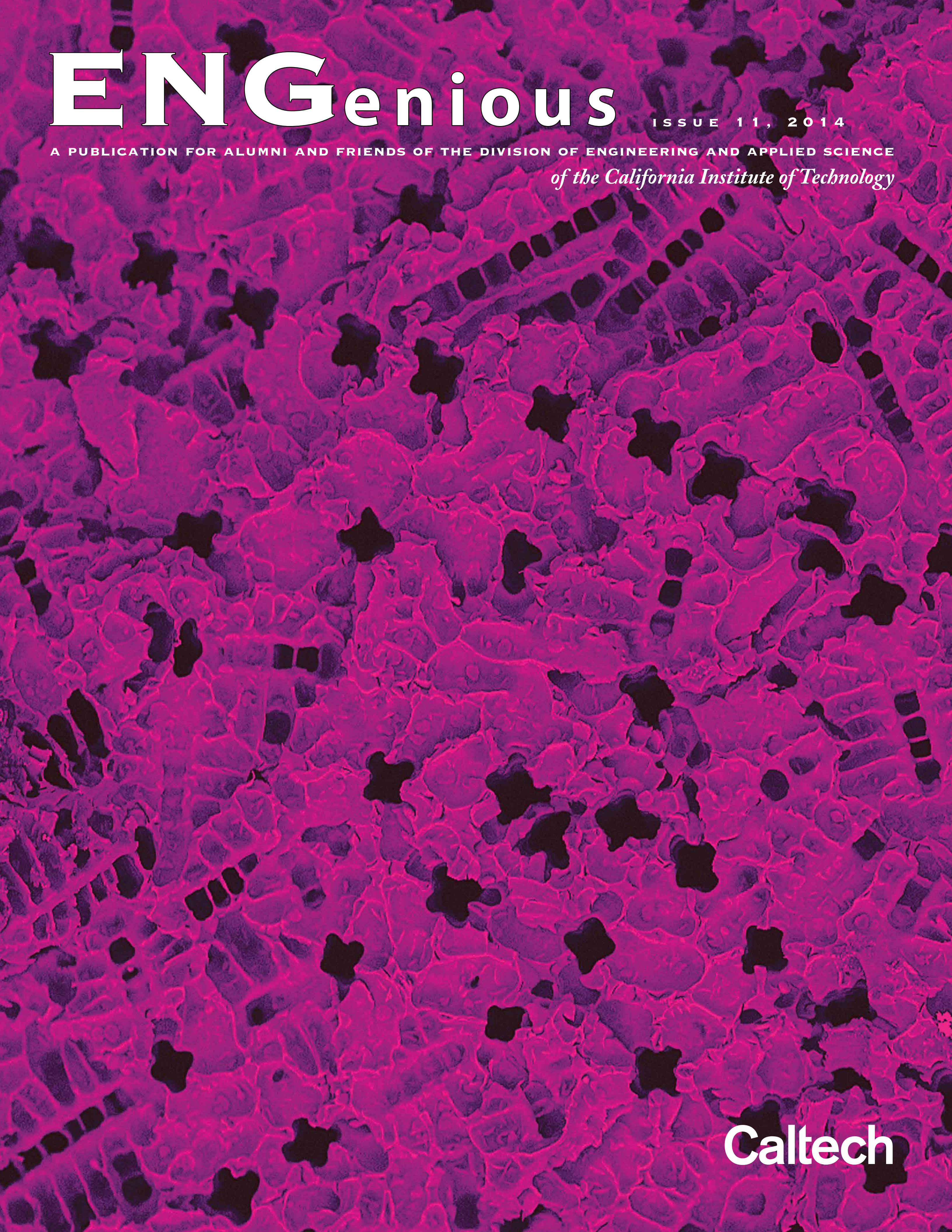
ISSUE 11, 2014

ENGenious

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



Caltech

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

ENGenious

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p. 3: Courtesy of Foster and Coco Stanback
p. 4: Resnick: Vicki Chiu; International Space Leadership: Christine Ramirez
p. 5: CDS 20: Sydney Garstang; Carver Mead: Courtesy of the Archives, California Institute of Technology
p. 6: Courtesy of Domniki Asimaki
p. 7: Courtesy of Victoria Kostina
p. 8: Courtesy of Thomas Vidick; Courtesy of Yisong Yue
p. 9: Courtesy of Robert Braun
pp. 10–13: Courtesy of NASA
p. 14: Middle image courtesy of Paul Bellan
p. 19: Lance Hayashida
p. 21: Dr. Fabian Stolzenburg, working with Professor Katherine Faber
p. 22: Courtesy of Julia Greer
p. 30: Courtesy of Sandra Troian
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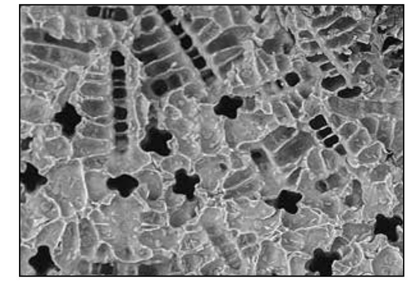
The Caltech Division of Engineering and Applied Science consists of seven departments and supports close to 90 faculty who are working at the edges of fundamental science to invent the technologies of the future.



Front Cover Image

Porous ceramics are playing an increasingly important role as high-temperature filters, catalyst supports, electrodes for batteries and fuel cells, and biomedical scaffolds. Shown here is porous silicon oxycarbide prepared in Professor Katherine Faber's laboratory by freeze casting a solution of a siloxane preceramic polymer with cyclohexane. By imposing a temperature gradient across the solution, phase separation ensues prior to cyclohexane directional freezing; the remaining polymer is compacted between the growing cyclohexane dendrites. The cyclohexane, now a sacrificial template, is removed via sublimation, and the polymer is pyrolyzed to produce a robust ceramic with pores the size and morphology of the cyclohexane dendrites that appear as dark X-shapes in the image. The image was taken using scanning electron microscopy perpendicular to the dendrite growth direction; pore sizes are approximately 20 micrometers.

Back Cover Image

This porous aluminum oxide was prepared in Professor Katherine Faber's laboratory by freeze casting aluminum oxide powder suspended in water. By imposing a temperature gradient across the slurry, water freezes, ejecting ceramic particles at the freezing front, where they are compacted between the freezing ice crystals. In contrast to the siloxane/cyclohexane described above, ice solidifies as lamellae, resulting in porous layers, rather than dendrites, which provide for easy flow. The image was taken perpendicular to the freezing direction using scanning electron microscopy; lamellar spacing is approximately 150 micrometers.


Ares J. Rosakis

Since becoming Chair of the Division of Engineering and Applied Science (EAS) over five years ago, I have observed again and again that the size effect is the single most important factor that determines the advantages and constraints, as well as the behavior and choices, of both Caltech and EAS. Caltech is a tiny but elite institution with a reputation of outsized impact. Similarly, the EAS Division is very small compared to most schools and colleges of engineering worldwide. In relation to our hiring practices, the size effect translates into our adoption of a very careful approach. It has been to hire young stars, capable of generating multiple interdisciplinary connections with other departments and divisions, whom we support very generously. We also recognize that it is impossible to cover the entire spectrum of engineering activities, so we tend to hire on the basis of overall excellence rather than to fill a specific gap in a research area.

In this issue of *ENGenious* you will be introduced to eight new faculty members. Here I mention them briefly: joining the Department of Applied Physics and Materials Science are Simon Ramo Professor of Materials Science Katherine T. Faber and assistant professors Marco Bernardi and Stevan Nadj-Perge (both joining in 2015). Joining the Department of Computing and Mathematical Sciences are assistant professors Yisong Yue and Thomas Vidick. Electrical Engineering is welcoming assistant professor Victoria Kostina. Returning to Caltech is Joanna Austin (PhD ’03), who is joining the Aerospace faculty in GALCIT as a full professor. And finally, the Department of Mechanical and Civil Engineering will be the new home of professor Domniki Asimaki. I want to give a special thanks to all the EAS faculty who served on the search committees that selected these stellar new colleagues. We are looking forward to seeing them shine!

Our faculty recruits often inquire about the support they may receive should they wish to bring their research from the lab to commercialization, and I am delighted to let them know about the work of the Caltech Office of Technology Transfer and Corporate Partnerships (OTTCP), which is being featured in this issue of *ENGenious*. Start-up creation and technology transfer activities are absolutely flourishing within Caltech. EAS has played a leading role in these efforts, and our faculty have been among the main beneficiaries of Caltech’s technology transfer revolution. Since 2007, 28 start-up companies have been founded by EAS faculty. Caltech (excluding JPL) receives more invention disclosures per faculty member than any other university in the nation. In the last 10 years, licensing efforts have resulted in 40 to 50 patent licenses per year, and OTTCP fosters start-up companies at a rate of about eight per year—a very high number in view of our small size.

Finally, I have wonderful news to share regarding three exceptional gifts to Caltech from Foster and Coco Stanback. First, GALCIT will be establishing a mentorship and research program with Orange Coast College called Bridge to the Future: NXT Program. This program is centered on the development of a special-purpose biofueled aircraft. The project is a test bed for new composite materials and technologies. The imaginations of the faculty have been piqued in a new direction, and this project gives them and their students an opportunity to mentor community college students in research and to encourage them to pursue advanced degrees in a variety of engineering fields.

In addition, the Stanbacks are establishing an endowment for the Foster and Coco Stanback Fellowships in EAS, which will allow us to bring stellar graduate-student talent to Caltech in any area of aerospace engineering—giving us the opportunity to nurture and develop these young people to create impact in areas with which we are familiar and, most importantly, in areas in which we only dream at present.

These two gifts will contribute to the vitality and evolution of GALCIT and the Division both in the short and long terms, and they would be cause for great celebration on their own. However, the Stanbacks are also endowing the Foster and Coco Stanback Space Innovation Fund in EAS, permitting us the incredible freedom to pursue the best ideas from wherever they spring and in perpetuity support space-related engineering research across the entire Division—the type of research that is the hallmark of the Caltech style and vocation.

Taken together, the Stanback gifts total $7.8 million and represent enormous opportunities for EAS to create lasting impact in research and in the development of human potential. I would like to thank Foster and Coco for seeing so clearly into the heart of Caltech, particularly in the areas of aeronautics and space, and for taking such magnanimous action on our behalf.


Foster and Coco Stanback

Yours proudly,

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

Transformational Impact: Resnick Sustainability Institute Enters Second Phase

Over the past five years, the Resnick Sustainability Institute has focused on establishing its headquarters in the Earle M. Jorgensen Laboratory. Its first phase of programmatic activity included graduate fellowships, development of corporate and academic partnerships, the fielding of solar decathlon student teams who built zero-net-energy solar-powered homes, and the orchestration of a national Cleantech business plan competition. These programs have supported fundamental advances in science and engineering at Caltech, which can have transformational impacts on energy, science, and technology—sometimes in unexpected ways. Harry A. Atwater, Howard Hughes Professor of Applied Physics and Materials Science and Director of the Resnick Sustainability Institute, puts it this way: "Very often the key critical factors, the tipping points so to speak, that determine whether or not any given technology or initiative has a transformational impact are socio-political and sociological, rather than purely technical."

It is with this vision and a new $15 million gift from Lynda and Stewart Resnick that the institute has entered its second phase. The programs and activities of this phase are focused on a global search for people who will have or are already having an impact, with the goal of advancing research aimed at helping humanity sustainably meet its needs for energy, food, clean water, and a healthy environment. Professor Atwater explains, "The toughest issues in sustainability are not short-term; they require a 50-year view and need to be approached with creativity and a transformative perspective. We are looking outwards to have an impact and a presence in the global context of sustainability and energy science." Specifically, they have established a prize postdoctoral fellowship and the Resonate Awards, designed to honor breakthrough achievements of outstanding innovators in the area of energy science and sustainability around the world.

To learn more, visit resnick.caltech.edu.

Ares Rosakis and Koppillil Radhakrishnan

International Space Leadership

The Engineering and Applied Science Division and Caltech have been instrumental in the training of many international space leaders, including Satish Dhawan (PhD '51), who was pivotal in the creation of the Indian space program and Tsien Hsue-Shen (PhD '39), the father of Chinese rocketry. Continuing in this tradition, the Director of the Jet Propulsion Laboratory (JPL), Charles Elachi, and the Chair of Caltech's EAS Division, Ares Rosakis, recently hosted the Chairman of the Indian Space Research Organization (ISRO), Dr. Koppillil Radhakrishnan, who was also Satish Dhawan's last student. The visit focused on plans regarding a joined Earth-orbiting mission that will be the first radar mission to systematically and globally study the solid Earth, the ice masses, and ecosystems, all of which are sparsely sampled at present.

Visit eas.caltech.edu/news/653.

Celebrating 20 Years: Control and Dynamical Systems at Caltech

The Control and Dynamical Systems (CDS) program at Caltech celebrated its 20th anniversary with a workshop in August 2014. The workshop brought together over 150 former students, visitors, colleagues, and friends of the CDS option, including a large fraction of the 120 PhD students and 60 postdocs who have been affiliated with the program since its inception. The workshop provided participants with a 20-year retrospective on areas of research relevant to CDS. Following the retrospective, the next sessions were devoted to the interaction of the research theme with external communities. Sample application areas that were covered included aerospace and transportation, biology and medicine, communications and networking, economics and finance, energy and infrastructure, materials and processing, and robotics and intelligent machines. The workshop ended with a look forward to the next 20 years, with speakers asked to make predictions about what the world will look like and what advances will have happened to make that future possible.

To view the presentations, visit cds20.caltech.edu/program.html.

Making the Computer Era Possible

Carver Mead, Gordon and Betty Moore Professor of Engineering and Applied Science, Emeritus, is best known for his pioneering work on VLSI (very-large-scale integration) circuit technology in the 1970s and 1980s, which made it possible to greatly increase the number of transistors placed on a single semiconductor chip. It is no exaggeration to say that the computer era we live in would not have been possible without VLSI technology. To celebrate Carver Mead's 80th birthday and accomplishments, a number of events were organized by Caltech this year, including an evening co-hosted by EAS Division Chair Ares Rosakis and Caltech Trustee Milton Chang (PhD '69), along with his wife Rosalind Chang.

Students and colleagues are encouraged to share their memories of Carver Mead through the interactive website carvermead.caltech.edu.

New Faculty

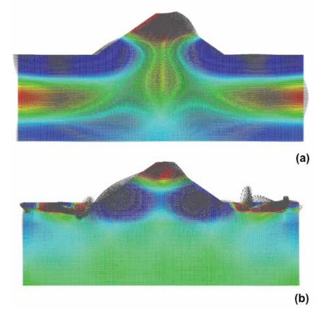
Our newest faculty members join the Division of Engineering and Applied Science in 2014.

Domniki Asimaki

Professor of Mechanical and Civil Engineering

Domniki Asimaki's research combines geotechnical engineering, computational mechanics, and structural dynamics to study how natural and man-made geotechnical systems (ridges, valleys, dams, tunnels, building foundations, and offshore structures) respond to dynamic loading induced, for example, by earthquakes, hurricanes, and blast. She then uses results from these studies to develop predictive models for resilient design procedures for geotechnical systems, and for hazard assessment and mitigation in urban environments.

Domniki Asimaki has a BS in civil engineering from the National Technical University of Athens, Greece (1998), and an MS (2000) and PhD (2004) from MIT. She has worked as a researcher for the European Research Program Safety Assessment for Earthquake Risk Reduction (SAFERR) at Géodynamique et Structure in Paris, France (2001), and as a postdoctoral researcher at the Institute for Crustal Studies at the University of California, Santa Barbara (2004–2005). Prior to joining the EAS faculty at Caltech, she was on the faculty of the School of Civil and Environmental Engineering at Georgia Tech (2005–2014). Dr. Asimaki is associate editor for the *Journal of Computing in Civil Engineering* (ASCE), for *Earthquake Spectra* (EERI), and for *Soils and Foundations* of the Japanese Geotechnical Society. She is the principal author and co-author of more than 50 publications in the areas of geotechnical engineering, strong motion seismology, engineering mechanics, and geophysics, and the recipient of the 2009 Arthur Casagrande Award from the ASCE Geo-Institute and the 2012 Shamsher Prakash Research Award in Geotechnical Earthquake Engineering.



