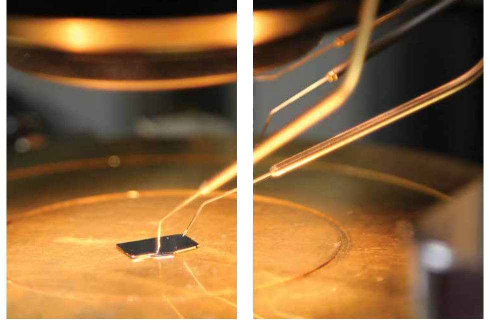
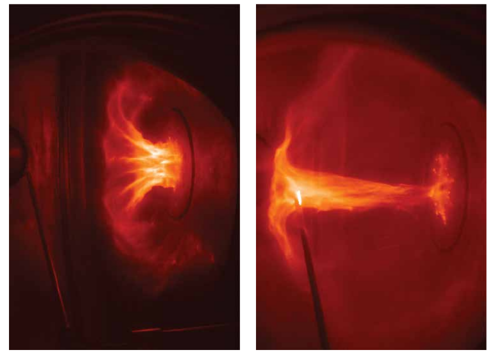




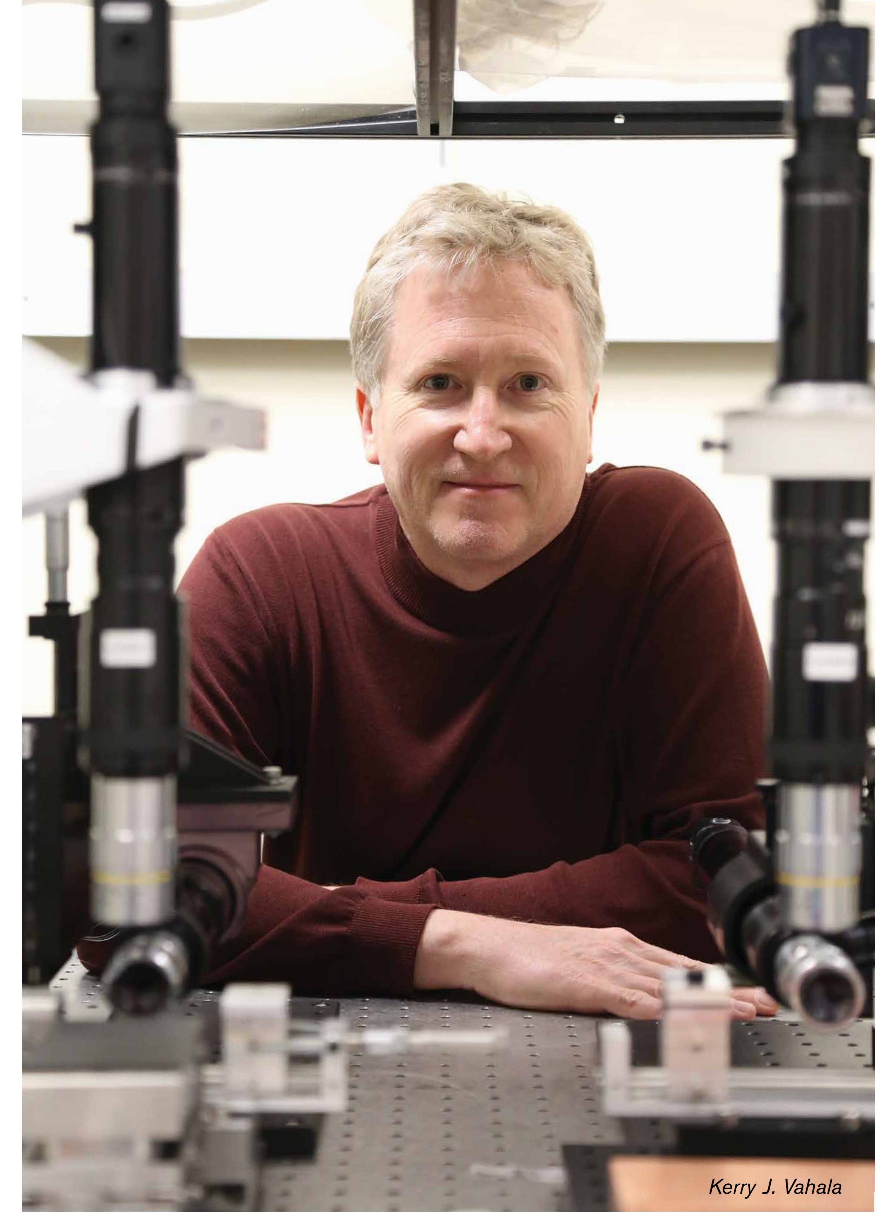
Strikingly Passionate

Applied Physics and Materials Science Faculty

The Caltech Applied Physics and Materials Science (APhMS) faculty are strikingly passionate about their unique mix of theoretical and experimental work. They are thriving in the creative and collaborative intellectual environment provided by the Division of Engineering and Applied Science and Caltech. As they work at the frontiers of their fields, they know that understanding and teaching the fundamental sciences is what has led to their long individual and collective track record of success. *ENGenious* had the opportunity to interview a subset of the APhMS faculty as they were preparing for a celebration in November of the future of their department. The faculty shared their excitement about measuring physical phenomena that could only be dreamed about a decade ago and tackling problems of societal significance, such as the energy crisis and mapping the human brain.

The current Executive Officer of the APhMS Department is Kerry Vahala, who is the Ted and Ginger Jenkins Professor of Information Science and Technology and Applied Physics. "There's always been this natural affinity between applied physics and materials science, which is strengthened by proximity on the Caltech campus," Vahala says. "We have an actual bridge between our buildings in addition to the intellectual bridges we have!" This affinity has been well recognized by the impressive group of materials science and applied physics alumni planning to attend the November celebration. Vahala can speak for those past students of applied physics, as well as today's: "Every student has a different set of passions and interests. The applied physics curriculum is foundational and lends itself to branching out in many different ways; it gives the students the flexibility to pursue their passions." Though he is a newcomer to materials science, Vahala says in his capacity as Executive Officer, he is learning fast. "Even before the formation of the APhMS department, materials science was a great partner with applied physics. Many faculty have worked together on the curriculum and jointly taught classes."

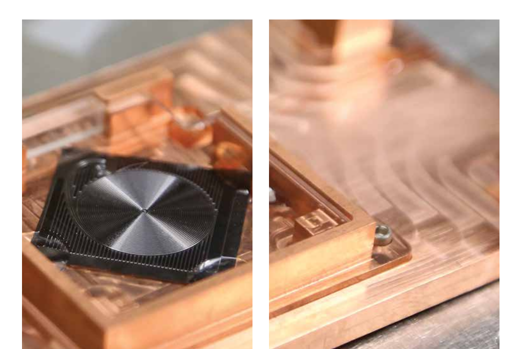
Today, research opportunities that maximize that overlap abound in the department. For example, Vahala explains, "Many applied physics groups, including my own, are interested in taking fairly well-understood materials systems and then exploring the physics of turning these materials into devices. This mission is highly complementary to the research of many Caltech

