ENGenious

ISSUE 10, 2013

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

of the California Institute of Technology

DIVISION OF ENGINEERING & APPLIED SCIENCE

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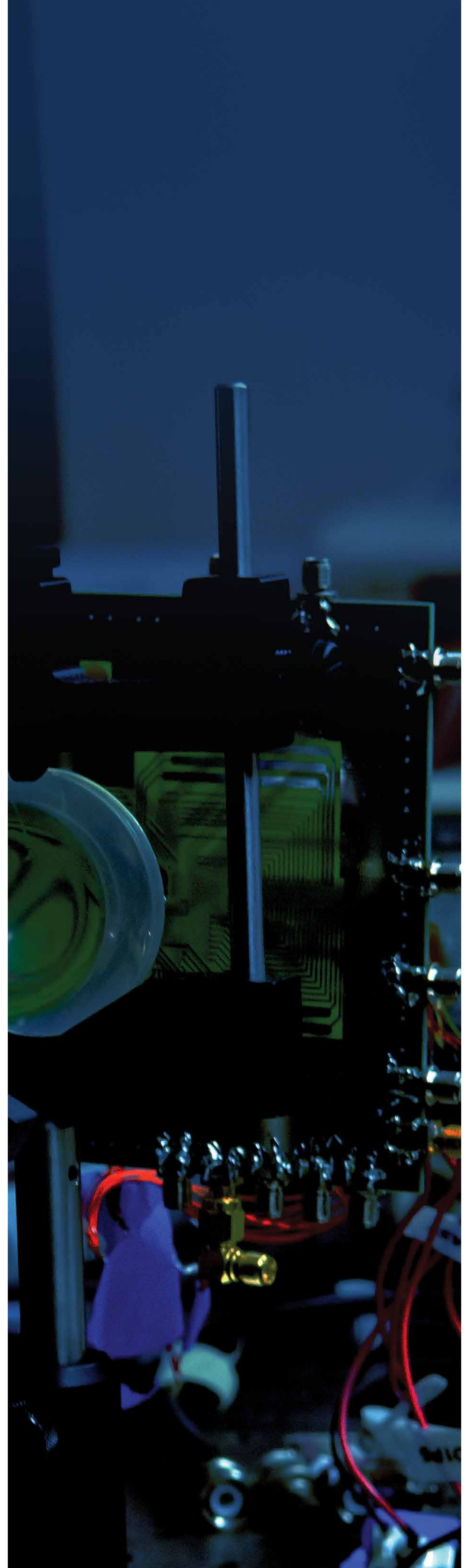
We invite you to learn more about the Division through our website, *eas.caltech.edu*.



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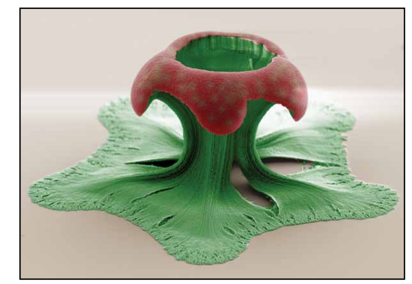
The Caltech Division of Engineering and Applied Science consists of seven departments and supports close to 90 faculty who are working at the edges of fundamental science to invent the technologies of the future.