This simulation shows how a soft soil layer can affect the seismic shaking near convex topographies, a problem with implications for seismic hazard assessment in mountainous regions as well as in the design of dams.

Joanna Austin

Professor of Aerospace

Joanna Austin's research is focused on fundamental problems in reactive, compressible flows across a broad range of applications, including hypervelocity flight and planetary entry, supersonic combustion and detonation, bubble dynamics, and explosive geological events. She joins EAS's Department of Aerospace from the University of Illinois at Urbana-Champaign, where she was an associate professor and Willett Faculty Scholar. Austin received a BE (mechanical and space engineering) and BSc (mathematics) from the University of Queensland, Australia, and an MS (1998) and PhD (2003) from GALCIT at Caltech. As a faculty member in the Aerospace Engineering Department at Illinois, she established the Compressible Fluid Mechanics Laboratory and built the hypervelocity expansion tube. Her honors and awards include becoming an AIAA Associate Fellow in 2011 as well as receiving the Xerox Award for Faculty Research in 2011, the NSF CAREER Award in 2010, the AIAA Best Paper Award in 2009, and the AFOSR Young Investigator Award in 2007.

Katherine Faber

Simon Ramo Professor of Materials Science

Katherine Faber is interested in the fracture of brittle materials and the mechanisms by which such materials can be toughened and strengthened through composite strategies and residual stresses, often using synchrotron radiation for internal stress measurement. Her studies comprise ceramics for energy-related applications, including thermal and environmental barrier coatings for power generation components and porous solids for filters and flow. More recently, she has worked with the Art Institute of Chicago to establish 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.

After receiving a BS in ceramic engineering, she earned an MS in ceramic science at the Pennsylvania State University and a PhD in materials science and engineering from the University of California, Berkeley. Prior to joining the Caltech faculty, she held appointments at the Ohio State University and Northwestern University. Among Professor Faber's awards are the National Science Foundation's Presidential Young Investigator Award, selection as Distinguished Life Member of the American Ceramic Society and Fellow of ASM International, the Charles E. MacQuigg Award for Outstanding Teaching at Ohio State, the Society of Women Engineers Distinguished Educator Award, and the YWCA Achievement Award for Education. She is an ISI Highly Cited Researcher in Materials (2003), served as president of the American Ceramic Society (2006–07), and was elected to the 2014 American Academy of Arts and Sciences class of fellows.

Victoria Kostina

Assistant Professor of Electrical Engineering

Victoria Kostina's research spans information theory, coding, and wireless communications. Her current efforts explore one of the most exciting avenues in today's information theory: the nonasymptotic regime. Leveraging tools from the theory of random processes and concentration of measure, she pursues fundamental insight into modern delay-constrained communication systems.

She holds a bachelor's degree from Moscow Institute of Physics and Technology (2004), where she was affiliated with the Institute for Information Transmission Problems of the Russian Academy of Sciences. She was granted the Natural Sciences and Engineering Research Council of Canada postgraduate scholarship in 2005 and obtained a master's degree from the University of Ottawa in 2006. She completed her PhD at Princeton University in 2013, where she received the Electrical Engineering Department's Best Dissertation Award for her thesis on information-theoretic limits of lossy data compression.

Thomas Vidick

Assistant Professor of Computing and Mathematical Sciences

Thomas Vidick's research is situated at the interface of theoretical computer science, quantum information, and cryptography. He is interested in using complexity theory as a lens to approach fundamental problems in quantum computing. He has investigated the role of entanglement in multi-prover interactive proof systems and obtained the first substantial computational hardness results on the power of entangled provers. He has made important contributions to the field of device-independent cryptography, where the property of entanglement monogamy plays a key role. His work also demonstrates that insights from quantum information theory can be productively transferred to yield novel perspectives on fundamental techniques in theoretical computer science such as semidefinite programming and approximation algorithms.

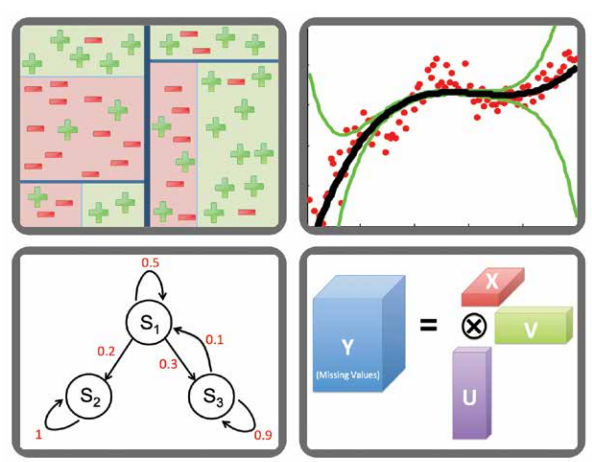
Vidick received a bachelor's degree in pure mathematics from École Normale Supérieure in Paris, a master's in computer science from Université Paris 7, and a PhD in computer science from UC Berkeley. His PhD thesis was awarded the Bernard Friedman Memorial Prize in Applied Mathematics. Before joining Caltech, he was a postdoctoral associate in CSAIL at the Massachusetts Institute of Technology. He has held visiting positions at the Centre for Quantum Technologies in Singapore, the Perimeter Institute in Waterloo, and the Simons Institute for the Theory of Computing at Berkeley. His paper "A multi-prover interactive proof for NEXP sound against entangled provers," co-authored with Tsuyoshi Ito, was co-awarded the best paper award at the FOCS 2012 symposium.

Yisong Yue

Assistant Professor of Computing and Mathematical Sciences

Yisong Yue's research interests lie primarily in the theory and application of statistical machine learning. He is particularly interested in developing novel methods for structured prediction, spatiotemporal reasoning, adaptive learning systems, and learning with humans in the loop. In the past, his research has been applied to information retrieval, content recommendation, text classification, learning from rich user interfaces, analyzing implicit human feedback, data-driven animation, sports analytics, policy learning in robotics, and adaptive routing and allocation problems.

Dr. Yue received his BS in computer science from the University of Illinois at Urbana-Champaign (2005) and his PhD in computer science from Cornell University (2010). During his PhD, Dr. Yue spent time visiting Microsoft Research and Google, where he worked on machine learning approaches to training and analyzing search engines. Dr. Yue was then a postdoctoral researcher in the Machine Learning Department at Carnegie Mellon University (2010–2013), where he worked on interactive personalization of recommender systems and adaptive routing and allocation of large fleets of vehicles in urban environments. He was also a research scientist at Disney Research (2013–2014), where he worked on data-driven visual speech animation and modeling player behavior in sports. He is the recipient of a Microsoft Research graduate fellowship (2008).



Moore Scholar

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

Robert Braun

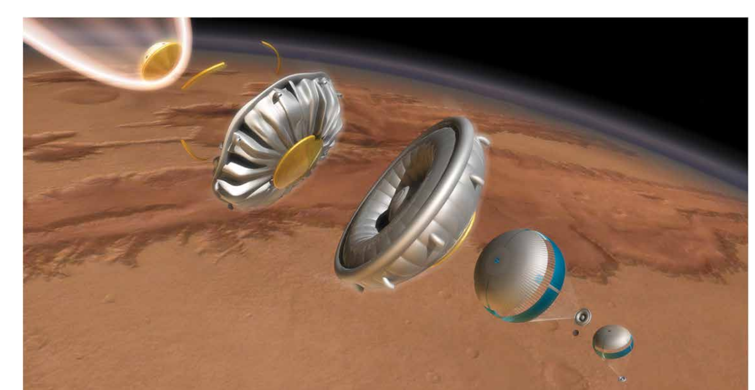
David and Andrew Lewis Professor of Space Technology, Georgia Institute of Technology

Robert Braun's research interests center on the design of advanced flight systems and technologies for planetary exploration. His research integrates aspects of conceptual design and analysis, optimization theory, technology development, modeling and simulation, and experimental validation. Through these efforts, he has advanced the state of the art of entry, descent, and landing technology and contributed to the design, development, test, and operation of both robotic and human space-flight systems. He has also been active in the development of theory and methods for multidisciplinary design, systems engineering, and optimization.

He joined the Georgia Institute of Technology faculty in 2003. Prior to this, he served on the technical staff of the NASA Langley Research Center. He has also served as a senior leader for several large engineering organizations at NASA. In 2010–2011, he served as the first NASA Chief Technologist in more than a decade. In this capacity, he was the senior agency executive for technology and innovation policies and programs and created the NASA Space Technology programs. In 2012, Dr. Braun co-founded Terminal Velocity Aerospace, LLC, a small business focused on developing a suite of reentry devices to improve orbital debris hazard prediction and promote space utilization.

He received a BS in aerospace engineering from Penn State in 1987, an MS in astronautics from the George Washington University in 1989, and a PhD in aeronautics and astronautics from Stanford University in 1996. He is a member of the National Academy of Engineering, an AIAA Fellow, and the principal author or co-author of over 275 technical publications in the fields of atmospheric flight dynamics, planetary exploration, multidisciplinary design optimization, and systems engineering. He lives on a small farm in Newnan, Georgia, with his wife, Karen, and is the proud father of Zack, Allie, and Jessica Braun.

In this visualization, a reentry black box data recorder survives destruction of its host spacecraft during atmospheric breakup, improving orbital debris hazard prediction and reentry safety knowledge.



A supersonic inflatable aerodynamic decelerator enables delivery of significantly more mass to the Mars surface.

Robert Behnken

Furthering the Exploration Frontier

Robert L. Behnken (MS '93, PhD '97) has been serving as the 14th chief of the NASA Astronaut Office for the past two years. He is overseeing the day-to-day operations of the Astronaut Office as an exciting new chapter in space exploration in the post-Shuttle era begins: one that is expected to feature the inaugural flights of U.S. Commercial Crew vehicles and the first piloted voyages beyond Earth orbit in almost five decades.

ENGenious had the opportunity to interview him at the Johnson Space Center, where he also suited up with fellow Caltecher and astronaut Stanley G. Love to carry out a practice contingency spacewalk in the NASA Neutral Buoyancy Laboratory.

ENGenious: What inspired you to become an engineer?

Behnken: My father is a construction worker, and when I was young I saw firsthand a lot of the projects that he worked on. Whether it was pumping stations, pipelines, or something else, I was interested in all the machinery being constructed or that made the construction possible. But since I also spent some time working as a construction worker in the summertime in St. Louis, I also learned that it might be nice to have a job where air conditioning was at least sometimes available! At that age, I could do it and it paid relatively well so it was worth the effort, but as a lifelong career, it can be quite a bit harder on your body than being an astronaut.

ENGenious: How has your Caltech education influenced you?

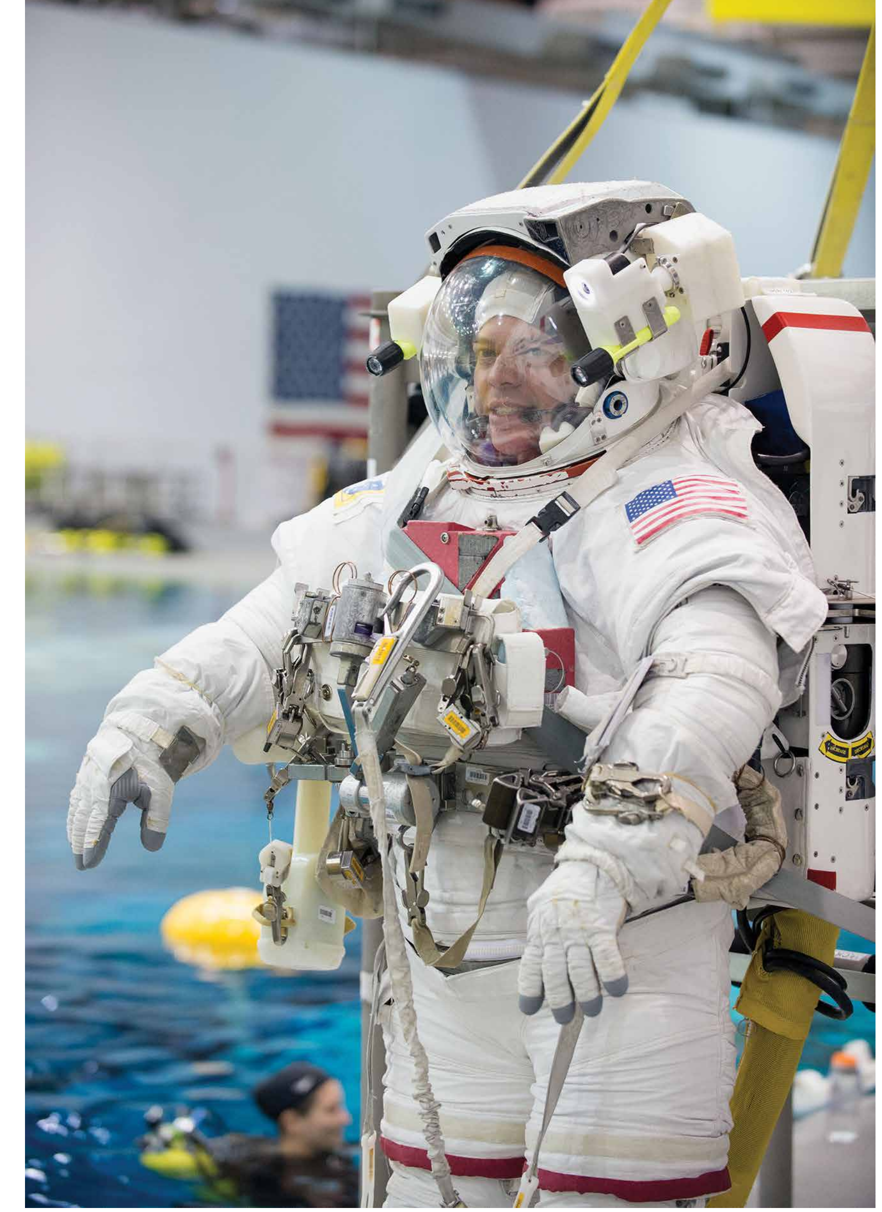
Behnken: My graduate advisor was Professor Richard Murray, and he espoused a hands-on approach combined with a strong theoretical background. That's probably the thing that's been the most valuable, being able to translate the mathematics or theory into real things. For example, when we go out for a spacewalk, someone has to understand and then manage the risk associated with the theoretical charging levels on a large structure that's moving in low Earth orbit. We need to understand the physics behind this and what the repercussions are going to be. Practically, that translates into something very real: What is the risk of electric shock to the astronaut inside the space suit and how do we best manage that?

ENGenious: How does the space suit protect you? How long does it take to be fitted for one?

Behnken: The suit itself is very much an exoskeleton for your body. It protects you from outside temperature extremes and from being in a vacuum in space, clearly a place that we human beings are not designed to operate in. It's very important for that exoskeleton to be the same size as you. It's a rigid structure and as you move your body inside of it, if the suit and your body aren't identically sized, you could stretch or compress an elbow, a shoulder, or some other joint in a way that it shouldn't be. We put significant effort into ensuring an exact fitting so that the person who puts on the suit does it in a safe way. As for how long it takes to get fitted for a suit, it depends on how close your body is to the suits and pieces of suits that have already been built. To produce a set of gloves for a specific individual takes well over a year. I've been an astronaut for quite some time and I don't yet have my own set of gloves because there are some that are close enough to my hands that I can successfully operate in them. They still injure my hands somewhat; I did lose fingernails during the training for and execution of the spacewalks on each of my missions.

ENGenious: Spacewalks are so glamorized, few of us think about this level of detail and this much potential danger with just the suit. What else could happen?

Behnken: The spacewalking suit has an elegant mechanical engineering design; it doesn't need power to provide basic life support. If the suit were to lose electrical power, it would still provide breathing air. You could still get some cooling out of it. You could still make it back inside the space station. With power, the suit of course works significantly better. During a recent spacewalk, however, a failure in the suit pumping system caused the water used for cooling to accumulate in the helmet of a crewmember who was outside the space station in the vacuum of space. Clearly you can't take the suit off outside, and so he and his partner rushed back inside to remove his helmet. In the future, our crewmembers are all prepared with more options in response to this failure. One is to turn the pump off that moves the water around. There's also a snorkel that will allow you to breathe from another pocket of oxygen inside of the suit. There is also now a system for absorbing water should it pool in the helmet, so that it can't accumulate on the spacewalker's head. Losing electrical power or accumulating water in the helmet are just two of the many things that astronauts are prepared for going "off nominal" during a spacewalk.