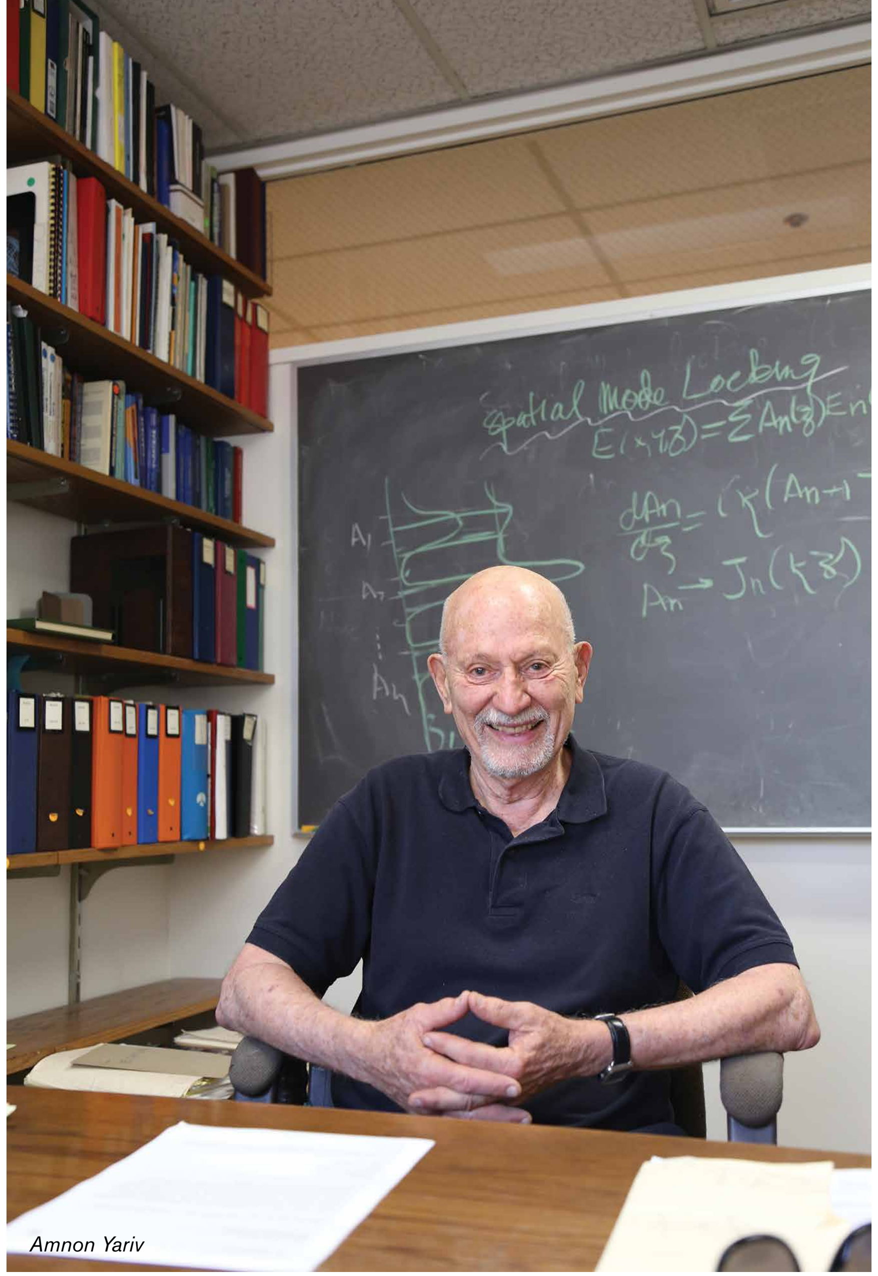


Kerry J. Vahala

There's always been this natural affinity between applied physics and materials science, which is strengthened by proximity on the Caltech campus. We have an actual bridge between our buildings in addition to the intellectual bridges we have!

Kerry J. Vahala, *Ted and Ginger Jenkins Professor of Information Science and Technology and Applied Physics; Executive Officer for Applied Physics and Materials Science*





Amnon Yariv

materials scientists, who are acquiring a fundamental understanding of materials at the atomic level, the structural level, and then using that information to design better materials." Vahala studies high-Q optical resonators, which are like tuning forks for light. Most recently, his group has developed and demonstrated a method to stabilize microwave signals in the range of gigahertz, or billions of cycles per second, using a pair of laser beams as the reference instead of a crystal. This new technique, dubbed electro-optical frequency division, has the potential to revolutionize electronics containing oscillators.

Revolutionizing and creating new fields is a tradition at Caltech. Vahala's PhD advisor, Professor Amnon Yariv, has made scientific and engineering contributions to photonics and quantum electronics that have transformed light-wave communications and the field of optics as a whole. The Martin and Eileen Summerfield Professor of Applied Physics and Professor of Electrical Engineering has been at Caltech for more than three decades and was instrumental in starting the Institute's applied physics program. How does Professor Yariv see applied physics? "To use a chess analogy, in physics you are looking to discover the basic moves of the pieces, the laws governing the universe. In applied physics, we take the discovered laws and ask what kinds of new games we can make with them, preferably games of societal interest," he says. In establishing the applied physics program at Caltech, Yariv was a pioneer. "When Professor Roy Gould and I started the department in the early '70s," he explains, "we were driven by the then-recent appearance on the scene of new fields such as lasers and plasma fusion that, though applied, required a basic physics background of its practitioners. We were the first or second applied physics department at any university, and with our success we became the model."

Over the years, Yariv's group has created a number of new research areas. He notes, "There are a number of fields that owe their beginning to work in our group, such as quantum non-linear optics, optoelectronic integrated circuits, phase conjugate optics, and the distributed feedback semiconductor laser—still the main light source for the Internet optical fiber backbone."

Yariv appreciates the distinctions that draw some students to applied physics over physics. "The choice is one of natural inclination," he argues. "Are you driven by discovering secrets of the universe, or are you driven more by creating new applications capable, hopefully, of enriching our lives? Put in more personal terms: is your role model somebody like Albert Einstein who elucidates the phenomena of stimulated and spontaneous emission of light by atoms, or is it more like a Charles Townes—by the way, a Caltech physics PhD—who uses this understanding to invent the laser and thus opens up the strange and wondrous field of light manipulation and quantum optics?"

William L. Johnson, Caltech's Ruben F. and Donna Mettler Professor of Engineering and

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> *"I still see myself as a physicist who is masquerading as a materials scientist. When I was hired by EAS Division Chair Bob Cannon in 1977, he told me I had to wave the materials science flag, and I have done it proudly."*
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William L. Johnson


William A. Goddard III

> *We need to solve many of the technical problems as a community. Our society is faced with extreme problems in the development of clean energy and providing people with clean water. Applied physicists and materials scientists must help solve these problems.*
>
> William A. Goddard III, *Charles and Mary Ferkel Professor of Chemistry, Materials Science, and Applied Physics*

Applied Science, who was one of the first Caltech students to get an applied physics degree, came to just this kind of realization. He was in the right place at the right time, he explains: "I came to Caltech in the Fall of '70 to be in the physics PhD program, but after a year and a half, I decided I wanted to do something more practical, something a little more related to engineering devices, real things. That was when applied physics was just forming, and I became one of its first graduates in 1974."

Now, 40 years later, Johnson explains that he still sees himself as "a physicist who is masquerading as a materials scientist. When I was hired by EAS Division Chair Bob Cannon in 1977, he told me I had to wave the materials science flag, and I have done it proudly." Johnson attributes his success and his students' success to the intellectual freedom offered by Caltech."There are no real barriers to interacting and collaborating," he says. "Faculty share students even between divisions. The students can decide whether they want an applied physics degree, a materials science degree, or a chemistry degree. That's an academic decision for the students; it's not really an issue or any kind of intellectual barrier to what the faculty work on."

A longtime collaborator of Professor Johnson's is William A. Goddard III, Charles and Mary Ferkel Professor of Chemistry, Materials Science, and Applied Physics. The two scientists have shared graduate students over the years, co-advising their work on problems of mutual interest in the areas of metals, materials, liquids, and metallic glasses. Goddard, Johnson recalls, "is able to interact with probably the most diverse cross section of faculty of anybody I know at Caltech. Anything that's a good science problem, Bill will tackle! Bill has worked on problems ranging from cell biology to nanomechanics to energy materials, fuel cells, and thermoelectrics."

Goddard, also an original founder of the applied physics program at Caltech, has expanded the intellectual environment at the Institute with his far-reaching problem-solving perspective. "We need to solve many of the technical problems as a community," he says. "Our society is faced with extreme problems in the development of clean energy and providing people with clean water. Applied physicists and materials scientists must help solve these problems." Since obtaining his PhD in engineering science at Caltech and switching to the chemistry faculty, Goddard's goal has been to use theory and computers to predict new materials with optimum properties. As he explains, "The experiments are getting more expensive and empirical developments are taking too long. Our goal is to use theory and computers to spec out new materials to identify the most promising and to work with experimentalists to focus them on the systems predicted to be the very best. That's our main goal as theorists (in addition to having fun)!" In the field of energy research, Goddard has teamed up with Professor Sossina Haile, an experimentalist, to develop the improved fuel cells needed for energy storage and production. "She continues to invent improved systems," he says, "and we try to understand why they are better and suggest new variations."

Haile, Caltech's Carl F Braun Professor of Materials Science and Chemical Engineering, notes that as a field, "materials science remains

> *Materials science remains at the frontier in terms of trying to understand how you can put devices together, atom by atom, to get unprecedented behavior and control.*
>
> Sossina M. Haile, *Carl F Braun Professor of Materials Science and Chemical Engineering*


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Katherine T. Faber

I think passionate *is probably the word that comes to mind with almost every faculty member here. It's just really striking. They're not here to bide their time. They're very engaged—and the other impression I get is that they love it here.*

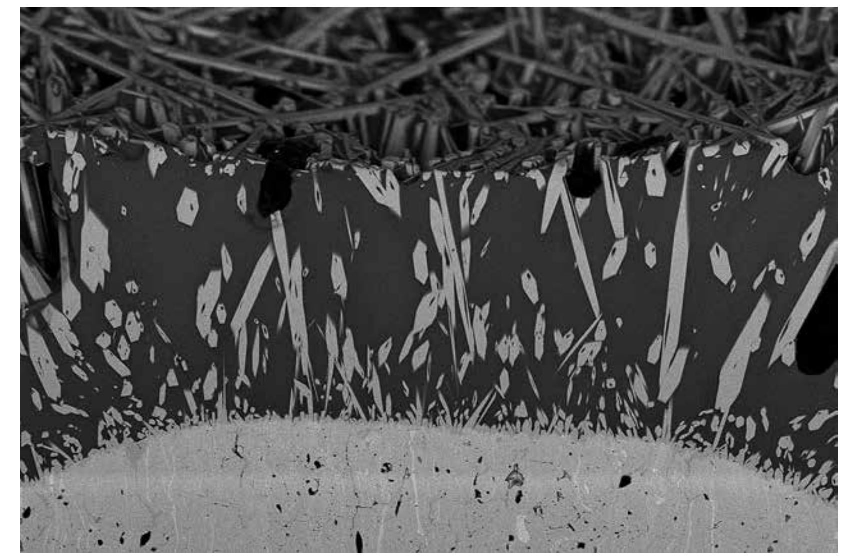
Katherine T. Faber, *Simon Ramo Professor of Materials Science*

at the frontier in terms of trying to understand how you can put devices together, atom by atom, to get unprecedented behavior and control." Rapid advances in technology and techniques, she adds, have made work in the field particularly exciting recently. "There has been tremendous convergence of techniques in that we can go smaller and smaller experimentally (using facilities like those in the KNI), and larger and larger computationally (collaborating with people like William Goddard)," she says. "This allows us to put things together in ways that were never done before. We can create functionality that we could hardly dream of a generation ago, and get at the results in a fraction of the time. The advances are so exhilarating, I wish I were a graduate student all over again!"