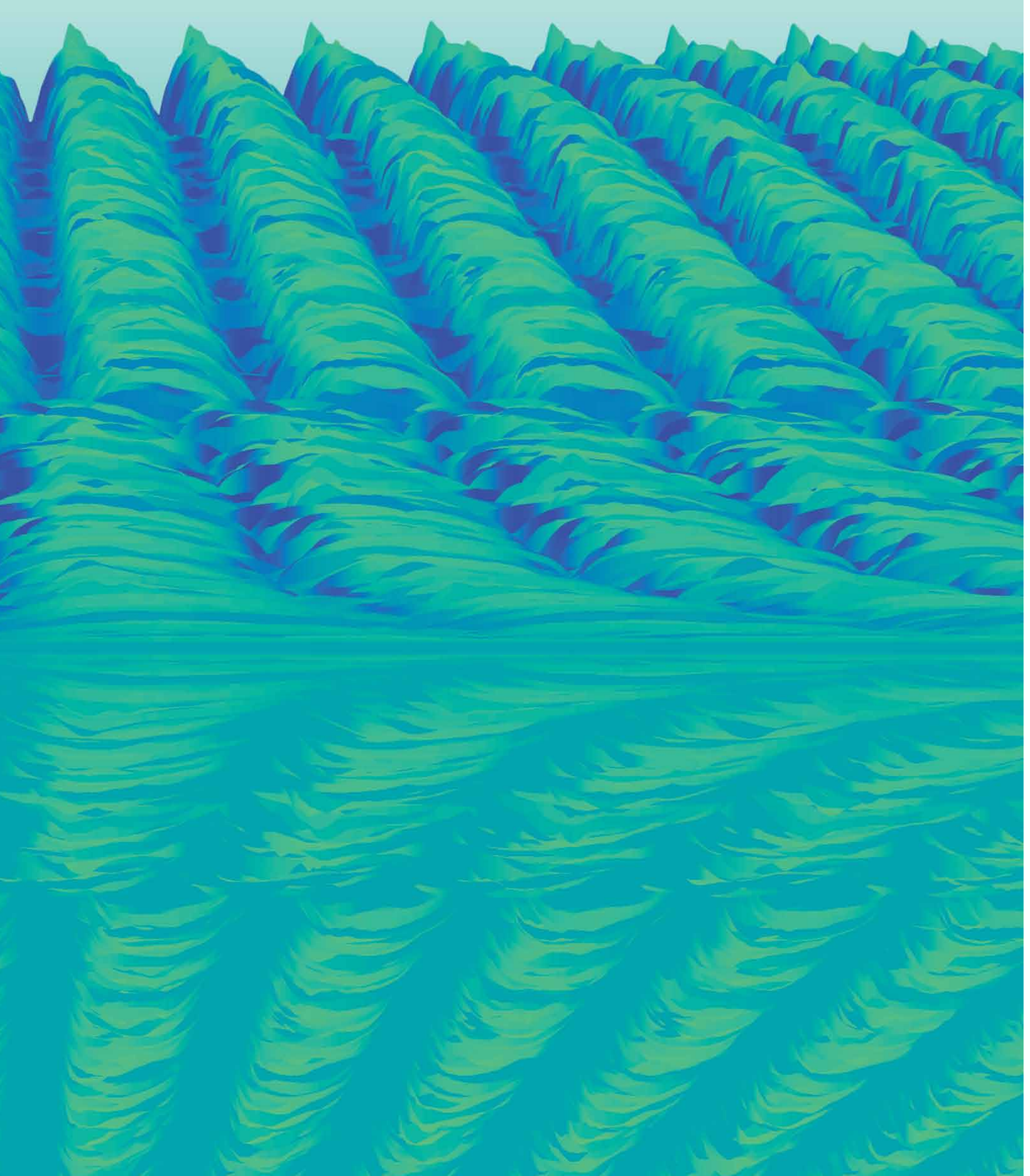


The Rarest Flower

This picture is a false-color scanning electron microscopy image of a collapsed carbon nanotube (CNT) pillar. The pillar is fabricated using chemical vapor deposition process on a substrate that has been pre-coated with a thin-film iron catalyst. Here, the catalyst layer is patterned with a periodic array of five-pointed stars. Subsequent to the growth process, this pillar is subjected to oxygen plasma treatment and capillography process. The role of oxygen plasma treatment is twofold: to functionalize each CNT with oxygenated groups and to etch the outer portion of the pillar. The capillography process is performed to collapse CNT pillars radially inward.

Generally, the etching process of CNT pillars by oxygen plasma treatment occurs isotropically in both lateral and vertical directions. However, the presence of CNT entanglement at the tip of the pillar creates a directional variation in the etching process. Thus, the mid-section of the CNT pillar is typically etched faster than the tip. The mid-section of the CNT pillar is further collapsed when it is subjected to capillography process. The flower-like shape is then formed due to the mismatch in diameter of the mid-section and the tip of the CNT pillar.

A combination of oxygen plasma treatment and capillography process is utilized to reduce the size and to improve the CNT packing density of CNT pillars subsequent to the growth process. Such modification is deemed necessary whenever the CNT pillars are used as scaffolds for composite microneedles. These microneedles have been envisioned for use in a rapid self-administered and painless drug delivery system, replacing the commonly used hypodermic needles.