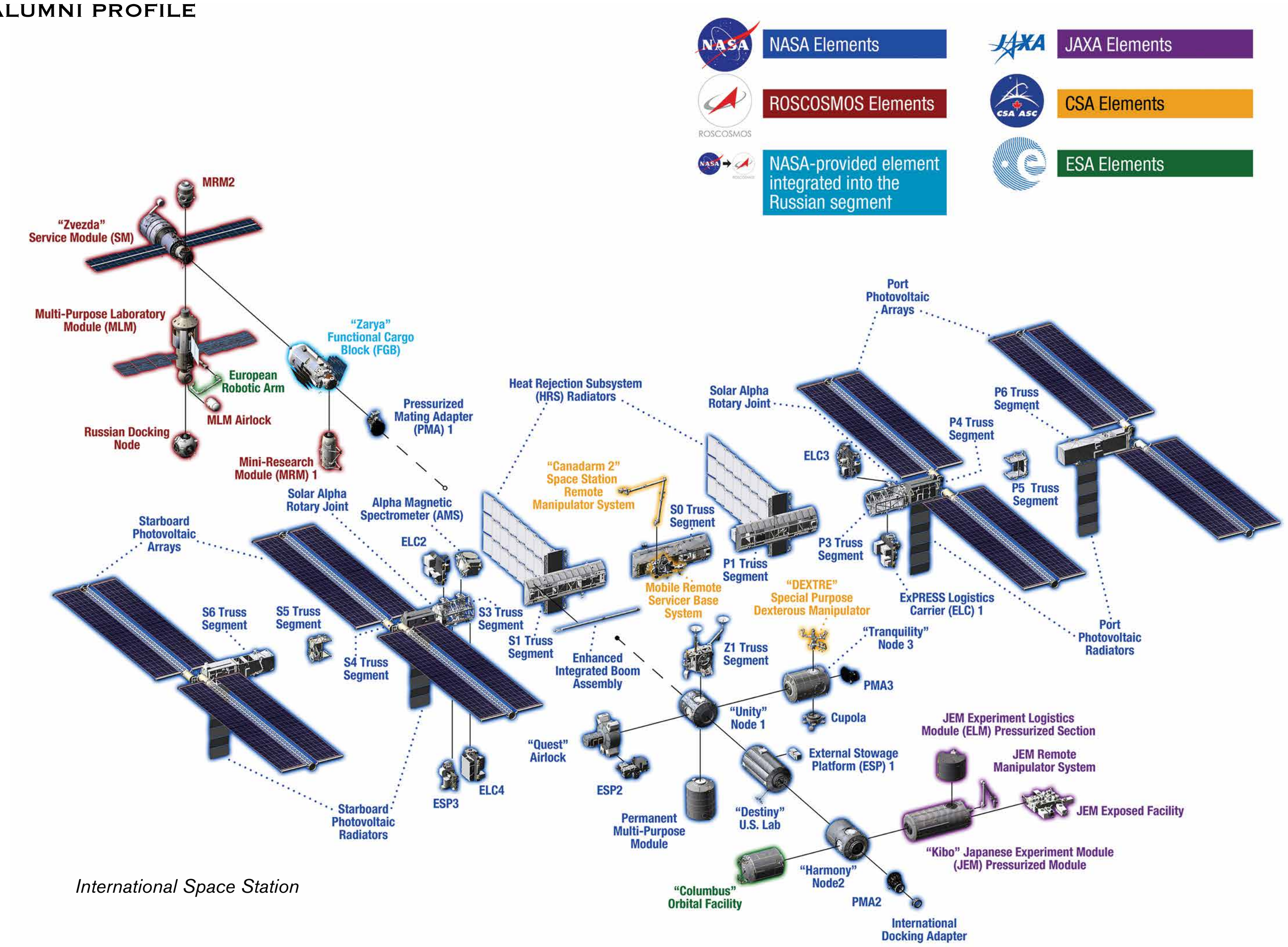
Robert Behnken preparing for a practice spacewalk in the NASA Neutral Buoyancy Laboratory.

ENGenious: How has your Caltech experience helped in your career?

Behnken: One of the things that was really brought home to me at Caltech was the importance of taking a jack-of-all-trades approach to problem solving. When it came time to do research, we didn't have the mindset of being a specialist who only looks at one little area. If you needed to learn to write computer code, you learned how to write computer code. If you needed to build an experiment, you built an experiment. You addressed the problem from all directions and picked up whatever skills you needed to go forward on it. Those I learned from at Caltech had the perspective that you're going to earn one advanced degree, and while maybe it's in mechanical engineering, that shouldn't limit you. If you need to learn electrical engineering to do your research, if you need to learn physics—learn those things. The degree you had earned shouldn't constrain your ability to learn in any area required to address your research.

ENGenious: How would you describe your professional contributions?

Behnken: We astronauts are often just a small piece of a much larger puzzle. The astronaut on board the International Space Station (ISS) or



International Space Station

who repairs the Hubble Space Telescope isn't the principal investigator for the research that will be accomplished. During my space missions, I was primarily a construction worker. I assisted in the installation of four different modules on the ISS: a Canadian robotic manipulator; a part of the Japanese laboratory; a living-quarters module; and the Cupola, a windowed portal for observing robotics operations that also provides spectacular views of Earth. Clearly my contribution during spaceflight was very much in the realm of facilitating others' ability to do research. Currently, as chief of the Astronaut Office, I facilitate other people being successful at carrying out the role I just described. We're primarily operators of the ISS and the hands for the investigator. In that role, it's very useful to have an educational background like I have from Caltech. If I need to know about combustion on a given day, I learn the details of the combustion experiment as quickly as possible and to the level that I need to in order to do what the investigator needs me to do. Tomorrow when I'm scheduled to execute a control systems experiment, I learn the details to the level needed to effectively accomplish the goals of the scientist who designed the experiment. As the chief astronaut, my goal is to make sure that I've created opportunities with training and education so that the astronauts are ready when they have the opportunity to be the hands for those scientists. More important than the glory and excitement, astronauts need to make sure that they are always focused on this responsibility. It's about furthering the envelope of understanding with ISS research. It's about furthering the exploration frontier. Those are not personal accomplishments. They're humankind's accomplishments. If you don't have that perspective, you may be very frustrated as an astronaut; there simply isn't time for you to be a true investigator at the center of every experiment.

***ENGenious*: How can Caltech medical engineers assist astronauts and the astronaut program?**

Behnken: Historically, the space program has been a driver for many of the medical devices that eventually became commonplace. Every time we do a spacewalk, we are instrumented to have our electrocardiogram (EKG) monitored on the ground throughout the entire event. That type of physical monitoring capability is an area that we would definitely like to expand. It is extremely cumbersome to bring samples back from the ISS. As we continue to move toward doing more biological science on board, if for example monitoring devices become implantable, we'd certainly be interested in taking advantage of them. Devices that allow us to not need to return samples would be hugely beneficial, as well as medical examination equipment that crewmembers can use on their own with limited coaching from a ground team. For example, we regularly do a significant number of eye exams in orbit now because it's been discovered that the geometry of astronauts' eyes are changing during prolonged exposure to the ISS environment. It's unclear if it's due to a zero-gravity-induced fluid shift that increases intracranial pressure, carbon dioxide in the environment changing the chemistry of the blood, or some other phenomenon resulting in pressure on the back side of the eye and changing the shape of the eye and impacting the optical nerve. So we have new equipment on board to measure this phenomenon and provide the data to the investigators multiple times throughout the mission (in the past we only had the pre-flight and post-flight measurements). This is one of many biological phenomena that we need to address, many of which are resulting in new, exciting areas of research. There are of course engineering hardware challenges as well, at least as numerous as the medical challenges.

***ENGenious*: How are astronauts monitored to understand the impact of space flight?**

Behnken: We all receive extremely thorough physicals annually. We have a significant number of astronauts who flew Shuttle missions, and they came back in pretty good shape after days or weeks in space, but for longer-duration missions it's becoming more apparent that there are long-term health consequences. Causes for these health impacts include radiation exposure, the fact that your skeleton is not being loaded in the same way as when you're on the ground, or one of the other phenomena associated with zero gravity. The skeletal changes are particularly interesting; astronauts after long-duration missions have structural differences to the interior of their bones, even though their overall bone density may remain relatively constant. Our astronauts haven't yet aged enough for us to see what the full repercussions of these changes will be. How much monitoring of these astronauts as they age is appropriate is an active area of discussion. One of the intents of such monitoring would be to truly understand what the impact of the space flights on the human body actually is. It's very much a statistics problem because the physiology of humans is so diverse, and it will take more data points—i.e., more astronauts who have flown these missions—in order to develop these statistics. It will also take an astronaut's lifetime for us to understand if their eyes completely recover or regress, if their bone health is impacted as they go through the normal aging process, or if some other phenomenon is significant.

***ENGenious*: What's next for human space flight?**

Behnken: We're hopeful that the next phase of acquisition for U.S. crew vehicles that will fly astronauts back and forth to the ISS will be under way very soon. Currently we expect to see a U.S. crew vehicle arrive at the space station in the 2017–2018 time frame. We also have programs under way to provide the capability to return humans to lunar orbit or to travel deeper into space. Those are a bit further out, closer to 2020 time frame.

***ENGenious*: What will it take for humans to travel deeper into space?**

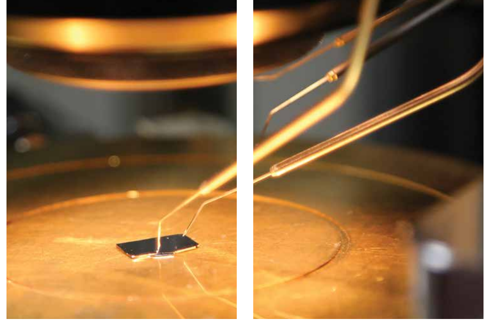
NASA astronaut Karen Nyberg, Expedition 36 flight engineer, conducts an ocular health exam on herself in the Destiny laboratory of the Earth-orbiting International Space Station.

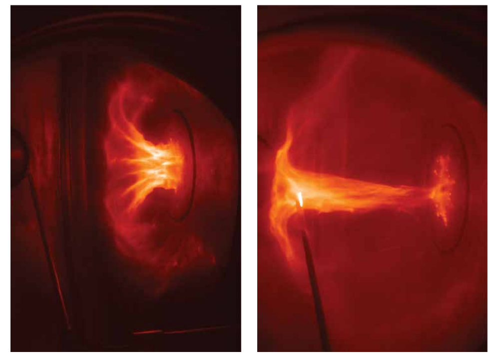
Behnken: I mentioned the eye phenomenon that astronauts are facing right now. There are other areas from a physical-phenomenon perspective that need to be managed in preparation for a longer stay in space than we have on board the space station. The biggest challenge is the radiation environment, and as you can imagine, there are many ways to address this challenge. Adding shielding that physically protects you from that radiation environment is one solution, but spaceships can only be so big and so heavy before they are unaffordable or impractical for other reasons. There's also a solution that takes a longer view and focuses on healing the cancer after it begins to develop. That solution could help lots of people, not just astronauts in space. A similar but a nearer-term solution is to focus on early detection of the cancer or other impacts of radiation so you have a better chance of effectively dealing with them. It's interesting because, whether it's medical professionals or physicists or engineers, there's room for everyone to contribute to the ability of humans to travel deeper into space. ENG

Robert Behnken is chief of the NASA Astronaut Office.

Visit www.nasa.gov/astronauts.

ALUMNI PROFILE





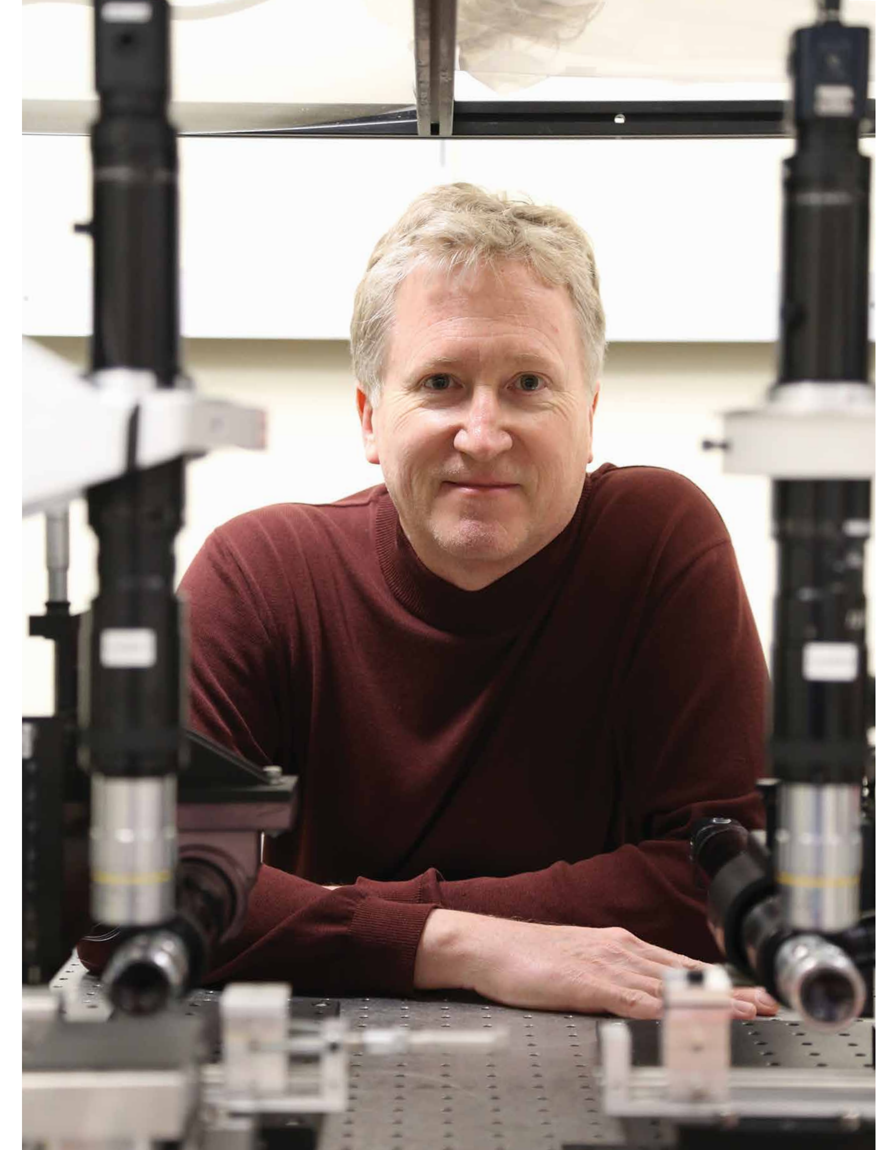
Strikingly Passionate

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."

