, we lived in the campus bubble. The Y really pulled me out of that bubble and helped me reconnect with the rest of the world. Later, in my graduate career, I got more involved with the student ExComm where I learned a lot of my leadership skills. After I graduated, I stayed on the board, and I'm currently the chair.

Agnes: I saw the growth of a current chemistry grad student, Matt Chalkley. When he first came to Caltech, he had many fellowships, including one from NSF. He was on the quiet side, and several years later, I ran into him on campus and he told me, "The Rise tutoring program has changed me drastically. I now get to communicate about science with high school students and get them excited and talk about why science matters. While research is not always perfect, I know that my students will always depend on me, and I'm making a huge difference in their lives."

2019 Y-Hike group in front of Half Dome

***ENGenious*: How does the Y challenge students?**

Greg: The Y challenges students in many ways—leading programs, going on trips or adventures, participating in civic life in different ways, and exploring various topics, any of which may be outside students' comfort zones. SASS has a long history of doing this. It was established in 1999 and followed in the footsteps of past Caltech Y speaker series, which had been bringing speakers to campus since the '50s—including Dr. Martin Luther King, Jr., in 1958. During the 2003-04 academic year, one of our students felt the Patriot Act was an important issue and knew of a congressman from Vermont—Bernie Sanders—who was opposed to it. So, we invited Sanders and he came. Now everybody knows him. The talks alone are thought-provoking, but from my perspective, the question-and-answer period is often better than the talk itself. It's a testament to our students that they are thinking and engaging with real issues, tough questions, and follow-ups.

Liz: Two years ago, we went to Texas to do clean-up work after Hurricane Harvey. We were ripping out walls. There were maggots. It was hard work. The undergraduate student who organized it, Noelle Davis [class of 2021], is an outstanding leader. We were a group of eight, all female. All of us looked to Noelle, our fearless leader, to guide us as to what to do and where to go, even on the kayaks. The undergrads were from different houses, and by the end of the trip all of us bonded and became great friends. Sometimes the impact goes beyond the service; it can be a deep learning experience about yourself.

***ENGenious*: How do students become leaders?**

Greg: Our leadership development is through practice, through involvement, and through doing. The staff works alongside the students to help mentor them, but not do it for them. There's a matching up of experienced leaders with novice leaders, so they get a chance to learn that way too.

Liz: It's experiential-based learning leadership. I see so many frosh come in, sit in meetings, and not say a lot. Then they might volunteer to co-lead something. Eventually, they start leading alternative spring breaks or other programs all by themselves. It's pretty amazing to see their growth as they come into their own and get more comfortable in their role as a leader. We've seen that countless times in students over the years. I love it.

Athena: The student ExComm that Peter was involved with has purview over a wide swath of programming. They play a large role in determining student program topics and budgets. They work closely with Greg and with the office in general. The Outdoors Committee fosters leadership skills through camping and outdoor programs. These programs connect students with the natural world and teach them to be self-sufficient in different ways than some of our other programs.

***ENGenious*: What is unique about the Caltech Y?**

Greg: Students really get a say—they are leading the Y. They are making decisions about programs, activities, community service, and how funds are allocated. All of that is being done by students. It's essential that the Y is student-driven.

Athena: What the Y offers is distinctive because it gives the students the opportunity and initiative to pick and choose—to do all or do some. A lot of campuses have student activities and leadership groups. And they have students who are leading the programs. But from what I've seen, ours is the most comprehensive.