This image, from the study of self-excited oscillations from fluid-structure interactions, shows the pressure within a device undergoing fluid-structure interactions for many different experimental conditions. The height of the plot is indicated by the magnitude of the pressure with time moving from left to right. The different lines going from front to back are for different experimental conditions and are sorted by the oscillation frequency. This yields an interesting visual where the data show periodic mounds of pressure in time.

ENGenious

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MESSAGE FROM THE CHAIR

Lynn Booth (seated) and Ares J. Rosakis

As Chair of the Division of Engineering and Applied Science (EAS), what gives me the most pride is the quality of our faculty and students and the standards that Caltech has always managed to keep in a world full of continuous compromises and scientific buzz words. We do not need large numbers of faculty and students to stand out among our peers, contribute, and make a great impact—we need only quality. In fact, our insistence on remaining small ensures that we continue to hire the best faculty and educate the most talented students.

One of our greatest accomplishments over the past year has been the formation of the Medical Engineering Department. This was in response to the desire of many of our faculty and of local research hospitals and medical foundations to jointly engage in engineering-centric technology development efforts for medical applications. We highlight the visionary research of the Caltech faculty who have come together to form this new department in the feature article in this issue of *ENGenious*.

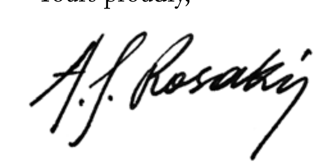
Over the past four years, the faculty and I have implemented the first large-scale structural reorganization of the Division since its formation more than 100 years ago. The purpose of this reorganization was to further enhance the Division's effectiveness in teaching, research, faculty recruitment, and fundraising. The new culture of fundraising that we have introduced has involved the creation of a system of multiple fundraising councils, composed of Caltech alumni, Institute trustees, and industrial and community leaders. Since 2009 we have raised over $140 million, including funds for 20 endowed graduate fellowships and seven endowed professorships.

One example of the transformational power of this new culture of fundraising is the creation of the endowed Otis Booth Leadership Chair for the Division, made possible by a $10 million gift from the Otis Booth Foundation. Franklin Otis Booth Jr., the late husband of Foundation President Lynn Booth, established the foundation in 1967. Booth became an investor, newspaper executive, rancher, and philanthropist after graduating from Caltech in 1944 with a BS degree in electrical engineering. This endowment will support time-sensitive research that is too high-risk for most traditional grants and teaching innovations—including future online courses co-taught by EAS faculty and JPL scientists—as well as providing increased funding for faculty recruitment and cutting-edge research equipment. Another example of the opportunities created by this culture is the establishment of the Caltech Resonate Awards to honor breakthrough achievement in energy science and sustainability. This was made possible by a generous gift from Stewart and Lynda Resnick.

In looking forward to the new academic year, one of my priorities is to explore international collaborations that are especially appropriate for the size and concentrated excellence of Caltech. For instance, last year the Indian Department of Space and the Indian Space Research Organization (ISRO) established a graduate fellowship at Caltech in the name of Caltech alumnus Satish Dhawan (Eng '49, PhD '51), who is a pioneer of India's space program. This gift honors Dhawan and recognizes the historical connections between engineers and scientists in the United States and India. Another international opportunity we created last year was the Vest Scholarship, named after my friend and colleague Charles M. Vest and intended to bring high-powered international graduate students to Caltech for one year to work with Caltech faculty on grand challenges for engineering identified by the National Academy of Engineering (NAE).

Finally, the Earle M. Jorgensen Laboratory, which was featured in last year's *ENGenious*, has received LEED platinum certification in addition to architectural awards from the American Institute of Architects, the Westside Urban Forum, and the Los Angeles Business Council. We are also excited to be nearing the start of the renovation of the Thomas Laboratory—I encourage you to view some of the architectural renderings for this project on the inside back cover.