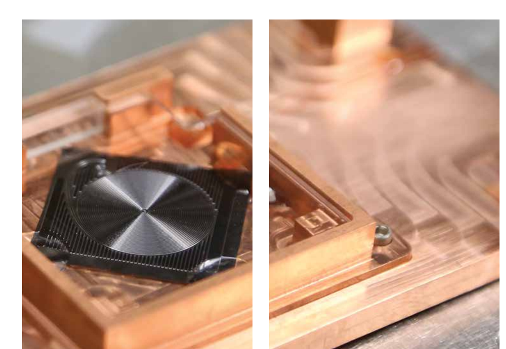
Today, research opportunities that maximize that overlap abound in the department. For example, Vahala explains, "Many applied physics groups, including my own, are interested in taking fairly well-understood materials systems and then exploring the physics of turning these materials into devices. This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

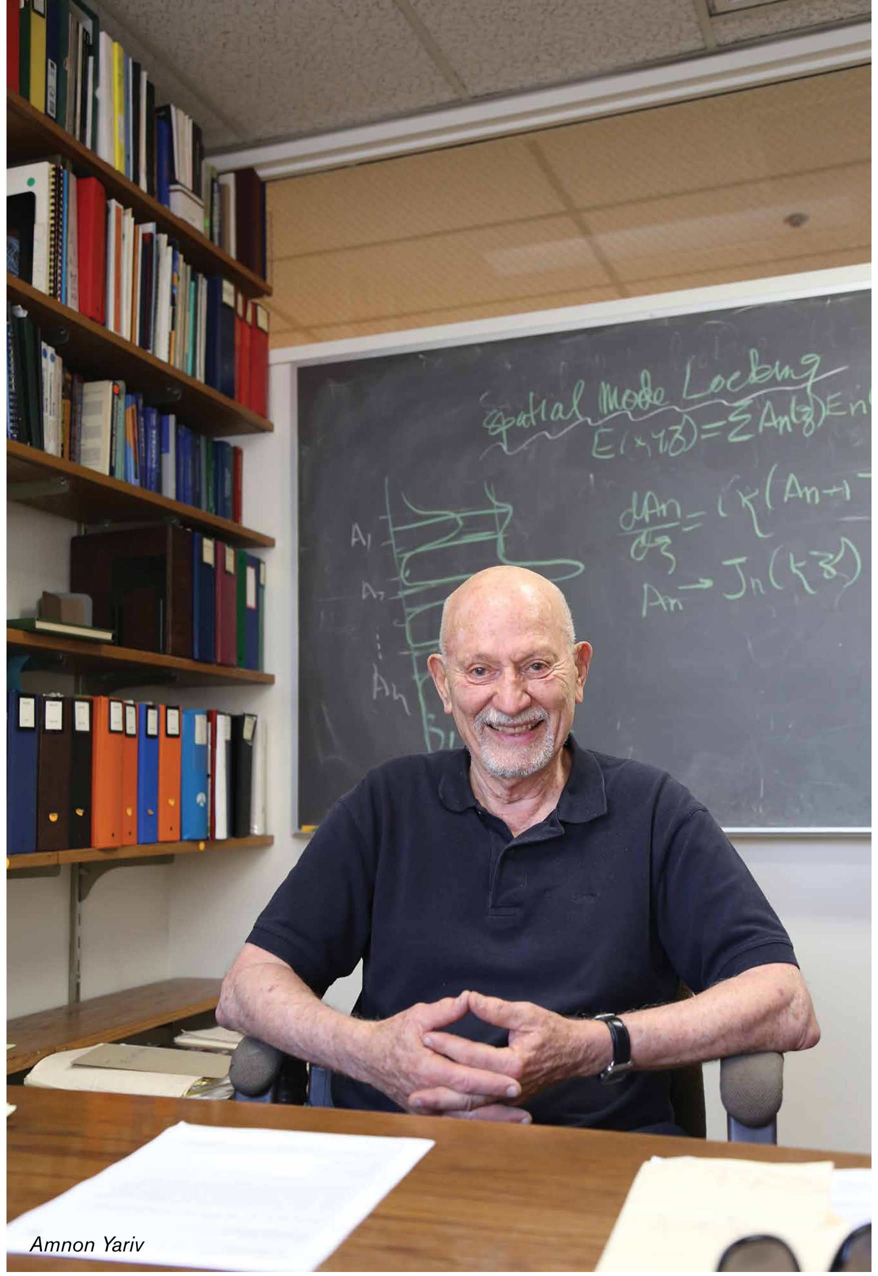


Kerry J. Vahala

"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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>
> Amnon Yariv, *Martin and Eileen Summerfield Professor of Applied Physics and Professor of Electrical Engineering*

> *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.*
>
> William L. Johnson, *Ruben F. and Donna Mettler Professor of Engineering and Applied Science*

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 scien-tists 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*


Sossina M. Haile

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.*

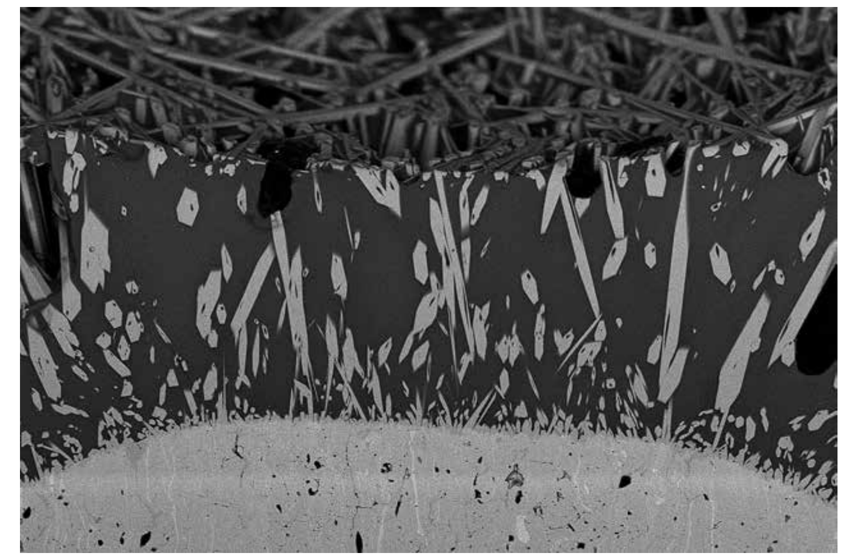
Katherine T. Faber, *Simon Ramo Professor of Materials Science*

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!"

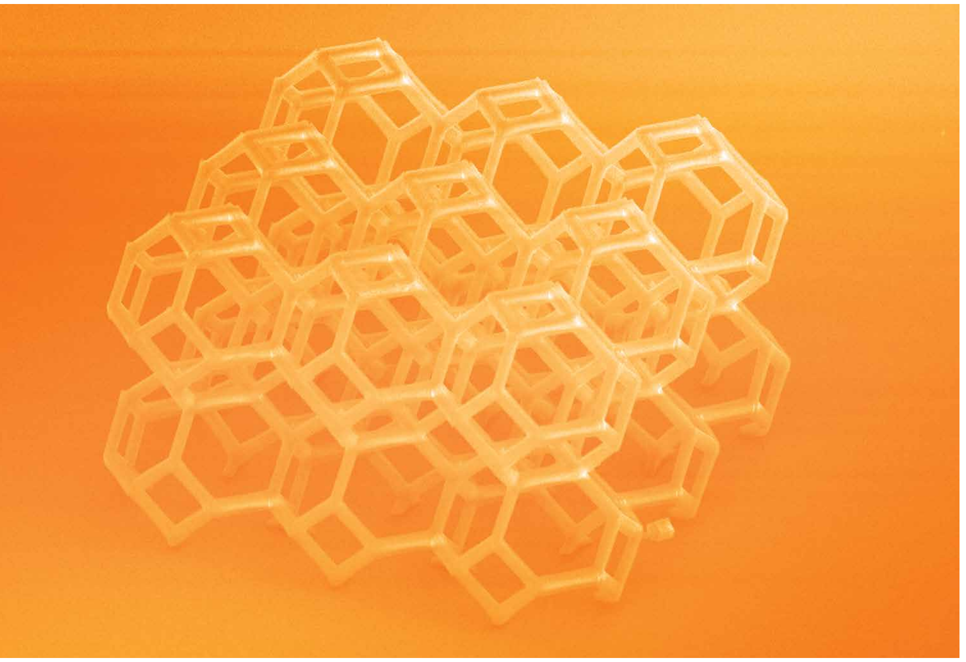
Haile has a demonstrated knack for channeling that enthusiasm. In terms of her own research, she says, "I look for the intersection between lasting scientific impact and lasting social value. Among all the exciting scientific endeavors that one could pursue, how does one down-select? For me, that down-selection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

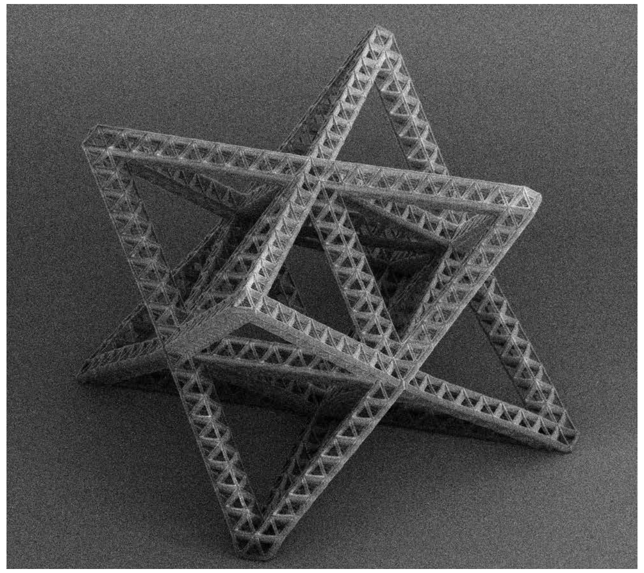
As a new faculty member in the APhMS Department, Katherine T. Faber, Simon Ramo Professor of Materials Science, has not had as much time as she would like to get to know her colleagues. Still, she says, "I think *passionate* is probably the word that comes to mind with almost every faculty member here. 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.”

EAS FEATURE

“*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.

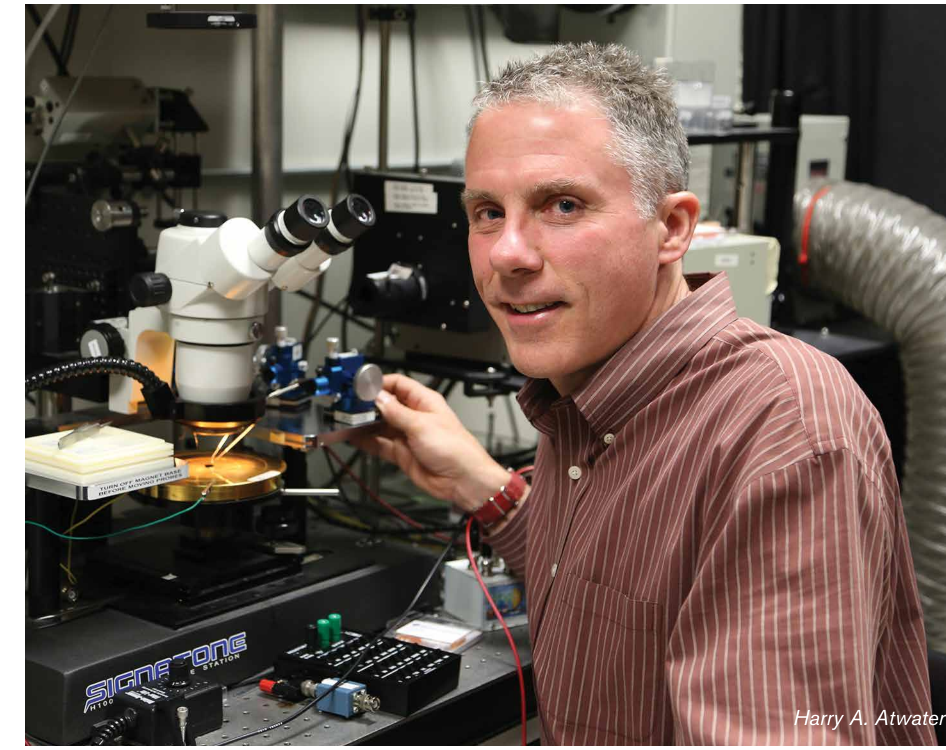

Austin J. Minnich

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

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."

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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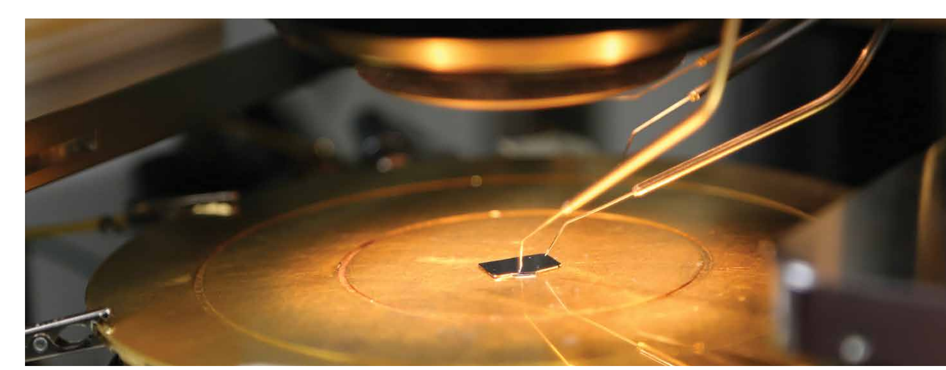
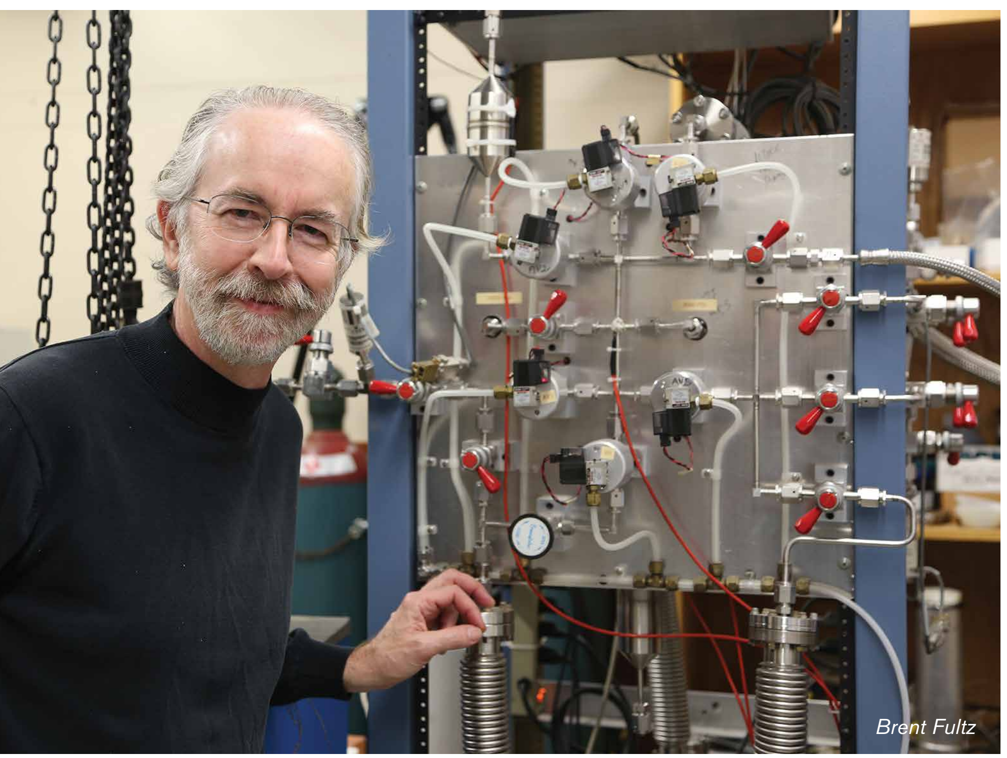


I am organizing the community of scientists who do X-ray and neutron scattering to more efficiently and effectively do high-performance computing with the materials codes that exist today that did not exist some 15 years ago, and to get more science out of their research.