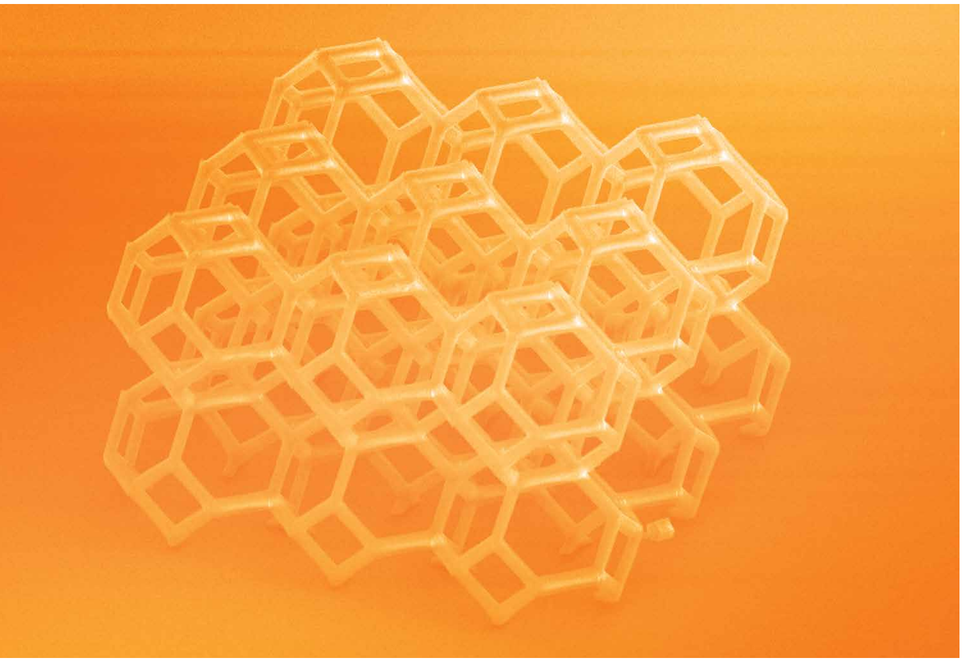
Haile has a demonstrated knack for channeling that enthusiasm. In terms of her own research, she says, "I look for the intersection between lasting scientific impact and lasting social value. Among all the exciting scientific endeavors that one could pursue, how does one down-select? For me, that down-selection is about the societal significance."

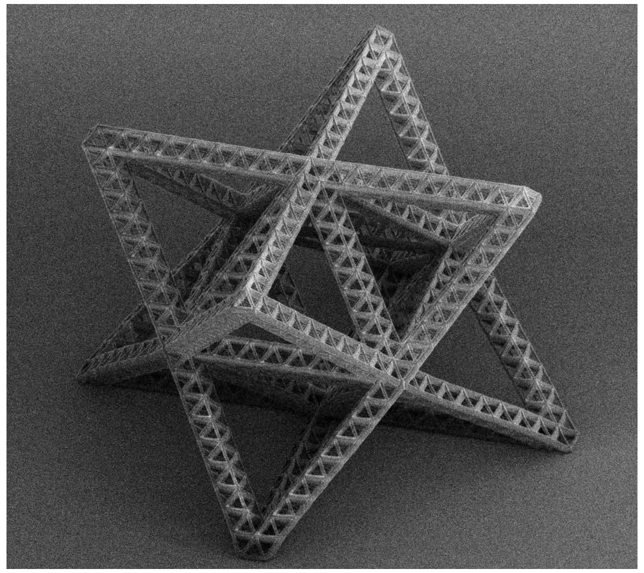
As a new faculty member in the APhMS Department, Katherine T. Faber, Simon Ramo Professor of Materials Science, has not had as much time as she would like to get to know her colleagues. Still, she says, "I think *passionate* is probably the word that comes to mind with almost every faculty member here. It's just really striking. They're not here to bide their time. They're very engaged—and the other impression I get is that they love it here. They all use the same sentence: 'Caltech is a very special place.'" Professor Faber describes her path to becoming a materials scientist as "serendipity." She recalls, "I went to a very small university in New York State, Alfred University. Within Alfred University is the New York State College of Ceramics. In this model students can attend the private university but pay state university tuition if they study particular programs. When I started, my goal was to become a chemist, but I went in through the ceramics college to get the lower tuition. Then, once I got to organic chemistry, I realized that ceramic engineering was much more exciting for me. I appreciated the applied side of it, which involved much more problem solving."

Professor Faber's research expertise is in the fracture of brittle materials and the mechanisms by which such materials can be toughened and strengthened. One application for her ceramics work is energy-related: it includes thermal and environmental barrier coatings for power generation components. She explains, "Work on high-temperature materials plays an important role in the energy domain. If we can operate engines at higher temperatures, they're going to be more efficient. The silver bullet has yet to be discovered in terms of the best material to use for these coatings, and that excites me!"



Silicon carbide and silicon nitride have been identified as some of the most promising materials for high-temperature structural applications in engine environments due to their low density, excellent mechanical properties, and good thermomechanical stability. These ceramics must be protected from water-vapor-containing combustion atmospheres and from airborne deposits, such as sands and volcanic ash, which are inevitably ingested into turbines. Environmental barrier coatings are being designed to protect these ceramic materials, but the coatings require further development, as evidenced here. The image shows a ytterbium monosilicate coating (lower layer) after exposure to a typical silicate (sand) deposit at 1300 °C for only four hours. The coating and silicate interact strongly to form a new phase, a ytterbium-silicon-apatite, the needle-like precipitates in the middle and upper layers, thus compromising the barrier. The image was taken using scanning electron microscopy of a cross section of the reaction couple.





Examples of three-dimensional architected nanomaterials made by the Greer group. **Top:** *A truncated dodecahedron nanolattice made out of hydroxy apatite that serves as a three-dimensional scaffold for bone cell growth.* **Bottom:** *A hierarchical nanolattice where each beam is comprised of self-similar nanotrusses instead of being monolithic.*

In addition to her ceramics research, Faber has been instrumental in establishing the Northwestern University–Art Institute of Chicago Center for Scientific Studies in the Arts, where advanced materials characterization and analytical techniques are used in support of conservation science. She explains with one example: "We've had electrical engineers using different imaging techniques to establish what some paintings would have looked like when they were first painted. These art/science connections give students a much broader context of what they can do with a science and engineering degree."

The intersection of art and engineering is also of great interest to Julia Greer, Professor of Materials Science and Mechanics, whose second passion is her work as a concert pianist. Her research group has created beautiful three-dimensional nanostructured rigid scaffolds, often hollow, that display remarkable strength and resistance to failure despite being more than 99 percent air. Similar fabrication techniques could be used to produce lightweight, mechanically robust small-scale components such as batteries, optical switches, catalysts, and implantable biomedical devices. "We are acting as architects to build novel materials whose properties are not conventional and are often useful and unprecedented," explains Greer. "Unlike in typical design of materials, we think in the opposite direction: we first identify the specific properties that we want, and we then try to create them by using our approach. One thing that sets our three-dimensional architected nanolattices apart is that they do not have to be pigeonholed into one particular field but rather can influence multiple areas."

"We are acting as architects to build novel materials whose properties are not conventional and are often useful and unprecedented."

Julia R. Greer, *Professor of Materials Science and Mechanics*

Julia R. Greer

Austin Minnich, Assistant Professor of Mechanical Engineering and Applied Physics, has been working with Professor Greer to explore the thermal properties of these nanotrusses. He sees great potential in this type of work. "Thermal sciences are very important to our society today," Minnich says. "Ninety percent of energy conversion today is thermally based, such as a steam turbine's coal fire or natural gas fire power plants. My research involves experimental and computational methods to looking at the microscopic picture of thermal sciences and heat transport."

The evolution of this research has been gratifying for Minnich, who never loses sight of the bigger picture. His excitement is justified: "We created a nanostructured version of a material that has been used for 50 years and increased the thermal efficiency by about 50 percent. What we're doing has clear and direct impact on the energy problem—we can do something about it!" Key to that process, he notes, are the talented students who move through Caltech: "We're producing really strong students—among the best in the world. We're giving them a really solid foundation in computation and experiment to help them be leaders after they leave Caltech. I see this as a very important role for Caltech and the APhMS Department."