Yours proudly,



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

Left to right: Ed Stolper, Charles Elachi, Ares Rosakis, and Axel Cruau

French Republic's Order of Academic Palms

Ares J. Rosakis has received the Commandeur dans l'Ordre des Palmes Académiques, which is the Commander grade of the French Republic's Order of Academic Palms. Founded by Napoleon in 1808 to honor educators and scholars, this distinction recognizes eminent personalities who have made significant contributions to the development of French culture, science, and education. Chair Rosakis was received into the order by the Consul General of France in Los Angeles, Axel Cruau, at a special ceremony hosted by Caltech Vice President and Director of the Jet Propulsion Laboratory Charles Elachi. Also present was Caltech's provost and acting president, Ed Stolper.

Visit eas.caltech.edu/news/428 for more information.

Decreasing the Energy Bill of California Homeowners

Renewable energy sources used in the generation of electricity, such as wind and solar power, can fluctuate rapidly, frequently, randomly, and by large amounts. It has been estimated that achieving California's goal of 33% renewable generation by 2020 will require three times the 2011 reserve generation capacity, wiping out the emission and cost benefits of renewable generation. One potential solution is to exploit flexible loads and adapt their power consumption to fluctuating supply, which is known as the "demand response." Summer Undergraduate Research Fellowship (SURF) student Esha Wang has been working with Professor of Computer Science and Electrical Engineering Steven Low to explore whether there is enough demand-response capacity in California to help stabilize the grid as well as to estimate the market value of this capacity. Specifically, she studied the flexibility of thermally controlled loads such as refrigerators, air conditioners, and pool pumps. Using the real-time energy prices from electricity market operators in California and other states, she has developed an algorithm to operate such controllable loads in a way that is not only most efficient for the users but also most helpful to the grid. Wang used the Caltech startup Chai Energy's detailed home energy data to understand the impact of her control algorithms. These types of technologies are very valuable in integrating renewable generations and transforming the grid into a sustainable energy system.

Esha Wang

To learn more about Professor Steven Low's research, visit smart.caltech.edu. For more about SURF, visit surf.caltech.edu.

"Interactive Game of Life" by Alan Menezes

The Art of Data

Visiting Professor of Art and Design in Mechanical and Civil Engineering Hillary Mushkin has been creating a variety of opportunities for Caltech students and faculty and Jet Propulsion Laboratory (JPL) researchers to explore new ways to visualize data. In her new-media art history seminar, students conceptualized, designed, and fabricated their own original new-media artwork using technologies and fabrication methods of their own choice. Students created electroencephalogram (EEG) art, automatic drawing machines, conceptual-art-inspired visualizations of mathematical concepts, interactive video projections, electronic instruments, and other novel forms. She has also organized a symposium hosted at Caltech in collaboration with JPL and Art Center College of Design in Pasadena, where computer scientists, artists, and designers gathered to discuss the "emerging science of big-data visualization." Over the summer, the Caltech/JPL/Art Center Data Visualization Summer Internship Program brought together students with computer science and design backgrounds to create interactive visualization tools to explore complex data and visually communicate their discoveries. Working in multidisciplinary teams, the students created tools for a number of faculty and researchers, including Beverley McKeon's group, to explore and demonstrate decomposition of fluid turbulence.

Visit mushkin.caltech.edu for more information.

Hillary Mushkin; Rebecca Lawler's "Exoskeleton"

Engineers Without Borders

Four Caltech undergraduate students, one graduate student, and an alumnus have formed a new chapter of Engineers Without Borders USA (EWB). EWB is a nonprofit organization that serves underprivileged communities around the world by helping to provide basic necessities such as clean drinking water and adequate sanitation. The Caltech EWB team has begun a program to construct spring-water protection systems in the Ilam District of Nepal by partnering with the Namsaling Community Development Center, a local NGO. They are also receiving technical advice and mentorship from professional engineers in the Southern California area and the University of Colorado-Boulder EWB chapter, which has past experience with similar projects. The team members are preparing for their assessment trip to Ilam to survey the spring-water source and gather information about the community and its water usage. Then they plan to engineer a sustainable and economical technology that addresses the community's needs. A consequent implementation trip would then be undertaken to construct the water protection facility and to educate the community regarding proper usage and maintenance of the site.

For more information and to support the team, visit ewbcit.caltech.edu.

EWB members discuss water quality and cleanliness at a local spring in Ilam, Nepal. During this illustration, the young girl learns about variable water quality. She is surprised to discover that clear water does not necessarily mean clean water. In this case the water contains dissolved salts and sugars.