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*

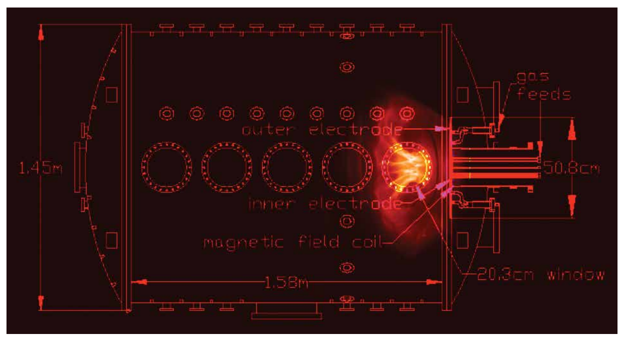
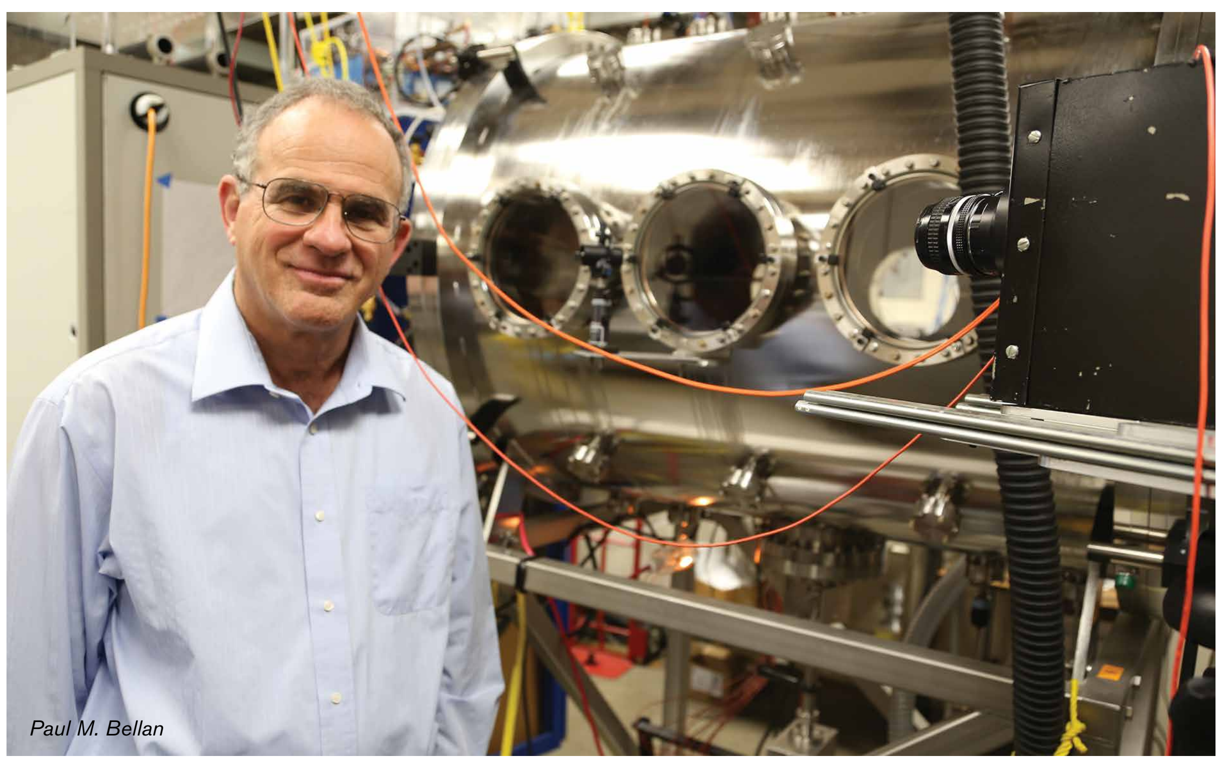


Image of a magneto-hydrodynamic plasma jet super-imposed on the outline of a vacuum chamber; the jet expands to the left at a velocity exceeding 10 km per second.

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



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*

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

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*

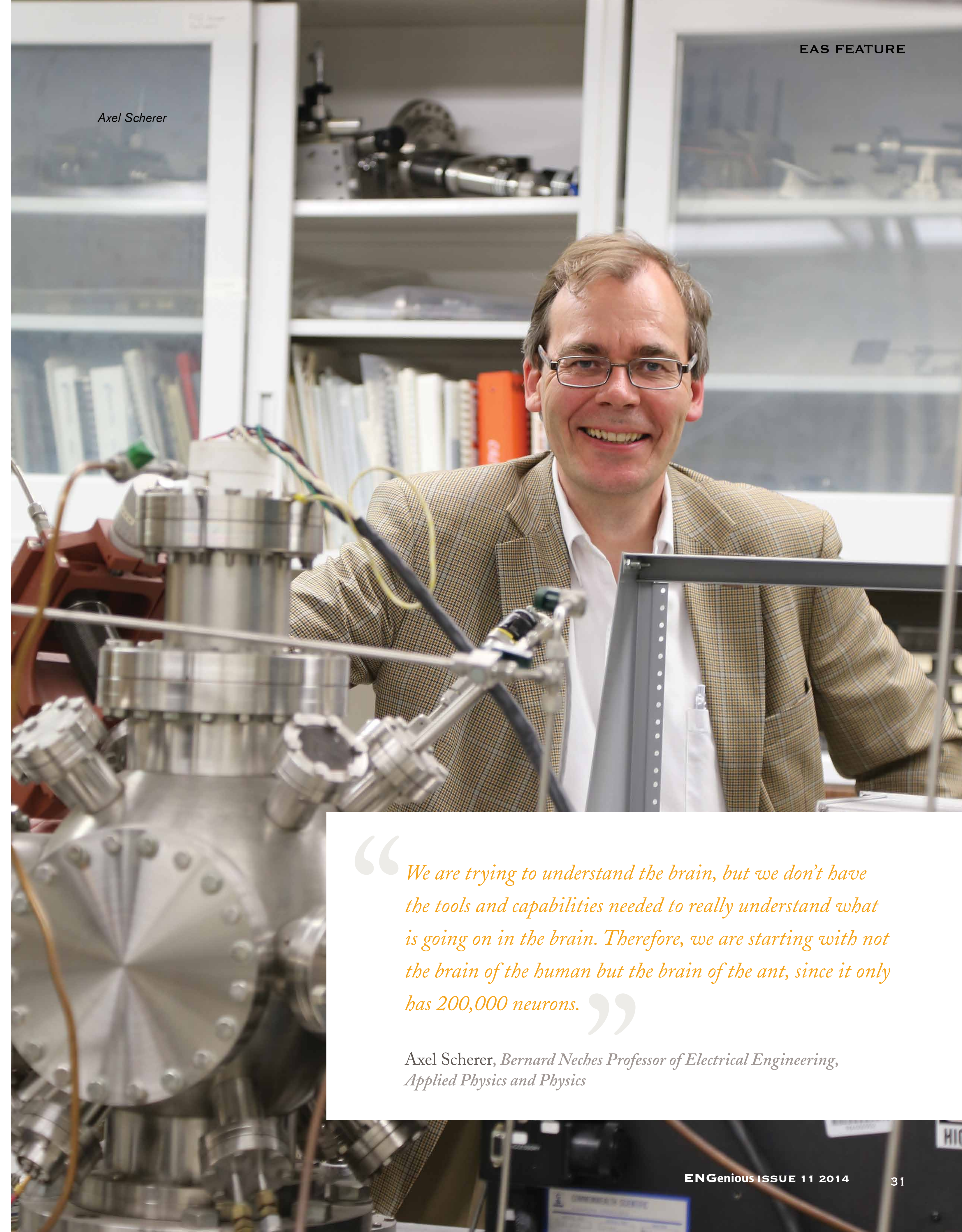
that fluid dynamics occurs at all scales in our world and the universe," he says. He goes on to explain that "the predominant fraction of matter in our universe is in a fluid state and turbulent. The range of scales in turbulence is so large that not even the biggest computers in the world are capable 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!"

EAS FEATURE



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!"

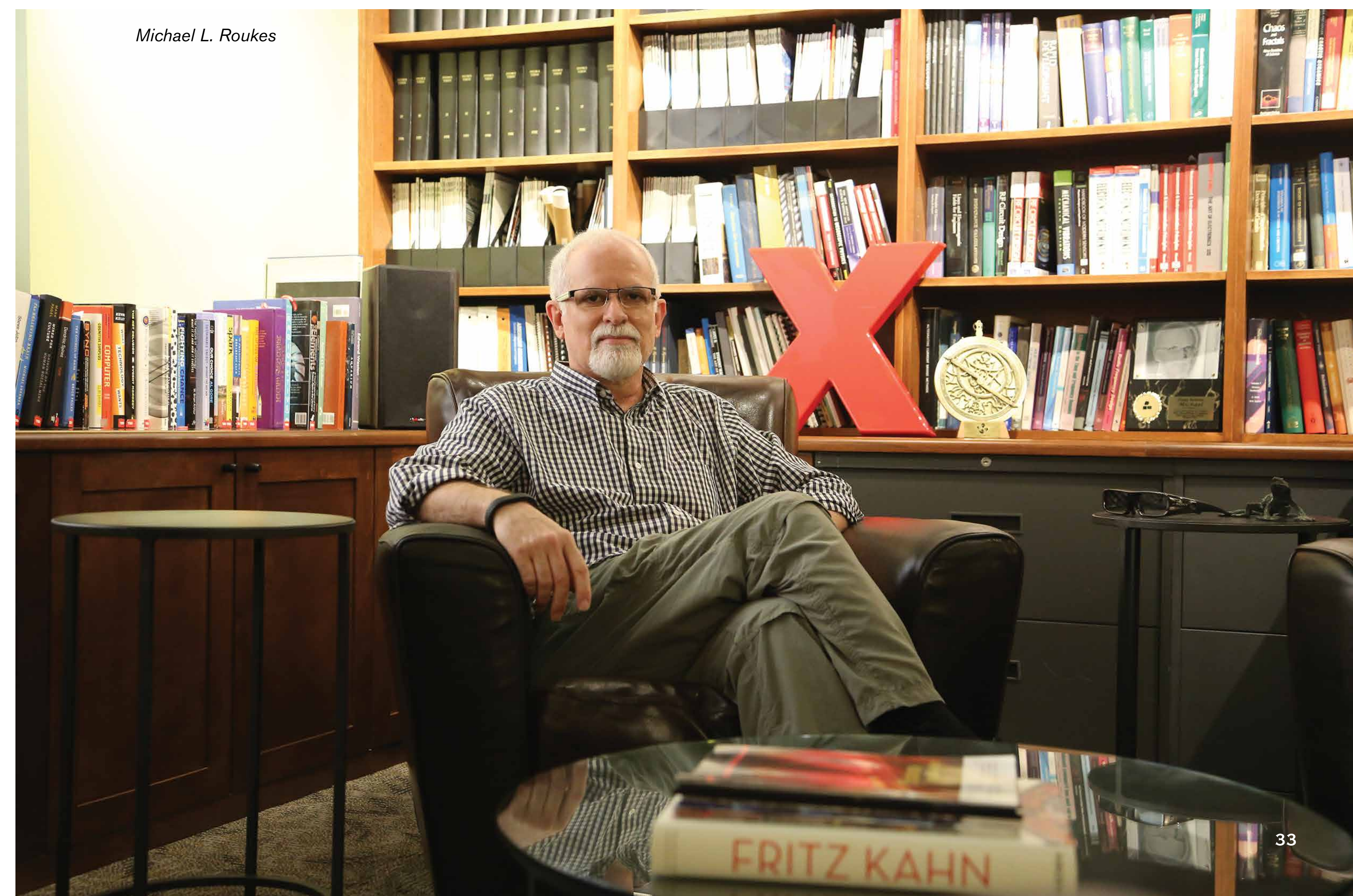
Axel Scherer, Bernard Neches Professor of Electrical Engineering, Applied Physics and Physics, shares Professor Troian's desire to map new knowledge onto other fields and think about problems in fresh ways. "By combining applied physics and materials science, which is not done in a lot of places, I think 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

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... I decided then that these sorts of collaborative frontiers are where I wanted to push most of my research.

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

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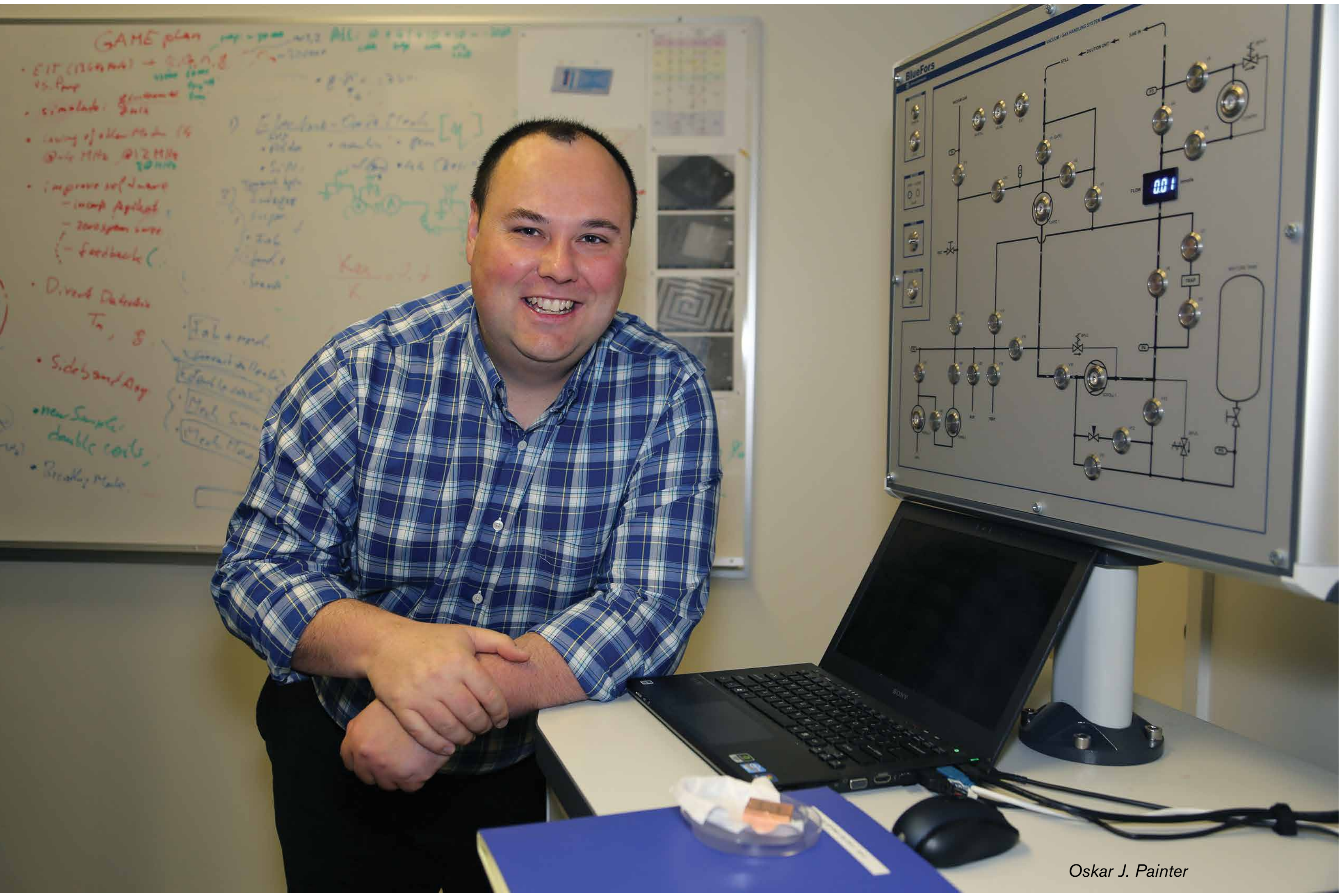


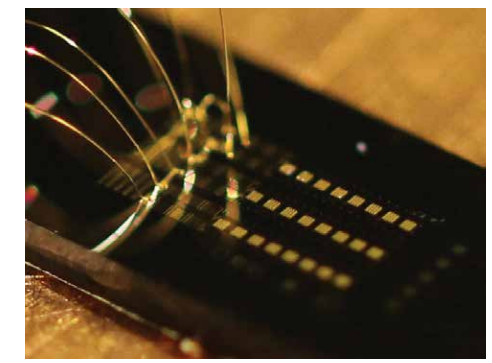
Oskar J. Painter

"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*

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."