The work of another APhMS faculty member, Harry Atwater, the Howard Hughes Professor of Applied Physics and Materials Science, is driven by curiosity about light-matter interactions at and below the scale of the optical wavelength itself, which is the realm of nanophotonics. He is also dedicated to researching and addressing global energy challenges. Atwater currently serves as director of the DOE Energy Frontier Research Center on Light-Material Interactions in Energy Conversion, and he is also the director of the Resnick Sustainability Institute, Caltech's largest endowed research program. His scientific interests have two themes: plasmonics and optical metamaterials, and photovoltaics and solar energy conversion. Atwater and his group have developed principles for light management in photovoltaics and have created new high-efficiency solar cell designs. He is also co-founder of Alta Devices, a solar technology company in Santa Clara, California, that has developed low-cost gallium arsenide (GaAs) photovoltaic cells and modules with world-record cell efficiency.

Professor Atwater's broad interest in and passion for energy was sparked during the energy crisis in the 1970s. He explains, "That was the first time I became acutely aware that energy was a precious commodity. When I was a teenager, I didn't have that much ability to impact the energy crisis—but now, as a working scientist, I do. I believe that high-efficiency solar energy and renewable energy conversion is a very significant component of an ultimate solution to some of the biggest challenges of our time—namely, climate change and energy security. Currently my group is designing materials that absorb and emit light in unusual and sort of extreme ways to benefit high-efficiency solar energy conversion and thermal energy management. Our work is also driven by pure curiosity about the world of light, and so we are also interested in extreme light confinement in plasmonic and photonic structures and optical phenomena that emerge at the single- or few-photon level."

Austin J. Minnich

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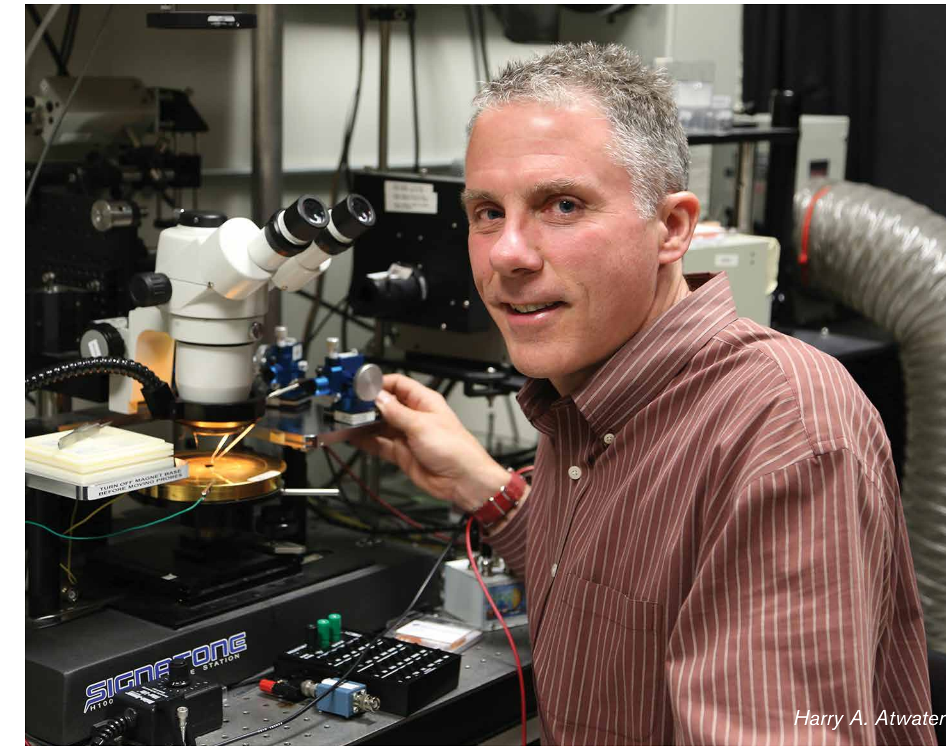
>
> Austin J. Minnich, *Assistant Professor of Mechanical Engineering and Applied Physics*

Reflecting on the interplay between applied physics and materials science, Atwater says, "What I've noticed at Caltech as we move into the 21st century is that 'physics is the new engineering,' so to speak, or at least it's hard to find the boundary between them. As understanding of fundamental engineering principles moves from a continuum to an atomistic-based description of materials, it's essential now for any scientifically learned person to understand quantum mechanics, statistical mechanics, and electrodynamics. Today, nanoscale phenomena are becoming more and more significant in determining the performance and behavior of materials, structures, and devices." A keen awareness among the faculty of this interplay is particularly beneficial to APhMS students—an advantage that is not lost on them. "The students also appreciate the fact that a degree from the APhMS Department is in essence a license to do almost anything that crosses the boundaries between the fundamental and practical," says Atwater.

Brent Fultz, Barbara and Stanley R. Rawn, Jr., Professor of Materials Science and Applied Physics, is no stranger to this APhMS approach. "We are less focused on a solution to a materials problem that can be done in a quick way," he says.



Harry A. Atwater

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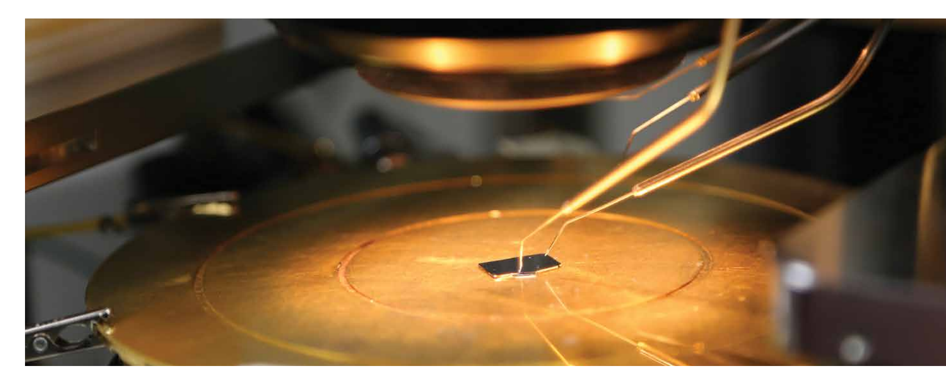
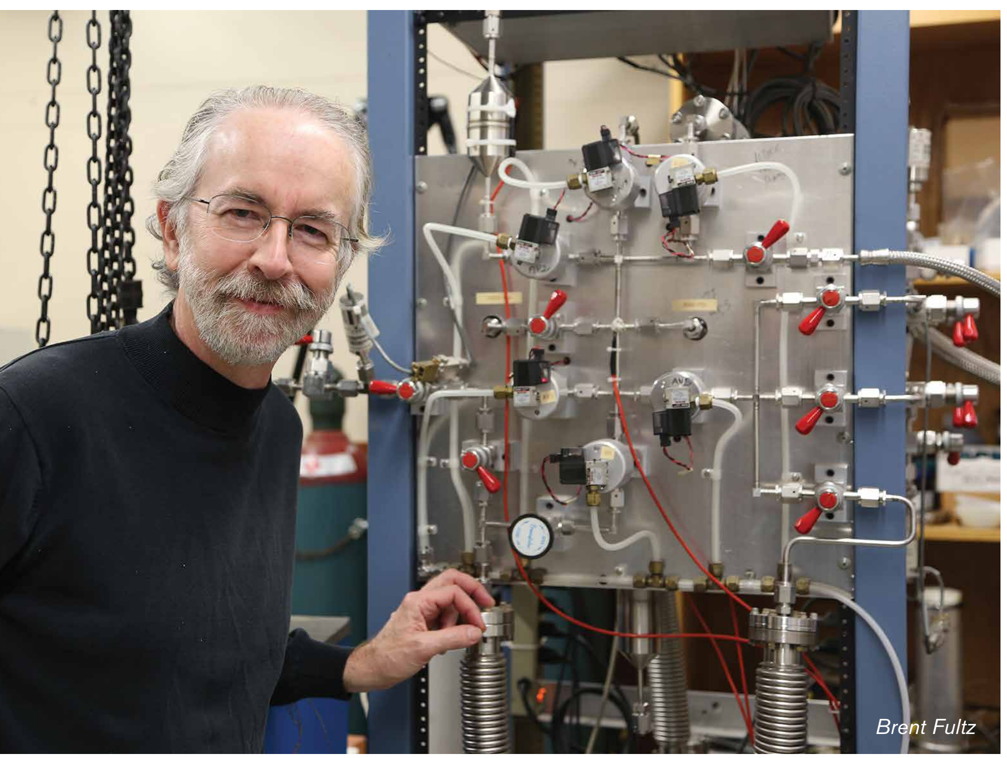


"I am organizing the community of scientists who do X-ray and neutron scattering to more efficiently and effectively do high-performance computing with the materials codes that exist today that did not exist some 15 years ago, and to get more science out of their research."

Brent Fultz, *Barbara and Stanley R. Rawn, Jr., Professor of Materials Science and Applied Physics*



Brent Fultz

"We try to take a long view of the fundamental issues. For instance, in my group, we look at the different structures of materials and figure out how their vibrations will differ and understand their differences and their thermodynamics. This tells us where entropy comes from." To maximize the impact of such work, Professor Fultz has also been forming larger collaborations: "I am organizing the community of scientists who do X-ray and neutron scattering to more efficiently and effectively do high-performance computing with the materials codes that exist today that did not exist some 15 years ago, and to get more science out of their research."