James E. Hall

Jim Hall received his Bachelor of Science degree in mechanical engineering from Caltech in 1957. He was also awarded a Caltech Distinguished Alumni award in 2001, which is the highest honor Caltech bestows upon a graduate. Mr. Hall's record as race-car driver, designer, and constructor includes driving Formula One for the Stirling Moss team in 1963, finishing 12th in the Drivers' World Championship. He was US Road Racing champion in 1964 and winner of the Sebring 12 Hour, the Road America 500, and the Canadian Grand Prix, all in 1965. His team won the 1000K World Championship for Sports Cars race at the Nürburgring in Germany in 1966. Teams he managed won International Formula 5000 Championships in 1974, '75, and '76; International Can-Am Championships in 1977 and '78; and the USAC and CART National Championship in 1980. His is the only team to have won auto racing's Triple Crown—the Indianapolis, Pocono, and Ontario 500-mile races—in a single season (1978). His team Chaparral won the Indy 500 again in 1980. Hall has appeared on the covers of *Sports Illustrated*, *Newsweek*, and numerous motorsports magazines worldwide, and he has been inducted into the Texas Motorsports Hall of Fame, the US Motorsports Hall of Fame, the International Motorsports Hall of Fame, and the Texas Sports Hall of Fame.

ENGenious: How did you come to study engineering at Caltech?

Hall: My first year at Caltech was in geology, and I found that it didn't excite me much. I wasn't interested in memorizing crystal structures. So I changed my major after the first year to mechanical engineering. I wasn't a wonderful student in high school and I was a little surprised that I got invited to attend Caltech. When I was in high school, the Caltech freshman dean came to interview a fellow who was pretty much the hotshot in our class, and I also got a chance to be interviewed. Interestingly, after my freshman year at Caltech, the same dean called me into his office and said, "Hall, if you don't pick it up a bit, you may not graduate."

ENGenious: How did you "pick it up"?

Hall: After my sophomore year, which was kind of a makeup year, I got into the upperclassmen classes in engineering and started to really enjoy school—mechanics and dynamics and materials and thermodynamics. I was interested in engines and how all things worked, and how to make them. My mom used to tell people that whenever it got real quiet around the house, she could go in the boys' room and undoubtedly Jim would be sitting on the floor with something that he'd found and taken apart. He always took things apart to find out how they worked, but he usually couldn't put them back together. Obviously, eventually I learned how to put things back together.

ENGenious: How has your Caltech education influenced you?

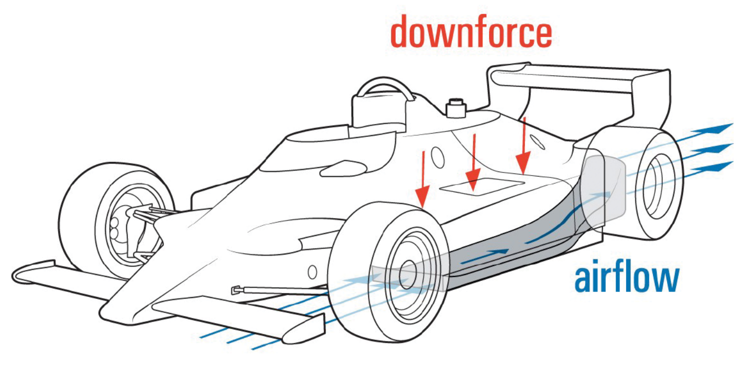
Hall: It was a fabulous education for me. Caltech treated you as a mature adult, and that fit my personality. As long as you knew where you were going and you got the answer, you didn't have to run it out to ten places—as long as they understood that you understood. I think my Caltech education helped me tremendously; I learned to do research and to set up a logical method to determine the answer to a question or solve a problem.