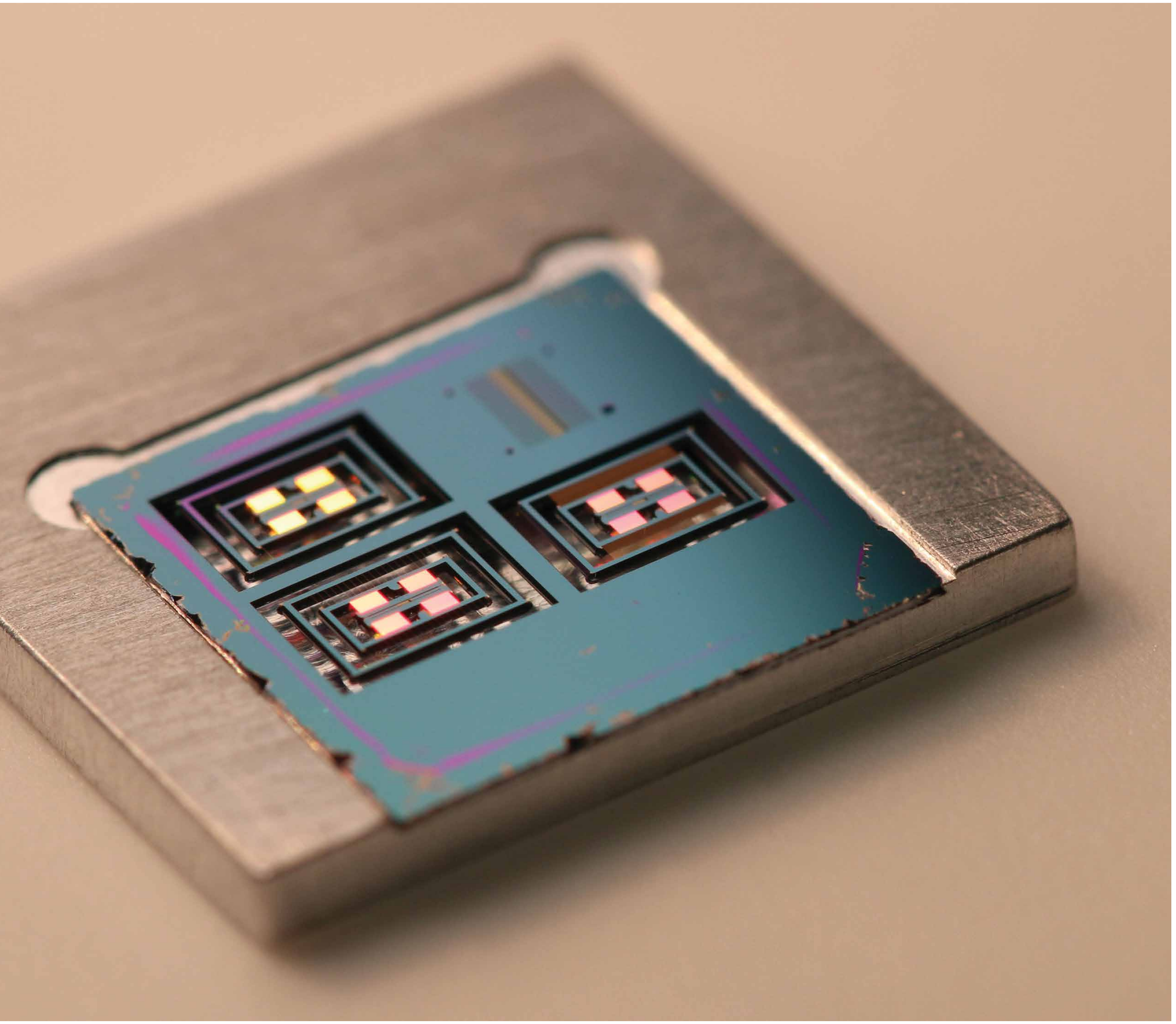
There have, Schwab notes, been dramatic changes in the field since he began this work. "Today's graduate students assume that everything will be quantum mechanical and work. They don't even know that 14 years ago, I used to hear people over my shoulder say this will never work. This is crazy! The field 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



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."

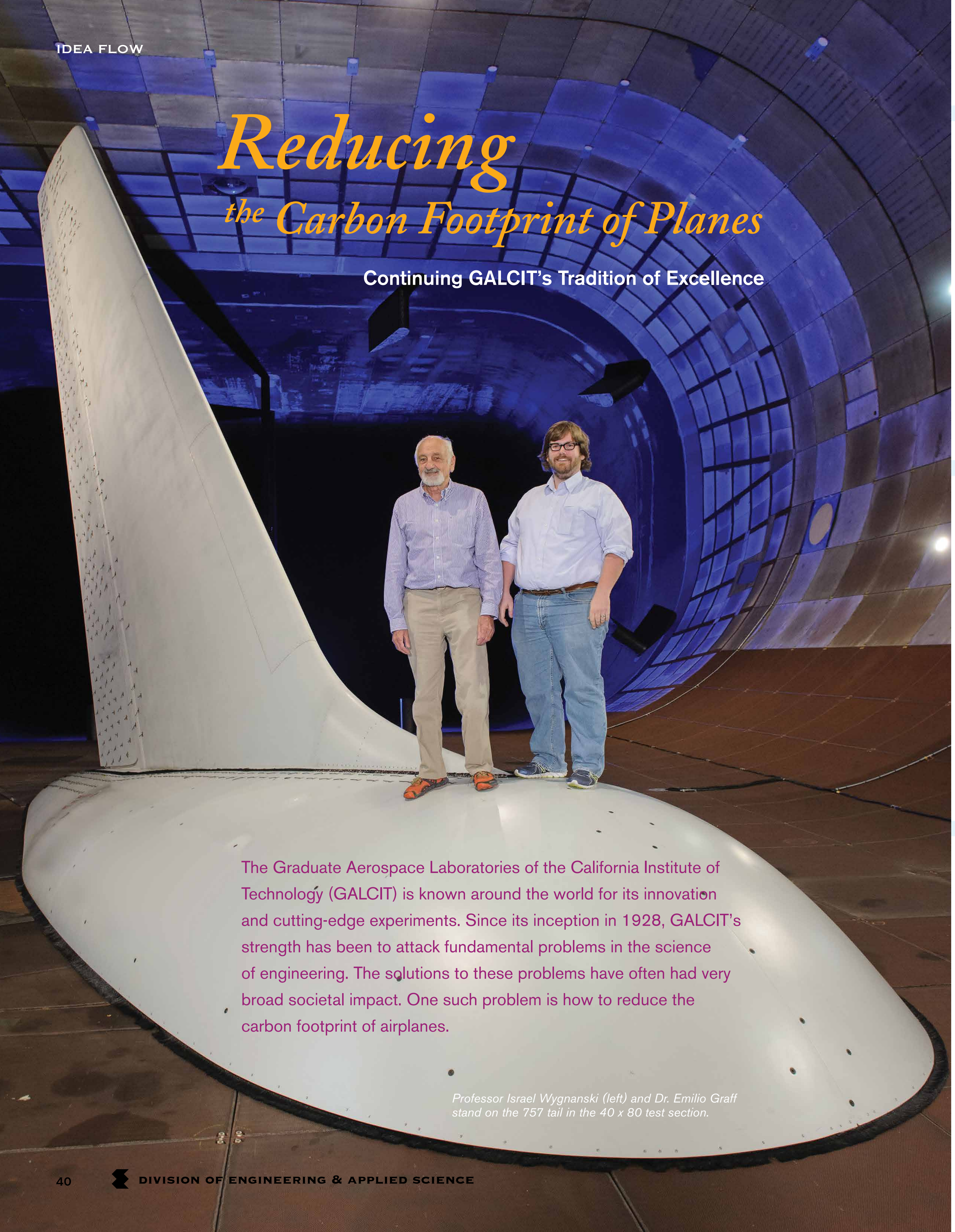
In the fall of 2015, the APhMS faculty are excited to be welcoming two assistant professors who are poised to "push beyond" in the ways that Professor Painter describes. The first is Marco Bernardi, who specializes in theoretical and computational materials science as well as condensed matter physics. 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



Reducing the Carbon Footprint of Planes

Continuing GALCIT's Tradition of Excellence

The Graduate Aerospace Laboratories of the California Institute of Technology (GALCIT) is known around the world for its innovation and cutting-edge experiments. Since its inception in 1928, GALCIT's strength has been to attack fundamental problems in the science of engineering. The solutions to these problems have often had very broad societal impact. One such problem is how to reduce the carbon footprint of airplanes.

Professor Israel Wygnanski (left) and Dr. Emilio Graff stand on the 757 tail in the 40 x 80 test section.

To tackle this problem, Morteza Gharib, Caltech's Hans W. Liepmann Professor of Aeronautics and Bioinspired Engineering, and Dr. Emilio Graff, Research Project Manager in Aerospace, partnered with University of Arizona professor Israel Wygnanski ("Wygy"). They focused on the vertical stabilizer of a plane, which is colloquially referred to as the rudder, or the large "tail" of the aircraft where companies usually place their logos. The Vertical Stabilizer Project surpassed everyone's expectations. The project used active flow control (AFC) to show that the wing efficiency can be increased, which in turn allows for the entire vertical tail to be shrunk, reducing drag, weight, and ultimately the plane's carbon footprint.

To learn more about the project and its path to success, *ENGenious* interviewed Professor Gharib and Dr. Graff.

***ENGenious*: How did the project get started?**

Gharib: Professor Wygnanski, who is a world-renowned expert in aerodynamics and active flow control, approached me about whether we were interested, and at the time Emilio was joining us. I saw this as a golden opportunity. The project brings back the traditional GALCIT, where we basically started the Southern California aerospace industry.

Graff: Wygy's research group had been employing sweeping jets (a form of "fluidic amplifier") in various configurations to show the potential benefits of the technology. He then joined NASA as the principal investigator of the project to apply sweeping jet technology to a vertical tail of a commercial aircraft. Boeing was also part of the project, as they had been looking at active flow control for various applications and in fact had already been working on testing the system on the tail with Rensselaer Polytechnic Institute. Professor Gharib received a NASA research grant under the Environmentally Responsible Aviation program to explore the potential of sweeping jets and synthetic jets on the same vertical tail model. Boeing additionally provided funds for Professor Gharib's group to investigate the flow physics behind the sweeping jet actuators and their effect on the flow.

Gharib: The Vertical Stabilizer Project is especially interesting for me because my PhD thesis was focused on a similar topic: manipulating and directing fluid flows through active flow control.

***ENGenious*: What part did GALCIT play in this project?**

Graff: We actively participated both in the preparation for the large-scale tests, which meant producing all the hardware, and also on the scientific side to attend the full-scale tests as a representative.

Gharib: Caltech is the only place in the country that can really rig up this new technology and implement it to become reality. Thus, GALCIT was charged with combining its historic tradition of aerospace innovation with its modern facilities. But this wasn't a resurrection—this was a continuation of a tradition of excellence.

***ENGenious*: How did the investment from the Lucas family and the reopening of the wind tunnel impact the project?**

Gharib: It was the Lucas family's generous support that allowed us to revamp the Guggenheim Wind Tunnel into the modernized Lucas Adaptive Wall Wind Tunnel facility, which made this project possible. If the wind tunnel hadn't been reopened, this project may have never taken place here at GALCIT. A whole country and nation is benefiting from the Lucas family investment.

Graff: The Lucas Tunnel was an ideal facility due to its size and quality. Nearly 800 hours of wind tunnel time were used to characterize the behavior of the sweeping jet system and eventually arrive at the configurations to be tested on a full-scale 757 airplane tail.

The Project

ENGenious: What was the main goal of the project?

Graff: To prove that active flow control can increase wing efficiency.

ENGenious: Can you be more specific?

Graff: The rudder of an airplane is most important in two situations: (1) when an airplane faces a cross-wind and needs to go straight, it points its nose in the direction that the wind is coming from, and (2) in the case when an engine fails. If the engine fails, the airplane will naturally turn toward the dead engine due to the asymmetry between thrust and drag forces, and it's up to the rudder to keep the plane flying straight. The shorter an airplane, the larger the tail must be in case the engine is lost. A wing or tail generates force by redirecting the air that flows over it. A symmetrical wing won't generate any force, because the air flows above and below follow the contour of the wing. But if an asymmetry is created by slightly deflecting a wingtip, air flow above the wing is pulled down, generating a lift force. When a wing needs to generate more force, it will deflect its flap at a larger angle—just as a bird flaps its wings. But this deflection comes at a price of energy and efficiency.

Gharib: Believe me, if birds had the option *not* to flap, they wouldn't flap.

Graff: There's a point of the deflection angle where the flow becomes "separated," creating drag and impacting efficiency negatively. Thus, in order to make up for this inefficiency, vertical tails are designed largely enough to operate well into the region where the flow becomes separated. This means the size of the tail is dictated by the inefficient operation of the wings!

Professors Gharib and Wygnanski with Dr. Graff

ENGenious: What was the idea behind this project?

Gharib: The idea was to blow high-speed jets of air across the rudder's upper surface—pushing away slow-moving air, sucking in faster air, and ultimately limiting the separation of the flow. Because the tail is designed for a rare condition, it is one of the most low-risk regions to tweak on an airplane—perfect for the GALCIT team to experiment with. If active flow control was successful in increasing wing efficiency, then the entire vertical tail could be shrunk, reducing drag, weight, and ultimately the plane's carbon footprint.

The Results

ENGenious: What were the findings?

Gharib: Our initial base estimation was not only correct, the results were even better. There was a 20 percent lift increase; that can translate into a huge amount of fuel savings, stability, and also a much lighter airplane.

Graff: The project proved that by reducing the size of the rudder, or vertical stabilizer, of an airplane, the amount of CO_2 emission and carbon signature will decrease, thus causing less environmental impact and decreasing the overall amount of fuel needed.

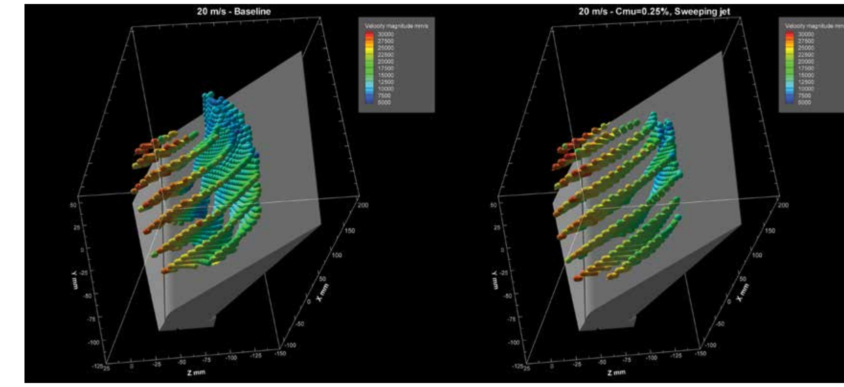
ENGenious: How will these results impact commercial flights?

Gharib: The overall fuel savings make more of an impact on longer flights due to the amount of time spent actually flying. The fuel savings are in the Los Angeles-to-Hong Kong and Los Angeles-to-Frankfurt flights, where you're in the air a very long time with respect to how much you spend landing and taking off.

ENGenious: What challenges did the project face?

Graff: One of the biggest challenges was in the transition from a scale model to full scale. On one side, Dave Bauer and his team at Boeing showed a tremendous amount of consistent focus in turning a real airplane tail into a wind-tunnel test article. At first, you may think that this should be easy; if it can survive flight, it can survive a wind tunnel. But this tail was modified to allow for the plumbing, and the wind tunnels like to work with huge safety margins to protect the equipment. Everyone on the tunnel staff was very excited to see the tail; it really was an impressive beast. Under some conditions, it would shake the whole building!

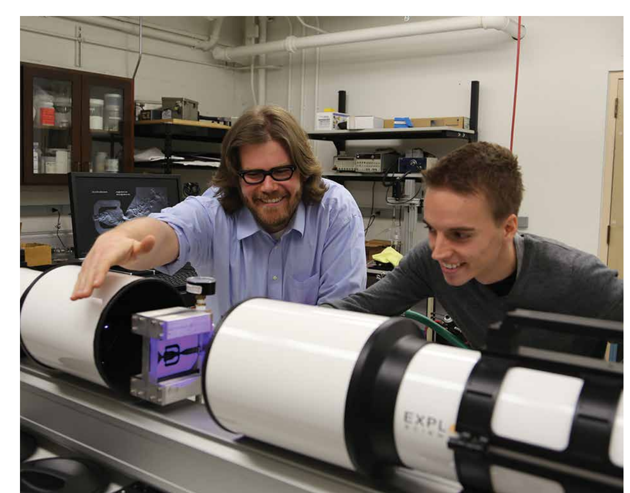
On our side, we had to fight to convince NASA and Boeing that our predictions based on the Lucas tests were correct. This was an uphill battle because simulations at the time showed that we were wrong and the system could not work. Just prior to the test, we argued that we should start ramping up the system slowly—we were still convinced our predictions were correct. We were vindicated immediately when the first data point with all the jets running exceeded the structural limit imposed by new analysis of the modified tail.