Fultz learned that this kind of collaboration is especially fruitful when balanced with individual innovation, which requires the freedom to take risks. He recalls a pivotal moment in his career—an interaction that took place during his first few years at Caltech. "I had been here as an assistant professor for maybe two years, and I was getting into a small controversy with someone else in the field," he explains. "It was just a question on viewpoint. I mentioned this to a senior applied-physics faculty member, Noel R. Corngold, and he said, 'Well, just do it your way. Work it out yourself. You can figure out later what the literature says.' And I thought: That is a good attitude! I was naturally inclined that way anyway, and he just pushed me over the edge. That was fun!"

This freedom to play and explore, a fundamental part of Caltech's orientation, was a key motivator for Roy Gould, Simon Ramo Professor of Engineering, Emeritus, to start the applied physics program along with Professor Yariv and to serve as its first Executive Officer. "As a graduate student at Caltech," he recalls, "I had decided that high-energy physics was not for me. I was more interested in the applied aspect, and I had dabbled a little bit in astrophysics, so I ended up doing my thesis in electronic

Roy W. Gould

"As a graduate student at Caltech, I had decided that high-energy physics was not for me. I was more interested in the applied aspect... As a faculty member, I explored the nebulous boundary between electrical engineering and physics."

Roy W. Gould, *Simon Ramo Professor of Engineering, Emeritus*

Magnetohydrodynamic plasma jets routinely produced in our lab are about half a meter long, and yet they look like and behave in much the same way as astrophysical jets that are about 50,000 light years long. It is delightful and amazing that the same plasma ideas apply to such fantastically different circumstances.

Paul M. Bellan, *Professor of Applied Physics*

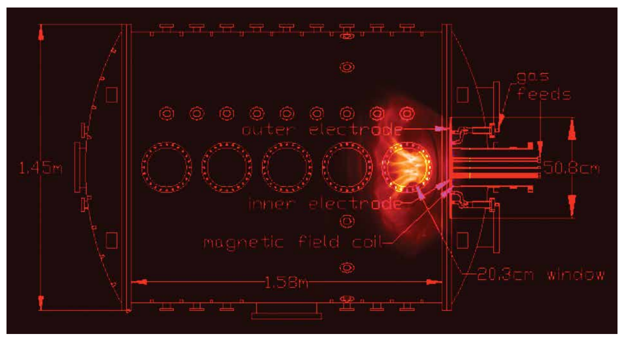
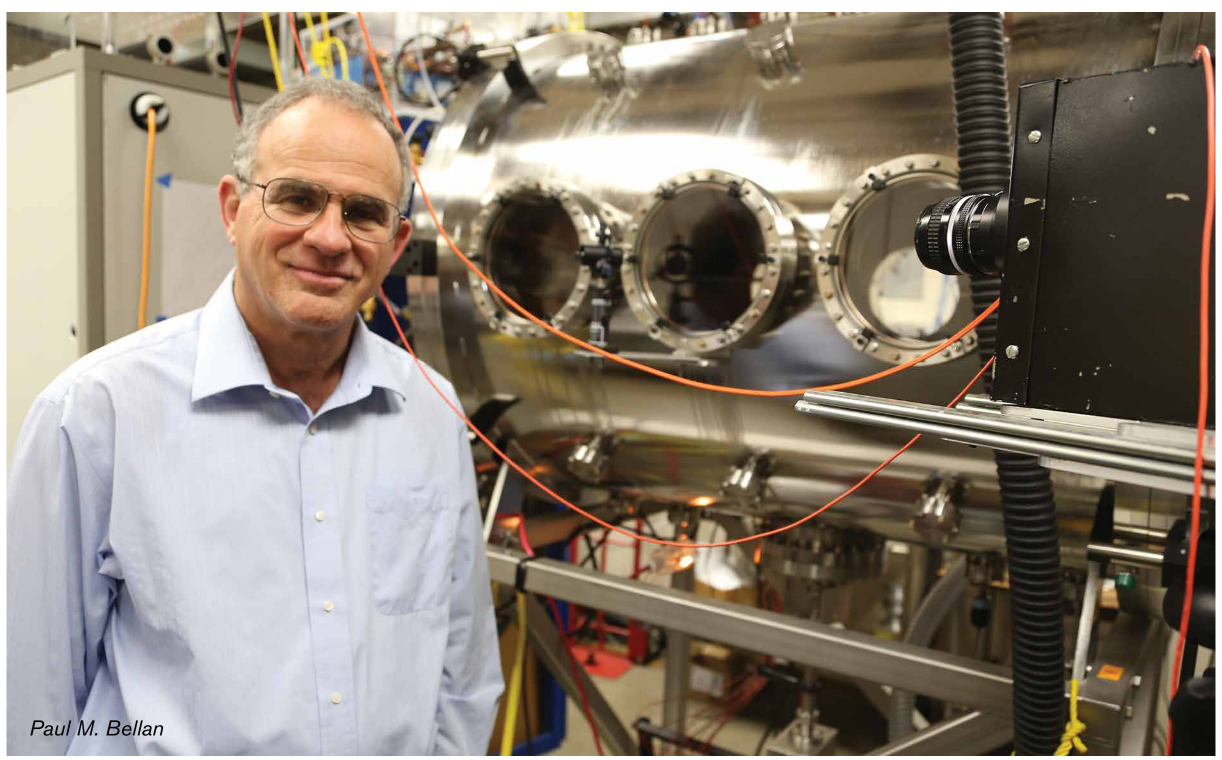


Image of a magneto-hydrodynamic plasma jet super-imposed on the outline of a vacuum chamber; the jet expands to the left at a velocity exceeding 10 km per second.

devices and radio noise from the sun. Then a lucky thing happened: my advisor decided to leave just about the time I was getting my PhD, and I got an offer from Caltech to stay on the faculty and take over his program and students. As a faculty member, I explored the nebulous boundary between electrical engineering and physics, which is what we called applied physics. The students got more physics than most engineers did at the time. The laser had just been invented and optics was just starting, just emerging as a new field. Solid state was around; so was materials science. But the materials science was nothing like the materials science being done today!"

Professor Gould describes applied physics as a vehicle for training students to think about very complex problems. Professor of Applied Physics Paul Bellan takes that idea a step further, arguing that the field serves as an incubator for new ideas that spread into other fields. His own research, which focuses on dusty plasmas, bears this out. "A dusty plasma has three components: electrons, ions, and negatively charged dust grains," he says. "These components all interact with each other and, in particular, the negatively charged dust grains can repel each other to form macroscopic lattice structures. An example of dusty plasmas in nature are the more diffuse rings of Saturn. These rings are made of large numbers of tiny grains of water ice, presumed to be electrically charged because of interaction with ambient plasma and with sunlight. We are making an ice dusty plasma in our lab—we feed water vapor into a plasma that has liquid nitrogen cooling on the electrodes and observe that micron-size ice dust particles spontaneously form. The ice dusty plasma has the remarkable feature of being hot and cold at the same time, because the temperature of the electrons is about 20,000–50,000 °C, whereas the temperature of the water molecules, neutral atoms, ions, and ice dust grains is about -100 °C." Professor Bellan appreciates that this research has a certain beauty and elegance, in that he can start from first principles and go on to describe complicated, realistic situations. He explains, "Because plasmas have no intrinsic scale, the same ideas apply over many orders of magnitude. For example, magnetohydrodynamic plasma jets routinely produced in our lab are about half a meter long, and yet they look like and behave in much the same way as astrophysical jets that are about 50,000 light years long. It is delightful and amazing that the same plasma ideas apply to such fantastically different circumstances."

Paul Dimotakis, John K. Northrop Professor of Aeronautics and Professor of Applied Physics, is also exploring dynamics across very large ranges of scales. "I think the most exciting thing about fluid dynamics, in addition to trying to answer fundamental questions, is



Paul M. Bellan

Paul Dimotakis

Once we understand how fluid flows, we can build vehicles that can fly many, many times the speed of sound. Five, six times the speed of sound!