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

Hall: I have two professions, one that's made me a very good living and another one that was my passion. My two brothers and I started an oil and gas business as partners shortly after I graduated from Caltech. Together we have been quite successful as independent oil and gas operators. My older brother, Richard, was also involved in a foreign car dealership in Dallas with Carroll Shelby, the famous race-car driver, and he asked me to help manage it. Dick also got me started in racing. He had purchased an Austin-Healy sports car in the early '50s, and I got a chance to drive it in races when I was a teenager. After racing as an amateur for a while, I realized that in order to reach the top I needed to do something besides just go out weekends and have fun at it. I got involved in actually building a car because I saw what the other people were doing and I thought I could do as well or maybe better. With partner Hap Sharp, I started a company named Chaparral Cars to design and build racing cars. Within a couple of years, we were very successful. Some of the things that we did changed the whole sport of motor racing. Up until that time, people who designed race-cars thought about aerodynamics as a negative force to deal with. One day it occurred to me that if we have all of this force to deal with, why not use it for something positive? That's when the light bulb came on. We did a lot of things to change the aerodynamics of racing. The metrics are completely different now, because it's understood that vertical aerodynamic forces are one of the most significant factors in race-car design.

ENGenious: How have the metrics in racing evolved?

Hall: I started looking at the metrics as a problem to solve. I set up the equations of what the car was doing. I looked at the forces that were involved. I figured out how to measure them, and we set up instrument systems to measure them. If you look at it today, they were very crude systems, but as long as I was careful with my measurements, I could use the data. My first instrumentation was a system to measure vertical suspension deflection under load to document vertical forces on the car at speed. My next instrumentation was a pitot tube and a series of pressure taps on the body. I wanted to make a lot of readings on each test, so I made a manometer that had 20 tubes connected to 20 pressure taps on the body of the car. I snapped a Polaroid camera photo of the manometer at each stabilized air speed. I had to zero it, so the first thing I did was put the static tube into a thermos bottle, take the cap off before making a test run, and then screw it back tight so I could make the run with the static pressure that was there when I started. I'd finish the run, come back in, and make sure that my thermos-bottle pressure hadn't changed. I knew what the static pressure was at



Vertical aerodynamic forces are one of the most significant factors in race-car design.

speed because I had it captured. We then checked various positions on the car until we found a good static pressure source and could do away with the thermos. With these two systems, we documented the vertical aerodynamic forces on the cars over a significant speed range and mapped the surface pressure of the car body to help us develop shapes that produced the vertical forces we wanted. During the 1960s we were able to create race cars that produced substantially increased adhesion and predictable driving characteristics over a broad speed range. They proved to be a watershed in race-car design. In modern race-car design, nearly as much time and effort is put into aerodynamic design as into the remainder of the car. We were a team with a few mechanics, a machinist, two fabricators, and a draftsman in some cases. Our team was five or six people initially—it was small, the feedback loop was tight, and we all pulled together. It was a highly successful and satisfying experience.

ENGenious: How does your five member race-car team compare to today's teams?

Hall: Oh, today in Formula One racing, the teams have 300 members. I think there are 60 engineers on some of these teams.

ENGenious: You described the engineering part with the same excitement as the driving part.

Hall: Some people say I probably never really reached my potential as a driver because I was too interested in the mechanics of it. But I think it was an advantage for me because in American road racing, I was probably the first driver–development engineer on a team. I knew what I wanted and I figured out how to get it. I really enjoyed trying to make a better machine within the constraints—car specifications, budget, time.

ENGenious: What message do you try to get across to young people?

Hall: We have put our cars on exhibit in Midland and we spent a lot of time creating interactive exhibits for youngsters, on the principles involved in the engineering and science of racing. We need to try to help create interest in our younger generations in the sciences and engineering. I wanted to show them how exciting and enjoyable an engineering career can be. A lot of times they'll ask, Why do you think you were successful? And I say, I think I worked harder than a lot of others. I decided what I was going to do and I worked at it. My wife, Sandy, worked right alongside me a lot. She'd call me up at noon or 1 p.m. and ask, Did you eat lunch? And I might say no, I was doing something else. We used to go home, eat dinner, and then go back to the shop and work until midnight. It rarely seemed like work; I was hungry to learn, and to build better and better machines. Racing is a good model of the free enterprise system—you know what the rules are, there is a short competition cycle to evaluate your product, and you get paid according to how well your product performs. What a satisfying way to live.

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

Hall: Water! If we're going to be self-sustaining on this Earth, I think water is really important. It's not critical in a lot of places right now, but it's going to be.

ENGenious: Have you had any personal experience with managing water?