Here, three-dimensional flow is measured using the defocusing technique developed by the Gharib research group. The left figure shows normal rudder flow immediately turning upward; the right figure shows how the sweeping jets serve to straighten and speed up the flow.

Gharib: Also, it is important to note that in four years, the project went from concept to flight!

Graff: Yes, the test of the full-scale tail was a success, proving that sweeping jets can increase the effectiveness of the rudder by significant margins—enough to make an impact on the fuel consumption due to the tail. It is important for the future of aviation to find ways to make airplanes more efficient. Next, the objective is to make wings, in general, more effective using similar techniques.



Graff and aeronautics graduate student Damian Hirsch

ENGenious: What does the future have in store?

Gharib: This project has had a huge impact on the way that airplanes may function in the future. The "big" test is on an actual 757 sometime in 2015. If all goes as predicted, there may be a substantial reduction in the amount of fuel consumption.

Graff: GALCIT has played a huge role throughout this entire project and continues to do so, from small-scale to larger-scale testing. We have shown that we at Caltech can do the fundamental studies and the model tests and the measurements—but also, when it comes time to playing with the big boys, we can be there, too. Everything we delivered for the full-scale test worked from the start. Keep in mind that we don't have a huge engineering staff—two people maximum worked on this at any given time. ENG

Morteza Gharib is Hans W. Liepmann Professor of Aeronautics and Bioinspired Engineering; Director, Ronald and Maxine Linde Institute of Economic and Management Sciences; and Vice Provost. Emilio Graff is Research Project Manager in Aerospace and Manager of the Lucas Wind Tunnel.

Visit windtunnel.caltech.edu.

The Tale of Two Lasers

Forty years ago, Amnon Yariv, now Caltech's Martin and Eileen Summerfield Professor of Applied Physics and Professor of Electrical Engineering, and his research group at the Institute invented the semiconductor distributed feedback laser (DFB laser) (Figure 1). The laser still serves as the sole light source powering the Internet fiber system. Along with the optical fiber, it is one of the two main pillars of the optical communications revolution.

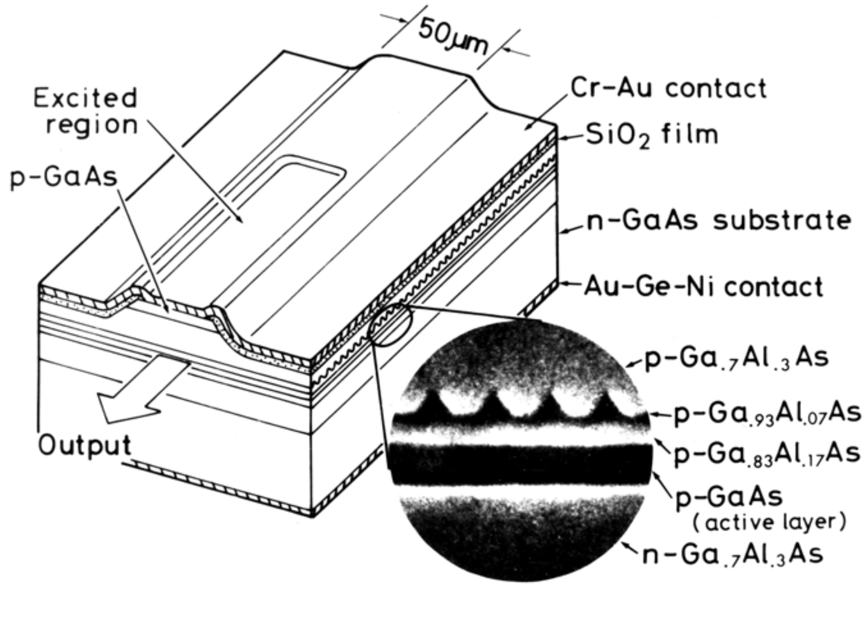


Figure 1: *Shown above is the 1975 version of the distributed feedback laser (DFB laser). Its essential feature was the incorporation of a corrugated, washboard-like interface with nanometer periodicity in the multilayered semiconductor structure. This periodic structure acted as an internal (Bragg) optical filter, allowing only one frequency to survive and become the output field. Such a pure frequency (or color) operation was a prerequisite to high-data-rate optical fiber communications and was the key factor enabling the increase of many orders of magnitude in the data rate carried by the optical fiber system compared to microwave antecedents.*

Laser light is capable of carrying vast amounts of information, but to utilize this potential, it needs to be as spectrally pure—as close to a single-frequency sinusoid—as possible. The DFB laser's unprecedented spectral purity enabled a larger information bandwidth and longer transmission distances via optical fiber. Its purity was achieved by incorporating a nanoscale corrugation within the multilayered structure of the laser, which effectively filtered out extraneous waves that contaminated the ideal wave frequency.

Over the last decade it has become increasingly clear that the demand for high-speed communication, as exemplified by the "Netflix phenomenon," is outstripping the capabilities of the stalwart DFB laser. What was good enough from 1975 to 2014 is no longer sufficient. In the DFB laser, once electrical current is converted into light in the active region of the semiconductor, the light is stored in the same neighborhood where it was born. Since semiconductor materials are strong light absorbers, it follows from basic physics that the coherence of the laser field must be degraded due to these losses.

Rather than tweaking the properties of the DFB laser to meet the bandwidth demand, something that the industry has been doing for nearly 40 years, the Yariv group decided to take a look at the origins of the phase fluctuations noise. Both the fabrication and processing techniques and the theoretical understanding of the laser physics have advanced during the intervening years, so a fresh look at the problem of high-coherence lasers was warranted.

But first, a brief primer on laser physics: Every laser, with no exception, has two main components. The first is an atomic medium with an "inverted" population of excited electrons (atoms, or molecules), the so-called active region. In this region, the optical wave is amplified in transit by inducing the excited electrons to make transitions to lower energetic states. In the ideal, nonexistent, laser, the excess energy released in the process is added in phase to the optical wave, thus amplifying it.

In the semiconductor laser, excited electrons are injected at a high energy, which they acquire in passing through a battery or power supply into the active region. Some of these electrons, however, rather than be induced by the optical wave to give up their energy in phase to the field, do so spontaneously. The power emitted by these spontaneous transitions constitutes noise, since they occur at a rate and phase independent of those of the optical field in the active region. The result is a degradation of the coherence. It should be noted that one of the most important consequences of applying quantum mechanics to electromagnetic fields is the relationship between the induced and the spontaneous rate. As a matter of fact, the phenomenon of spontaneous transitions cannot be explained classically and is thus of pure quantum origin, so the limiting noise in the semiconductor noise is quantum noise.

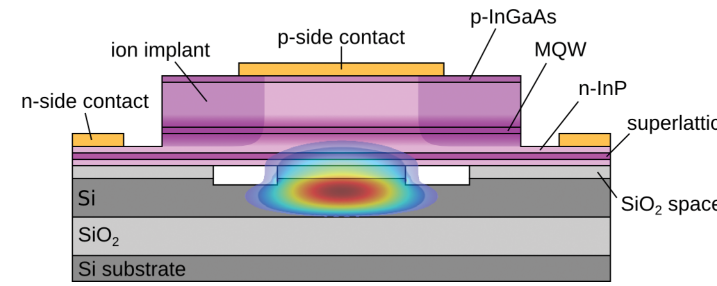


Figure 2: *The new Yariv group laser, shown here in cross section, includes a layer of silicon, which does not absorb light–a quality important for laser purity. The grooves shown require nanometer fabrication precision and serve to concentrate the optical energy near the central region, thus forming a high Q optical resonator, a key feature of the laser.*

The second important conceptual and structural component of a laser is the electromagnetic surroundings of the active medium, i.e., the optical resonator, which determines the form of the optical mode. Its role is to concentrate and store the optical energy emitted by the electrons and, in the process, provide optical feedback, a prerequisite for laser oscillation.

Now, returning to the story of the new Yariv group laser: To minimize the amount of spontaneous-emission optical noise power, Yariv's team needed to reduce the number of excited electrons in the resonator. Another consequence of quantum mechanics is that by the proper placement of the active region and the design of the resonator mode, one can reduce, by orders of magnitude, the rate of spontaneous transitions per electron into the lasing mode. To their great surprise, the Yariv group determined that the reigning canonical semiconductor design methodology, which evolved over the last 40 years or so, did not address this noise issue. The main concern over these years has been to maximize the optical gain.

In their new laser design (Figure 2), the Yariv group moved the active region where light is generated "far away" from the region where the light is stored, in this manner reducing both the optical losses as well as the rate of spontaneous emission into the lasing mode.

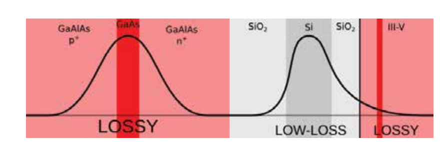


Figure 3a *(left) shows the optical energy distribution of a conventional distributed feedback (DFB) laser.* **Figure 3b** *(right) shows the modal optical intensity distribution of the new Yariv group laser design. The great majority of the optical energy now resides in the low-loss (white and/or gray) rather than in lossy (pink, red) semiconductor material. The low-loss material in the new Yariv laser is silicon (Si), such that the laser can be, and is, fabricated using a technology consistent with that of Si integrated circuits.*

The homemade first generation of the new Yariv group lasers demonstrated a phase noise nearly two orders of magnitude smaller than that of the commercial lasers used in optical communications systems today. The group believes they can go even further. Future design of semiconductor lasers will need to apply the main lesson learned by the Yariv group. These lessons can be summarized as the need to physically separate the active region where photons are generated from a low-loss (absorption) region where they are stored.

It took the Yariv group seven years to develop the tools, both theoretical and nano-fabricational, needed to realize the first generation of the new lasers. The process involved two generations of graduate students and postdocs as well as crucial support from DARPA, the Army Research Office, and the National Science Foundation. Major contributors to the recent effort that resulted in the high-coherence lasers were graduate students Christos Santis and Scott Steiger. The group is continuing research in the general area of high-coherence light sources. The effort involves pushing to shorter wavelengths—the first generation oscillated near 1.5 microns—and new resonator concepts designed to achieve even more extreme separation of the laser absorbing and amplifying regions. They are also looking at new materials and are exploring the potential applications of such lasers to 3-D imaging. ENG

Amnon Yariv is Martin and Eileen Summerfield Professor of Applied Physics and Professor of Electrical Engineering.

Visit www.its.caltech.edu/~aphyariv.

ALUMNI PROFILE

Costas Synolakis

Riding the Caltech Wave

Costas E. Synolakis (BS '78, MS '79, PhD '86) obtained all of his degrees from Caltech, starting with a BS in engineering and applied science that was followed by a master's and PhD in civil engineering. Currently, he is a professor of civil and environmental engineering at the University of Southern California (USC) Viterbi School of Engineering and the director of the USC Tsunami Research Center. *ENGenious* sat down with him to learn more about his time at Caltech and its impact on his career.

Costas Synolakis in the old port of Chania, Crete.

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

Synolakis: A desire to solve real problems. I was totally intrigued as a kid by all the mechanical things around me. I thought that engineers spend their time designing new things and putting together things that helped people make their lives easier.

***ENGenious*: How has your Caltech education influenced you?**

Synolakis: It gave me the fundamental background to really understand what are the big problems versus the small problems. One of the most difficult things for me as a teacher is to help students understand what is important in the problem and what is less so. At Caltech we learn critical thinking—how to take a real physical problem and abstract from it the parts that we can solve and that can give us useful results. I try to teach it in my classes at USC, but at Caltech, you get bombarded by it.

***ENGenious*: How did you come to work on tsunamis?**

Synolakis: My Caltech advisor, Fredric Raichlen, Professor of Civil and Mechanical Engineering, Emeritus, was a very enthusiastic proponent of studying the basics of waves, which I did, but what really attracted me were the experiments we did together with really long waves, which were models of tsunamis and held the promise that we could understand how they evolve. Unfortunately, when I graduated from Caltech in 1986, nobody in funding agencies was interested in tsunamis, until a medium-size tsunami hit Nicaragua in 1992. I went there because I thought this was my lucky break in science: I was going to see the impact of a real tsunami, possible the only one. Others had been studying tsunamis for three decades but had never seen firsthand the impact of a tsunami. Suddenly tsunamis started being reported about once a year, and by serendipity and good luck, I jump-started the science of tsunami surveys and showed how, by studying the impacts and the aftermath, we could make useful and targeted evacuation predictions, in many cases faster than the arrival of the waves. This went hand in hand with advanced numerical modeling, and simple paper-and-pencil-type results developed from applied math tricks I learned at Caltech. My greatest contributions, going back to my lab work with Fredric Raichlen, are the tsunami forecast codes and the early-warning methodology, now in use by the tsunami warning centers in the U.S. and most of the world. We had many different directions and false leads early on, but we finished "first" among what ended up as fierce competition, because at Caltech we learn to identify what is important. What is the first-order effect? In a tsunami, the first-order effect is what kills people, but believe it or not, we were the first to focus on overland flow depths and currents. Today, if you go on the beach anywhere in California, you will see tsunami evacuation signs, all based on my lab's work.

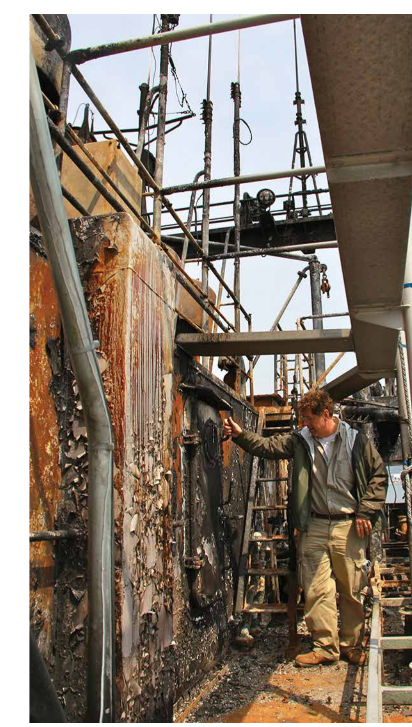
Costas Synolakis interviews eyewitnesses in Samoa.

***ENGenious*: What is a typical day for you?**

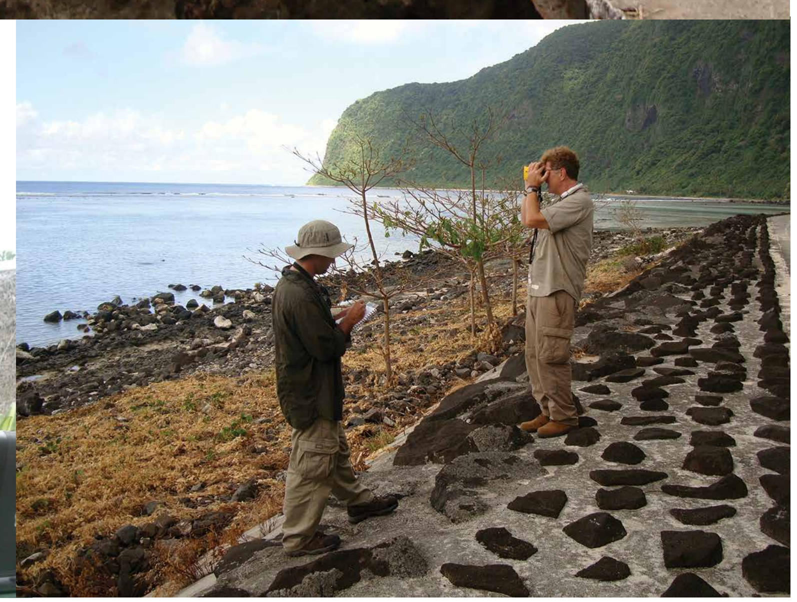
Synolakis: Tsunami fieldwork is very much like detective work. It is as if you are at the scene of a crime against humanity, and we just know vaguely the perpetrator. But we also have to convince local authorities to help out; sometimes they want to hide evidence out of shame or because they think they can use it better than the world community can. Fieldwork for natural disasters is not altogether different from studying the aftermath of the Malaysian Airlines flight blown out of the skies over the Ukraine. We need to understand how it happened and what steps we need to take to prevent it from happening again. We can't prevent people with missiles from shooting down planes, but we can make sure that planes fly out of harm's way and learn how to better understand when the threat is real. I spend a lot of time interviewing people and do quite a bit of social science and outreach work pondering questions such as: Why do some people evacuate right away while others wait? Why do some communities fare far better than similar neighboring communities that faced similar-size waves? What information do broken clocks showing different times or multiple water marks in the same affected area convey? What do burns on victims' bodies tell us about what took place, when we know there was no fire?