Paul E. Dimotakis, *John K. Northrop Professor of Aeronautics and Professor of Applied Physics*

Sandra Troian

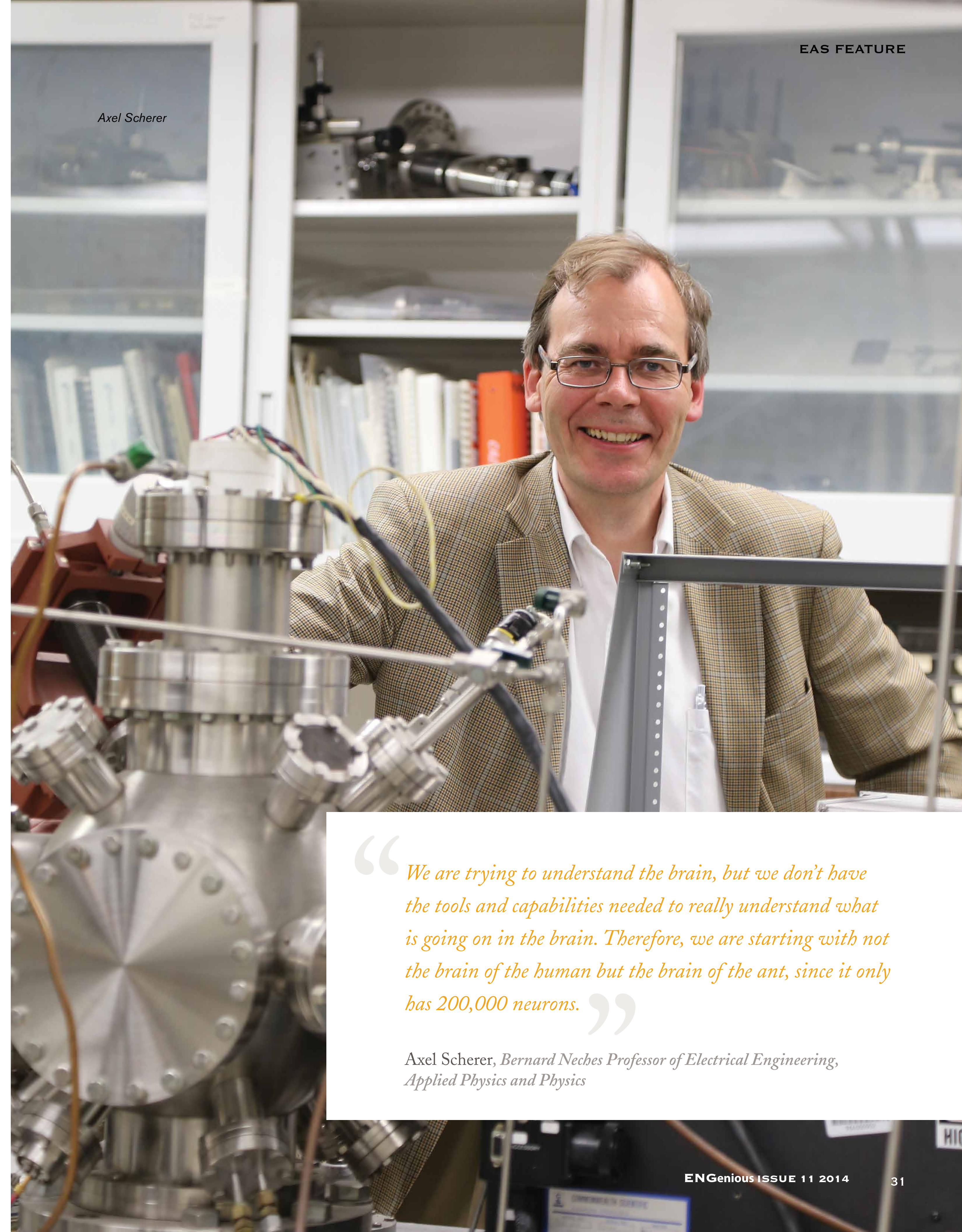
> *True breakthroughs in physics often require great personal courage, since bold new ideas are bound to clash with the old.*
>
> Sandra M. Troian, *Professor of Applied Physics, Aeronautics, and Mechanical Engineering*

that fluid dynamics occurs at all scales in our world and the universe," he says. He goes on to explain that "the predominant fraction of matter in our universe is in a fluid state and turbulent. The range of scales in turbulence is so large that not even the biggest computers in the world are capable of simulating the flow and its dynamics in detail. I consider this to be one of the most important research challenges—and one that I'm trying to address with my collaborators. If we are successful, it will close an important chapter in fluid mechanics."

The potential applications of this research, Professor Dimotakis says, are grand: "Once we understand how fluid flows, we can build vehicles that can fly many, many times the speed of sound. Five, six times the speed of sound! The propulsion for such vehicles is called a supersonic combustion ramjet (scramjet). A patent was filed for this concept about 50 years ago, and a successful scramjet only flew in the last two years. It took half a century because of the very interesting and challenging fluid dynamics that must be mastered. If you could fly at eight times the speed of sound, you get from Los Angeles to San Francisco in four and a half minutes. We wouldn't do this, of course, because it would take some time to accelerate to those speeds and then decelerate such that we can land. Therefore, in the short term, this technology will mostly have military applications. Nevertheless, being able to fly through the atmosphere at these speeds is a frontier of aeronautics."

While more conventional research in hydrodynamics has focused on large or mesoscale systems, Sandra Troian, Professor of Applied Physics, Aeronautics, and Mechanical Engineering, specializes in very-small-scale phenomena involving nonlinear wave propagation and structure formation in ultrathin films. In particular, she studies the influence of unusual surface forces on the transport of mass, momentum, heat, and light along moving interfaces. One of her favorite projects is called MicroAngelo, in which remotely controlled thermal and electric field gradients are used to sculpt three-dimensional liquid formations into micro-optical components whose shapes are inaccessible to conventional lithography. Similar approaches based on patterned electric fields are also being used to develop a microscale space propulsion device with collaborators at the Jet Propulsion Laboratory.

Such fine spatiotemporal control of surface forces for interface-mediated transport and "interface sculpting" requires a suite of tools. Professor Troian's group uses these tools to carry out full-scale experiments and perform first-principles modeling along with finite element and molecular dynamics simulations. "I always start with trying to solve the most basic related physics problem," she says, "and then eventually carry out the experiment that goes with it, though keeping several balls in the air is always so challenging." How does she set research priorities? "When I came to Caltech in 2006, it dawned on me that I have, at most, 20 years left to try and discover something significant," she explains. "So I asked myself: What are the two or three biggest problems that I really want to work on? Because as a scientist, my hope is to try and leave behind at least one finding that can change the way we think about a problem. I've put my heart and soul into these three problems, but as in *Gulliver's Travels* and the land of Lilliput, there is always a mischievous elf around the corner!"



Axel Scherer

> *We are trying to understand the brain, but we don't have the tools and capabilities needed to really understand what is going on in the brain. Therefore, we are starting with not the brain of the human but the brain of the ant, since it only has 200,000 neurons.*
>
> Axel Scherer, *Bernard Neches Professor of Electrical Engineering, Applied Physics and Physics*

Andrei Faraon

> *I work at the frontier of science and engineering. I am learning how to control, manipulate, and engineer quantum systems—and I get really cool toys!*

Andrei Faraon, *Assistant Professor of Applied Physics and Materials Science*

Professor Troian also enjoys fostering the type of environment that encourages students to question scientific dogma. "True breakthroughs in physics often require great personal courage, since bold new ideas are bound to clash with the old," she says. "Linus Pauling put it best when he said, 'The world progresses, year by year, century by century, as the members of the younger generation find out what was wrong among the things that their elders said. So you must always be skeptical—always think for yourself.'" A favorite exercise of hers to teach this approach is to have students read the current physics literature critically to "find Waldo," i.e., find the errors, in reference to the series *Where's Waldo,* with the trusty cartoon character in the red-striped hat and shirt hiding in a landscape of red-striped herrings. She adds, "Caltech undergrads reign supreme in finding Waldo!"

Axel Scherer, Bernard Neches Professor of Electrical Engineering, Applied Physics and Physics, shares Professor Troian's desire to map new knowledge onto other fields and think about problems in fresh ways. "By combining applied physics and materials science, which is not done in a lot of places, I think it's possible to have an integrated understanding, going all the way from the crystal structure and materials attributes to developing their applications," says Scherer. "By capturing this in one department, the EAS Division has enabled a very interesting opportunity of not stopping at the end of the materials science area, but rather capturing a continuum between the devices that are being built and designed and the fundamental characteristics of the materials they are made of. Within one option, we can think of new materials as well as ways to design and control their properties through composition and geometry to make them more useful for the devices we need in the future."

Professor Scherer looks to his own research, which seeks to better understand the brain, for an illustration of this sort of opportunity and promise. "We are trying to understand the brain, but we don't have the tools and capabilities needed to really understand what is going on in the brain. Therefore, we are starting with not the brain of the human but the brain of the ant, since it only has 200,000 neurons," he says. "We need to understand what happens in a system that has 200,000 neurons, and we need to measure the 200,000 neurons, or at least a large fraction—let's say a tenth of them. They all fire at rates of about every millisecond; therefore, we need to measure them at 20 kilohertz—200,000 times 20 kilohertz gives you a data baud rate of terabits per second, which we cannot deal with today. At the moment, we can sample maybe 20 neurons at a time if we're lucky and have a very crude understanding. The analogy I like to use for my students is that it's like trying to figure out what operating system is running on my laptop with a pitchfork. I take the pitchfork and I slam it into the laptop; then I measure the distance between the prongs and measure the voltages, but the display goes out. Then I assume I understand what runs the display, because I've shut it off! The kinds of tools that we are building now aren't up to the task for an ant's brain, let alone our own brain, which has 100 billion neurons—orders of magnitude more complex. So the challenge is to develop capabilities and build devices that allow us to measure this kind of information flow."