***ENGenious*: What should alumni know?**

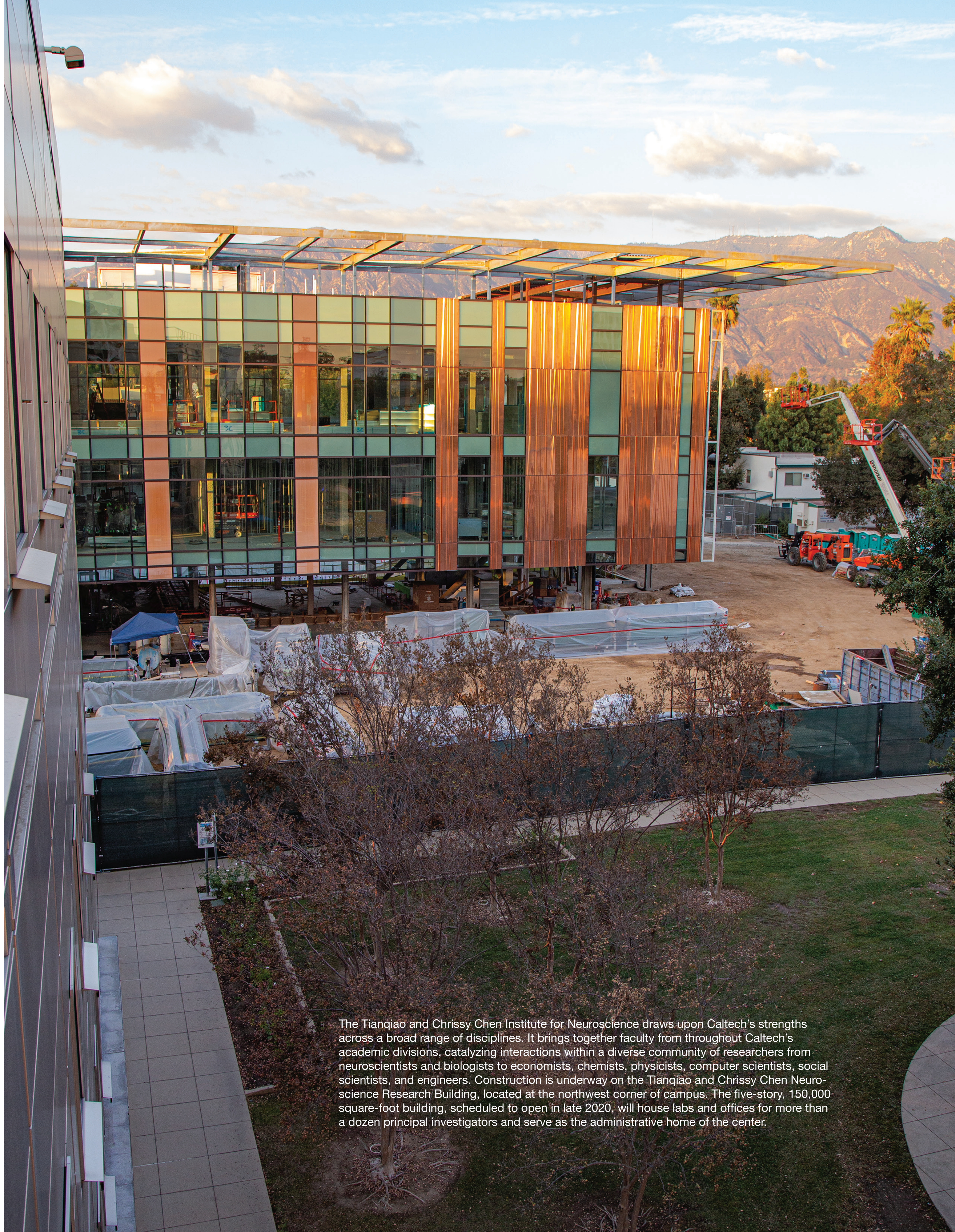
Peter: Alumni and community members can participate! We have seen people, especially alumni, who never participated in Y programs when they were students, but now see it's really worthwhile to contribute to the Caltech Y.

Greg: People are surprised to learn how much of our budget comes from individual donors. As a nonprofit, we raise funds for our activities, and the vast majority of that comes from alumni, faculty, and staff. They want to make sure that students have the opportunity to create new things and deepen their experience of the world.

Athena: We love to hear from alumni, and we want to stay connected. There's always an opportunity to be engaged with the Caltech Y, even after you graduate. And it doesn't have to be by giving money. It could be offering expertise or services, or contributing in some other way. Alumni come back and become board members. We remain student-focused because that is the heart and soul of the Caltech Y. We're here to enrich student life and challenge students to become responsible citizens of the world. ENG

Athena Castro is Executive Director. Greg Fletcher is Program Director. Agnes Tong is Director of Marketing and Development. Liz Jackman is Associate Director of Student Programs. Peter Hung (BS '08, PhD '16) is Board Chair of the Caltech Y and currently works at The Aerospace Corporation.

Visit caltechy.org



The Tianqiao and Chrissy Chen Institute for Neuroscience draws upon Caltech's strengths across a broad range of disciplines. It brings together faculty from throughout Caltech's academic divisions, catalyzing interactions within a diverse community of researchers from neuroscientists and biologists to economists, chemists, physicists, computer scientists, social scientists, and engineers. Construction is underway on the Tianqiao and Chrissy Chen Neuroscience Research Building, located at the northwest corner of campus. The five-story, 150,000 square-foot building, scheduled to open in late 2020, will house labs and offices for more than a dozen principal investigators and serve as the administrative home of the center.

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