***ENGenious*: Is there a particular incident that comes to mind as an example?**

Synolakis: The death toll in the 2011 Tōhoku, Japan, tsunami was small in comparison with the size of the wave, but far more people died than one would have hoped or expected in what was thought of as the most tsunami-ready nation in the world. For example, there was a two-story school in the Sendai plane in northern Japan, about a mile inland from the shore. The earthquake took place. The students, who took classes on the second floor, were taught to evacuate outside in the case of an earthquake, and they did so. Ten minutes later, they heard the tsunami warning and went back to the second floor. Then they felt shaking and again evacuated the building. But the tsunami sirens kept going, so there was confusion. Some students went back to the second floor; others stayed



Synolakis looking for tsunami signs in Japan.



Clockwise from top: *Measuring impact in Pago Pago; surveying in American Samoa; teaching tsunami basics in Nuku Hiva.*

in the courtyard outside. When the tsunami hit, it was the students who stayed on the second floor who survived; the others died. This is precisely the type of tragedy we need to better understand. The accident at the Fukushima nuclear power plant was a cascade of avoidable errors. To wit, a nuclear plant about 100 kilometers north of Fukushima survived unscathed, yet local flows there were of similar intensity as in Fukushima. Sadly, introverted societal structures influence engineering decisions and sometimes even education, and some engineers do not worry enough about the possible fates of their designs. To paraphrase a common maxim, engineering is about exploiting natural phenomena (anything from the photoelectric effect to wave energy) for useful purposes; great engineering is about working with nature versus antagonizing it.

***ENGenious*: Has there been a mistake that was critical to your progress and success?**

Synolakis: Yes. I used to think that tsunamis look like solitary waves, which are single-hump waves that can be described elegantly with math. This was the prevailing model, and this is what I did my PhD thesis on. But we had no idea what tsunamis really looked like, and this is where the fieldwork comes in. In the field, I heard people describing firsthand how the shoreline retreated first, before the final impact, consistent with tsunami folklore. For years I had thought that because we had the mathematics and the experiments, we had it all perfect.

Well, if you had a wave that looked like a single hump that propagates, that would cause a shoreline to advance first. Always. It wasn't until 1992 that I finally decided to go back to the drawing board. I developed a model to explain why this happens, and it showed that the tsunamis are dipolar waves, just as the seafloor motion that causes them. The part of the seafloor that uplifts causes an elevation wave; the part of the seafloor that subsides causes a depression wave. The depression wave propagates toward the beaches of the adjacent mainland and causes their shorelines to retreat first. A key part that was missing in earlier analyses was that in every tsunami disaster, if you are closer to the subsiding seafloor, the nearest shoreline will always retreat. Farther away and depending on where you are, you will experience different manifestations of the tsunami. So I threw out the solitary-wave paradigm. The publication of the hypothesis in *Physical Review Letters* was controversial, to say the least. Even my own advisor did not agree with me at first, as practically all the other senior people in the field did not. What I was saying was different from the zeitgeist, yet most knew intuitively that I was right. With the 2004 tsunami, my hypothesis was confirmed. In locales east of the earthquake zone that triggered the tsunami, such as Indonesia, Thailand, and Malaysia, people experienced the depression wave first, whereas on the other side of the earthquake zone in India, Sri Lanka, the Maldives, and East Africa, people experienced the elevation wave first. I was happy that I was able to clear up the confusion.

I used to preach that tsunamis were single-hump waves; now that they are dipoles, this makes them a bit more difficult to predict. Part of the classic Caltech education is learning not to be hooked to any particular model, and when new observations contradict your pet hypothesis, to throw it out or reformulate it to account for the new data—to never ignore outright what doesn't seem to fit.

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

Synolakis: Think in terms of the really big picture, even in nano-worlds, and worry about the details later. It often takes quite a while to know what's important, but always keep the big picture in mind. Learn how to meaningfully exploit nature, in a sustainable way if on a large scale, but never fight it. ENG

Costas E. Synolakis is Professor of Civil and Environmental Engineering at the University of Southern California (USC) Viterbi School of Engineering and Director of the USC Tsunami Research Center.

Visit www.tsunamiresearchcenter.com.

Cultivating Entrepreneurship

The Caltech Office of Technology Transfer and Corporate Partnerships

Four years ago, Professor Morteza Gharib became Caltech's Vice Provost for Research. One of the offices under his leadership is the Office of Technology Transfer and Corporate Partnerships (OTTCP). His extensive contributions to a wide array of engineering and research topics, ranging from fluid mechanics to bioinspired medical devices, as well as his recognized success as an entrepreneur, make him very well suited to lead this office.

Professor Gharib has been working closely with Frederic (Fred) Farina, the Chief Innovation and Corporate Partnerships Officer, to strengthen OTTCP and cultivate a culture of entrepreneurship at Caltech. In light of the fact that 50 percent of all inventions from the Caltech campus come from the Engineering and Applied Science Division and how often faculty comment on how Caltech is the best place to protect their inventions and technology, *ENGenious* sat down with Gharib and Farina to learn more about their efforts and successes.

***ENGenious*: What's distinctive about technology transfer at Caltech?**

Gharib: Over the past 20 years, Larry Gilbert, Rich Wolf, and now Fred Farina have established a culture at Caltech where faculty know that their ideas and inventions have value; furthermore, they let the faculty judge that value. One of the main reasons I decided to become vice provost was to help further develop this culture of entrepreneurship. Over the past four years, Fred and I have worked on many projects, such as bringing more entrepreneurship to education and combining Corporate Relations with the Office of Technology Transfer, which reflects how much industry now values intellectual property.

Farina: Larry Gilbert's great vision established the office with principles that still make it what it is. The first and most important is that we had to be completely oriented to serving the faculty and establishing trust with them. Faculty have to see us as an ally, as opposed to a bureaucratic office that stands in the way of what they are trying to accomplish. So we try our best to be a bureaucracy-free zone and help them to overcome the obstacles they encounter on the path to commercializing their ideas. Because of that, we get a lot of disclosures from the faculty. Once they disclose their ideas, we can start working on patenting and commercializing them. We really involve the faculty in deciding whether or not to file. It's important to think about what kind of product the idea could turn into and where it's going to fit in the market, but at the end of the day the faculty member's passion for the idea and drive to commercialize it are going to be the most important factors in the decision to file for patent protection.

***ENGenious*: What was your path to technology transfer?**

Farina: I got a master's in electrical engineering in '92 at Caltech and then right away got a job at JPL working on GPS technology. Although I enjoyed my job, I quickly realized that research, in the long run, was not what I wanted to focus on. At the same time I was very interested in the process of innovation, the creative process of inventing, and the tools available to inventors to protect their ideas and bring them to market. So I got a job in a law firm doing patent prosecution, which involves drafting patent applications, submitting them to the U.S. Patent Office, and advocating the patentability of the inventions, the ultimate goal being the grant of a patent. But soon I found out that once the patents are filed, it's somebody else that takes on what I think is the more interesting part: commercialization. I was seriously looking at law school when an alumna friend of mine told me about a job opening at Caltech in technology transfer. I had an interview with Larry Gilbert and Rich Wolf, who explained what tech transfer was, and I immediately knew it was what I was looking for. It turned out that they had previously offered the job to a guy who first accepted but then turned it down. His name was Fred, he had a master's in electrical engineering from Caltech, and he worked at JPL. So when I showed up at the interview, I was Fred with a master's in electrical engineering from Caltech and with JPL experience—I fit right in!

Frederic Farina and Morteza Gharib

***ENGenious*: How has the office changed over the past four years?**

Gharib: One key change has been the physical environment: OTTCP moved to a new space that's designed to be a point of gathering where students, faculty, and postdocs are encouraged to show up and exchange ideas. Therefore, we are spending more time with those interested in starting companies, discussing the pros and cons of having a business. One can teach certain tools useful to entrepreneurs, but in the end entrepreneurship has to be cultivated in the same way as creativity.

Farina: Having an environment that is open, dynamic, and looks in sync with its time is part of creating the buzz about tech transfer and entrepreneurship. In the eyes of the campus community, the location raises the importance of what we do. Also, we negotiate deals that have potentially really high value, and when you negotiate at that level with companies, you have a lot more credibility if you have a space that shows some level of success as opposed to the typical old academic space.

Gharib: Another key change is that we have streamlined many of the regulations. I'm hoping, before I step down as vice provost, to have all the pieces in place. We need to really make sure the faculty feel that they have an environment where they can be creative without worrying about all the nitty-gritty. For instance, in the past, if faculty had a one-percent stock in a company, that company could not send them any funds to do research. So, imagine that a faculty member starts a small company, she doesn't have that much cash, and she needs to utilize a unique and very expensive piece of equipment. The same equipment is sitting in her lab or somewhere on the Caltech campus, but the company cannot send her money to do research using that equipment because the policy does not allow it. I am happy to say that, working with the Caltech Office of the General Counsel, we have come up with a new rule that makes it okay for a Caltech-grown company to sponsor research at Caltech, even in the faculty member's own lab. To ensure that any possible conflicts of interest that might arise from a situation where a faculty member has a sponsored research project for her own company carried out in her Caltech lab, we have implemented Research Management Plans, which address numerous potential conflict issues. The Office of Research Compliance provides assistance to faculty members who need to develop a Research Management Plan. For example, if you're an interested faculty member, we sit down with you and make sure that students and postdocs who are in your group know that you have an interest in the company sponsoring the research and that the student or postdoc understands exactly what they're working on and your expectations for their work. This is an example of how we monitor the situation, such that nobody is taken advantage of. We endeavor to make sure that appropriate credit is given for innovation; we try to support people who want to be in the company; we discuss with faculty, staff, and students whether or not they can be involved; and, if they can, we give guidance as to how. If conflicts are identified, we manage, mitigate, or eliminate them, because we want to ensure transparency, integrity, and fairness in this process while supporting faculty entrepreneurship and the company by allowing both to benefit from all the talent and equipment available at Caltech. In the end, society benefits because incredible ideas become commercial realities, and Caltech benefits, too—financially, from licensing royalties and equity interests, and from a personnel perspective, by giving faculty, staff, and students unique entrepreneurial opportunities.

Farina: In addition to streamlining regulations and offices to assist the faculty, we are also trying to create a one-stop shop for corporations. There's been a movement toward that in academia, and Caltech is one of the first to really take a step actively in that direction. Thus, if the company needs intellectual property licensing, they can come to OTTCP. Also, if they need to start collaboration with a faculty member and they wish to write a contract, they can come to OTTCP. In the past, Caltech had an Office of Technology Transfer that just focused on the intellectual property, an Office of Corporate Relations in Development mainly focused on gifts, an Office of Sponsored Research that negotiated the corporate contracts, and the Office of the General Counsel, which got involved with legal issues. Thus, from the point of view of the corporation, the process got complicated really quickly. Now, the idea is to simplify everything on the Caltech side by having one office where there's one person that deals with the corporation and takes care of all of their needs, coordinating with other Caltech departments when necessary.

ENGenious: **Is this also one of the reasons the offices of Technology Transfer and Corporate Relations merged?**

Farina: Yes. The other reason is that, in the past, the companies gave a fair amount of gifts to universities, but that's been in decline for many years. Now companies tend to sponsor research projects and want to see a return on their investment in the form of intellectual property or people to hire. Since Caltech doesn't have a lot of students, they don't get a big bang for their buck when they come here to recruit. So, with the new office, we focus on showing them that they can get a lot out of sponsoring research and, of course, welcome gifts as well.

ENGenious: **How are you cultivating entrepreneurship in the next generation at Caltech?**

Gharib: The challenge is to establish a curriculum that helps us to actually educate the next generation of what I call chief technology/chief executive officers (CTO/CEOs). These individuals need to speak the languages of both business and technology. Then, once the company is in safe water, a seasoned CEO comes in and expands the company. In my experience, most companies fail because the postdocs or students that went to the company didn't have the right business tools. They don't want to start the company and then go learn management, but maybe they could take a one-year course at Caltech to prepare them to speak both languages. We're in a good position to have a great program that can educate the next generation to face the real challenges in starting a technology-based company. I want them to grasp the idea that entrepreneurship is not just about business. It's a way of thinking and a way to manage your life. We want our graduates to take risks and be bold. They shouldn't be just homework solvers but problem solvers! This way they can be better students and better citizens.

Farina: Last academic year, we started a 10-week lecture series on entrepreneurship. Working with Professor Gharib and the Engineering and Applied Science Division, we developed a course for undergraduate and graduate students taught in part by Rob Chess, who's a Caltech trustee and alum, an entrepreneur, and a professor at Stanford's Graduate School of Business. Chuck Holloway, also a professor at Stanford's business school, and Ed Zschau, who established the entrepreneurship program at Princeton, co-taught the course. We had 62 students apply for the course, which for Caltech is a big number! In 1995, when the tech transfer office was started, it focused on the faculty and intellectual property; the students were not as much of a focus. The idea now is to also give the students a state of mind that's entrepreneurial, wherever they want to take it. We're not trying to divert them from science and engineering careers, but there's a growing number of students who want to go into business careers, so we are trying to provide them with all the background they need to compete in that world. When students leave Caltech, we want to make sure they feel that Caltech helped them and provided them with the tools they need to succeed. This is particularly important because students who go into business careers such as entrepreneurship are the most likely to become significant supporters of the Institute.

ENGenious: **What do alumni and friends of Caltech need to know about OTTCP?**

Farina: They need to know that the office exists, and that it has become a really significant part of what Caltech is about and also what Caltech wants to do. I think it's very reassuring to alumni to see that we're connecting to the real world more through this activity. Also, we are in the process of putting in place a mentorship program for researchers and students, and we will reach out to alumni who understand how to start companies and have certain industry experiences. We need to continue to make sure Caltech plays a critical role, not just in pushing the boundaries of science and engineering, but also, connecting with society by commercializing the fruits of its research. We have to show the usefulness of the work we do. One way that we do that is by bringing new technologies, products, services, therapies, etc., to the public to increase quality of life. Alumni can and should be a big part of that!

Morteza Gharib is Hans W. Liepmann Professor of Aeronautics and Bioinspired Engineering; Director, Ronald and Maxine Linde Institute of Economic and Management Sciences; and Vice Provost. Frederic Farina is Chief Innovation and Corporate Partnerships Officer.

Visit ott.caltech.edu.

Jorgensen

Guggenheim

Annenberg

The renovations of the Guggenheim Building and the Earle M. Jorgensen Laboratory as well as the design and construction of the Walter and Leonore Annenberg Center for Information Science and Technology have received many awards and honors over the past seven years. The renovations of the historic Guggenheim Building, which was one of the seven original buildings established in the 1920s by the Guggenheim Foundation, has received 10 honors, including three from the American Institute of Architects. The Jorgensen Laboratory has received five honors, with the latest being a Sustainable Innovation Award from the U.S. Green Building Council. The newly built Annenberg Center has also received five honors, including being named the 2011 Project of the Year by the U.S. Green Building Council's Los Angeles Chapter. To learn more and view the list of awards, visit eas.caltech.edu/about.

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