Andrei Faraon, Assistant Professor of Applied Physics and Materials Science, is developing new technologies in the areas of solid state quantum optics and nanophotonics. He explains, "We take ideas from quantum science and use them to build devices like optical memories that can store and release the quantum state of single photons. These devices have

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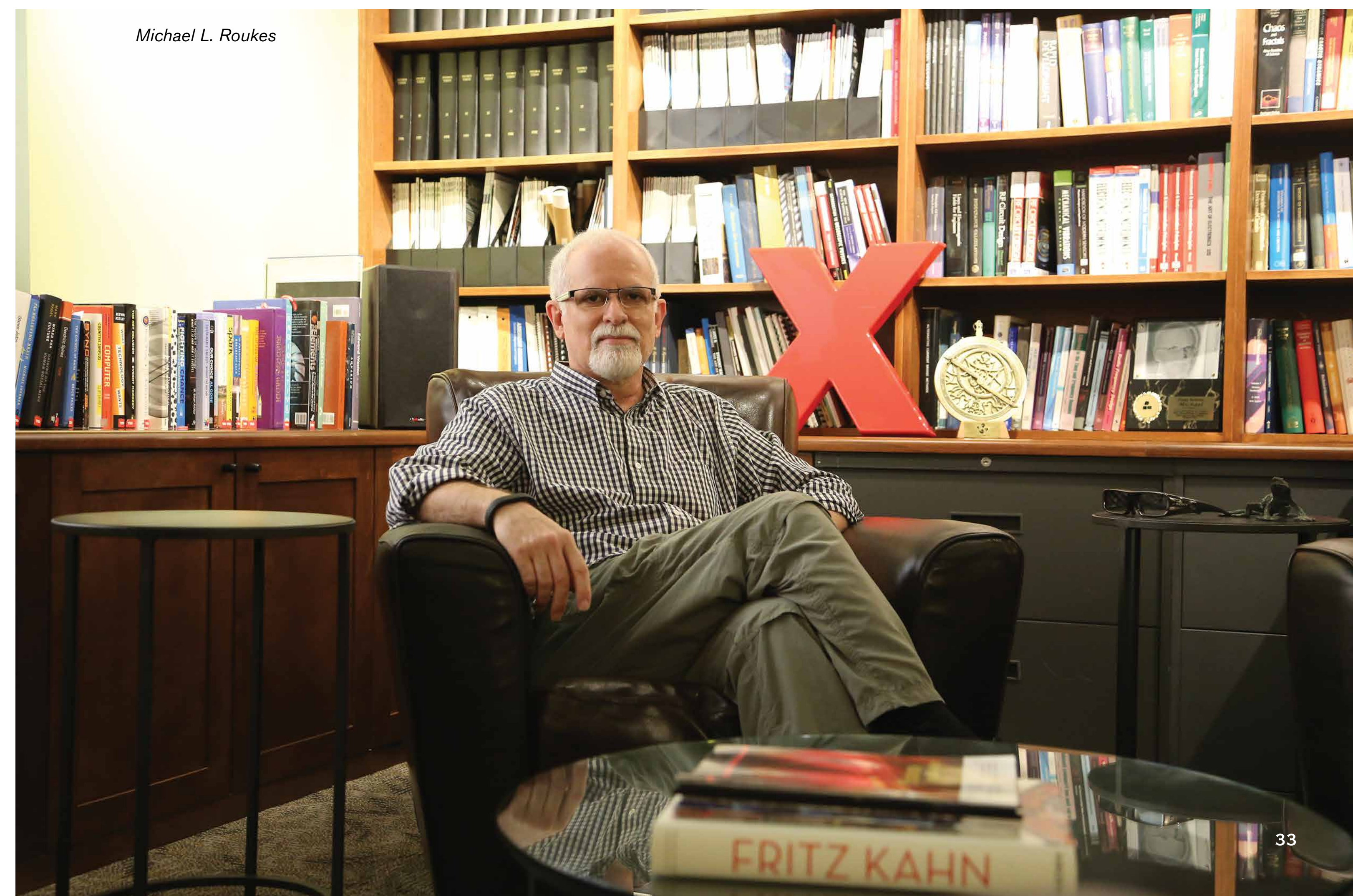
Michael L. Roukes, *Robert M. Abbey Professor of Physics, Applied Physics, and Bioengineering*



Michael L. Roukes

application in absolutely secure optical communications."

Professor Faraon's interest in applied science was first piqued as an undergraduate student at Caltech. "In my second year as a physics undergrad, I started working with Professor Roukes and was exposed to applied physics and engineering," he says. "I liked this freedom of doing fundamental science while still having the opportunity to work on neat engineering applications. Today, as a professor of applied physics and a member of the EAS Division faculty, I work at the frontier of science and engineering. I am learning how to control, manipulate, and engineer quantum systems—and I get really cool toys!"

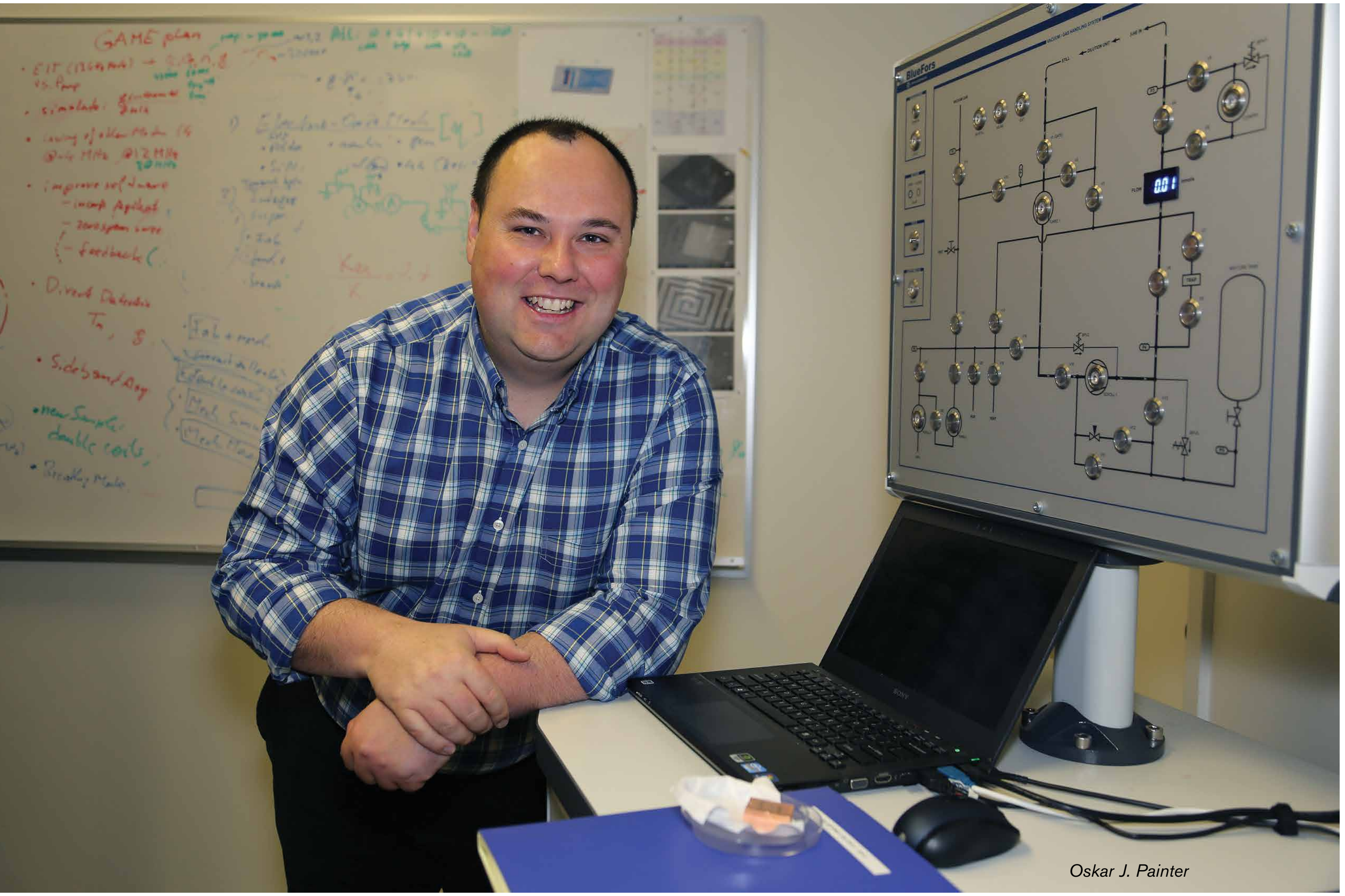
Also working at the frontier is Michael Roukes, Robert M. Abbey Professor of Physics, Applied Physics, and Bioengineering. "The small size of Caltech means there are really low barriers to cross-disciplinary collaborations. About 12 years ago, I started collaborating with professors in biology, and the experience of all of us sitting around a table brainstorming and bringing our different perspectives and areas of expertise to the collaboration was really fun! I decided then that these sorts of collaborative frontiers are where I wanted to push most of my research. To this day the areas that are super exciting to me and that make it a delight to get up in the morning and come to work are related to neuroscience and mapping the brain," says Roukes.

Professor Roukes's passion for this work has been recognized by the Obama administration, and he is a member of the NIH's collaborative BRAIN (Brain Research through Advancing Innovative Neurotechnologies) Initiative, which aims to map the activity of every neuron in the human brain. "Our research at Caltech has deep implications for understanding networks in the brain, how neurons interact, and how the brain actually computes," he says. "I think it's a really exciting new science to get involved in, and I'm happy to be the technologist in this group because this allows me to hang out with smart people and learn new things."