Hall: Yes, in a way. I have a mountain home in Colorado in a development that is governed by a homeowners' association. We realized that there's only so much good fishing water in Colorado and it's quite expensive to own. I proposed that we make a diversion of river water to create a fishing stream on this property, and became the manager of the project. It took me ten years to obtain the permits to divert the water because of all the bureaucracy we had to deal with. All we're doing is taking the water out of the river, keeping it for a while as it flows through our property, and then putting it back in the river. I pretty much designed the way this stream was to be built and oversaw the construction of it. It turned out to be a beautiful and quite good fishing stream. A couple of the homeowners fought the project pretty hard. One said messing with nature was the wrong thing to do.

Jim Hall and his wife, Sandy, at their Colorado home.

ENGenious: How did you address the concern?

Hall: I didn't feel like we were going to destroy a lot of ecology. In fact, I thought we'd probably make more opportunity for the fish and the other animals and plants that thrive off of it to live there. One homeowner was dead set against it. But about a year after we finished, I saw him and said, "I know you were against this stream, but I thought you conducted yourself in a really ethical, gentlemanly way, and I just wanted to tell you I appreciate it." He just said, "We love it." I think we ended up with a valuable addition to our property, which enhanced our recreation opportunities with no negative effect on the environment. The association decided to name it Hall's Run.

ENGenious: Any other memories of Caltech?

Hall: I had a good friend at Caltech that I've kept in touch with over the years, Gordon Fullerton. Gordo and I were friends as undergraduate students. We studied together; we hit tennis balls together for exercise and relaxation. We were both interested in aircraft, and we both joined the air ROTC. Gordo enlisted in the air force after graduation and has achieved an outstanding career in aerospace. He became an astronaut and has spent his whole productive life on projects that required great skill and great personal courage. I admire him tremendously.

ENGenious: Any closing thoughts?

Hall: I feel really fortunate to have been born an American and to have grown up in our free society where you have the opportunity to do what you choose. If you do it well, you are well compensated and can live your life the way you decide. I worked hard, and I obtained a good education that has been an asset throughout my life. I have always had marvelous support from my family and feel very fortunate. I am a lucky guy. ENG

Jim Hall is a founding partner of Chaparral Cars, Inc., and Condor Operating Company.

Colonel Charles Gordon Fullerton passed away on August 21, 2013, after a long battle to recover from a massive stroke he experienced on December 31, 2009.

PROGRESS REPORT

Untangling Turbulence

By Beverley McKeon,
Professor of Aeronautics and Associate Director of the Graduate Aerospace Laboratories (GALCIT)

On the wall of my office, where I can see it whenever I look up from my desk, is the old parable of the blind men trying to explain what an elephant looks like. Each one believes he's doing this by describing the part he's touching—the trunk, an ear, a leg, and so on—but none of them, of course, has the whole picture.

This is a great metaphor for the way our research is employing really new approaches to tackling old problems, and modeling and controlling turbulent flow. Richard Feynman called turbulence "the most important unsolved problem of classical physics." Thus people have been banging their heads on it for a very long time. Progress has been incremental, but we really feel that we have a chance to sort of blow this open at this point. I should make it clear that we specifically study flow over surfaces, which is different from free-space turbulence because the wall has a very strong effect. This is the form of turbulence that slows the progress of marine vessels, aircraft, or automobiles through air or water, or natural gas or petroleum products through pipelines. As I described in my Richard C. Biedebach Memorial Lecture at Caltech entitled "Taming Turbulence," suppress turbulence in the thin boundary layers on the surfaces of commercial airliners and total aerodynamic drag could be nearly halved. If you could reduce drag at the surface by 30%, you could save $140 billion in fuel burn per year, with concomitant emissions reduction.