Reflecting on when he first came to Caltech 22 years ago, Roukes says that "one of the dreams I had in pursuing research in nanomechanical systems was the possibility of making small mechanical systems that were quantum limited. At the time, there basically wasn't anybody else in the world that was working in this area. Today the field is broad and worldwide, and many different people, including many people in my group, are pursuing this dream."

> *"Today's graduate students assume that everything will be quantum mechanical and work. They don't even know that 14 years ago, I used to hear people over my shoulder say this will never work. This is crazy!"*
>
> Keith C. Schwab, *Professor of Applied Physics; Fletcher Jones Foundation Co-Director of the Kavli Nanoscience Institute*

Keith C. Schwab



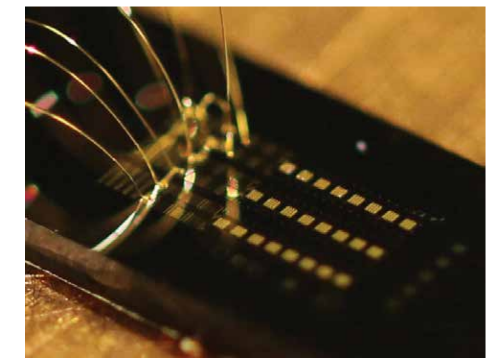
Oskar J. Painter

> *"I'm experiencing the richest and most exciting time of my career as I get more involved in quantum science, and a big part of this is the community here at Caltech."*
>
> Oskar J. Painter, *John G Braun Professor of Applied Physics*

EAS FEATURE

One such dreamer and former Roukes group member is Keith Schwab, Professor of Applied Physics and Fletcher Jones Foundation Co-Director of the Kavli Nanoscience Institute. "As a postdoc in the Roukes group, my experiment was to measure heat flow through a nanostructure," says Schwab. "It took about a year and a half just to put the electronics together on the refrigerator. It took a year and a half to figure out the fabrication of the device. Then the devices were just blowing up when I put them on the fridge. Eventually everything worked out, and it was a pivotal moment in my career. We demonstrated the quantum limit for heat flow that was predicted and measured it. It was one of the first illustrations of quantum effects for phonons and vibrations in the nanostructure." Schwab attributes much of this success to the facilities at the Kavli Nanoscience Institute (KNI) at Caltech: "We could not have made our devices, which go on to the refrigerators and needed to be taken down to ultra-low temperatures, without the KNI. The advanced experimental techniques developed at the KNI made the measurements possible."

There have, Schwab notes, been dramatic changes in the field since he began this work. "Today's graduate students assume that everything will be quantum mechanical and work. They don't even know that 14 years ago, I used to hear people over my shoulder say this will never work. This is crazy! The field has moved to the point where micron-scale devices are quantum mechanical. Also, we are looking at super-fluid devices as ways to try to see quantum effects and motion in gram-size things," he says.



Electromechanically tunable optical cavities

Oskar J. Painter, John G Braun Professor of Applied Physics, is also a quantum engineer—one who is, as he puts it, "developing new types of technologies that behave according to the counterintuitive laws of quantum mechanics." He explains, "I'm experiencing the richest and most exciting time of my career as I get more involved in quantum science, and a big part of this is the community here at Caltech. The Caltech Institute for Quantum Information and Matter (IQIM) was originally founded as a theory center, but now it has grown to encompass a diverse set of theorists and experimentalists working closely together to study quantum systems from the microscopic scale all the way up to human-sized objects. Going back in history, one notices key moments when there's a tremendous opportunity to do something that will be impactful within a couple of generations. Maybe you don't see exactly how things will turn out, or how certain technical challenges will be overcome, but one can sense the convergence of ideas and technical capabilities. I think that for me, this is one of these moments—quantum mechanics is a more expansive theory of nature, with numerous areas of technical application that wait to be developed."

As the first Executive Officer of the APhMS Department, Painter predicts that for the department to continue to lead and inspire, it needs to follow its historical path of "developing scientists that live at the boundaries, and that push beyond current understanding or techniques and seek the next set of opportunities

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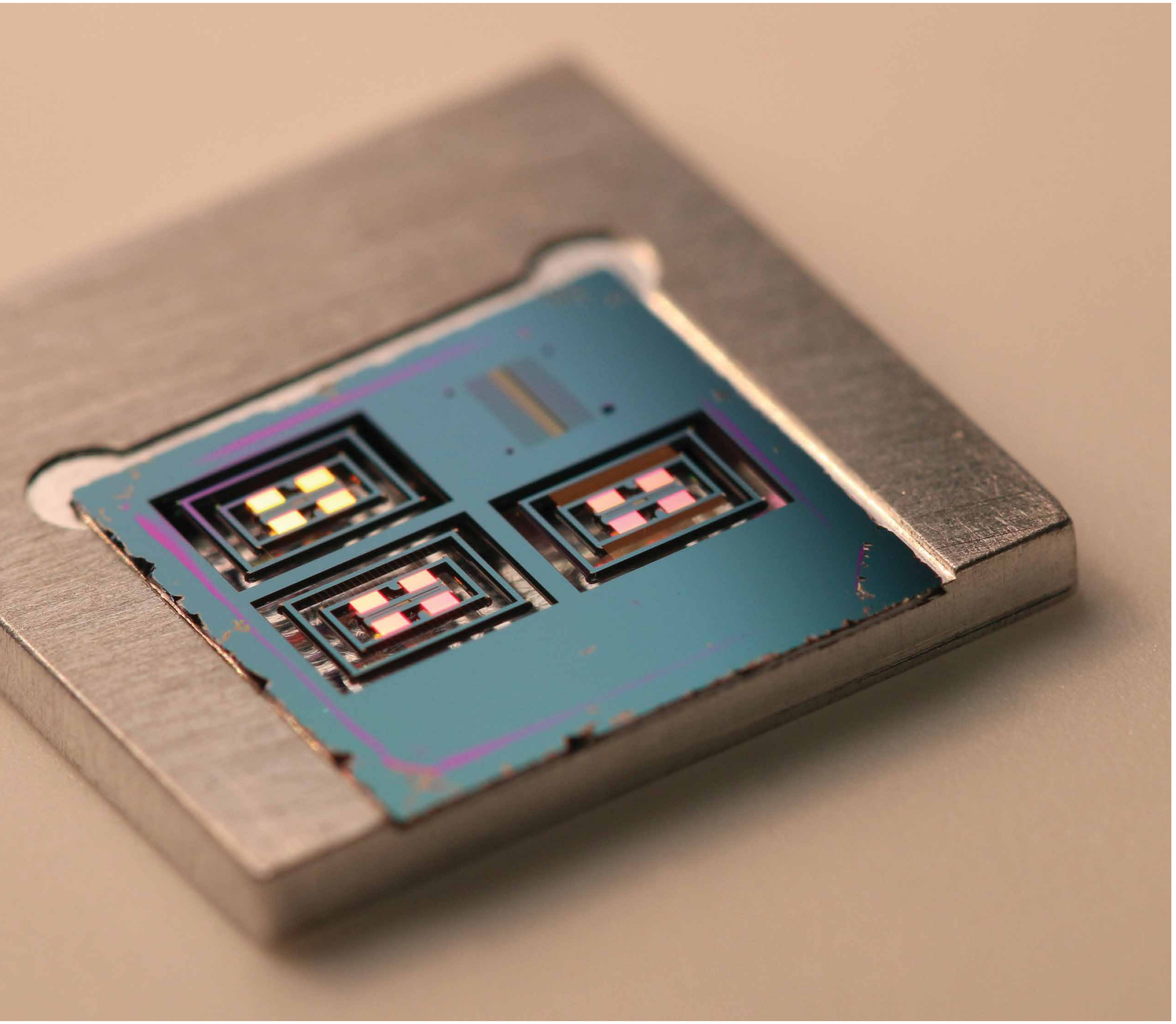

Optomechanical microchip gyroscope

and challenges. People that get just as much satisfaction from exploring fundamental physical phenomena as they do in tinkering with new materials, devices, or technologies."

In the fall of 2015, the APhMS faculty are excited to be welcoming two assistant professors who are poised to "push beyond" in the ways that Professor Painter describes. The first is Marco Bernardi, who specializes in theoretical and computational materials science as well as condensed matter physics. His Caltech research group will investigate ideas at the intersection of solar energy conversion, ultra-fast science, excited state dynamics, and many-body electronic structure calculations. The second is Stevan Nadj-Perge, who is interested in the development of mesoscopic devices for applications in quantum information processing. Such devices also provide a platform for exploring exotic electronic states at (sub)nano length scales.

These new faculty will experience and perpetuate the uniquely informal and accessible Caltech environment that Professor Amnon Yariv believes is so essential to the continued success of the department's endeavors. "The fact that I can talk to anybody I need without intermediaries, or very few, that's very important," says Yariv. "Furthermore, the lack of barriers affects the students, who are the most important single prerequisite for our continued progress and success. I have to close my eyes and think very carefully to tell which of my students are physicists, which ones are electrical engineers, which ones are applied physicists. This transparency and lack of barriers is very important." ENG

Visit aphms.caltech.edu to learn more about the Applied Physics and Materials Science Department's faculty.

Marco Bernardi

Stevan Nadj-Perge