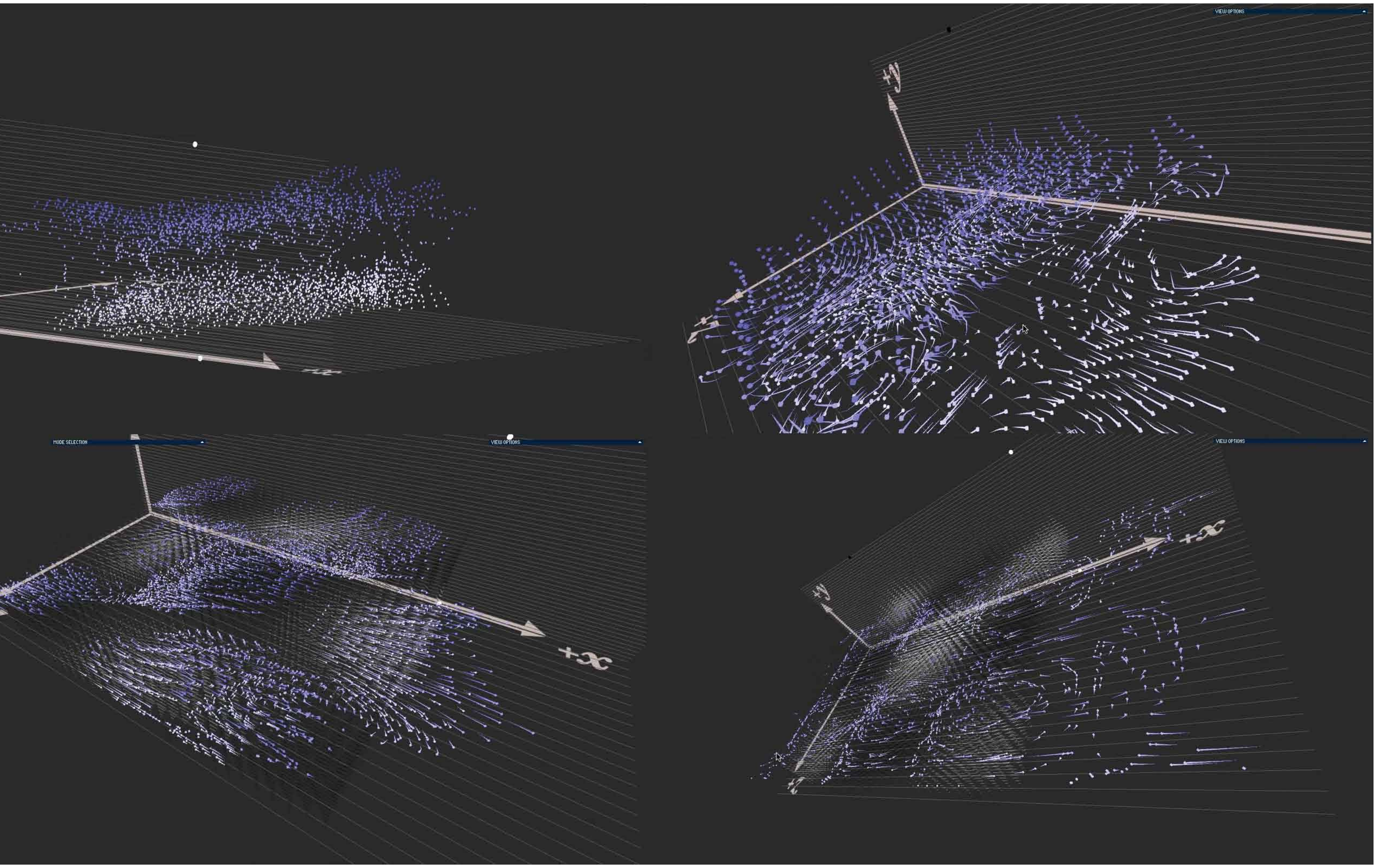
In a sense, what we're trying to do is capture the general outline of all the aspects of the elephant and learn how to talk to it. It's very easy to get focused on one aspect, but the non-incremental progress is going to come from being at the heart of the problem. A lot of the ideas underpinning wall turbulence came from Caltech in the '50s and '60s, so it's been half a century or more since we have taken a fresh look at its foundations. Research advances have tended to be somewhat incremental, partly because of the complexity of handling the massive range of scales active in turbulence. With a commercial airplane, for example, the largest lengthscale will be the length of the airplane and the smallest will be several microns. The research community has brute force tools now where we can do fully-resolved simulations of the range of scales observed in flows with simple geometries in the laboratory rather than over a full airplane; the tools are limited by the computer power and the way the algorithms scale at present.

We are aiming to understand turbulent flow as a system. We want to be able to pull apart turbulence so that we can analyze subunits of it, maybe change one, and then put it all back together. In our experiments,

we try to isolate certain parts of this system, change our interaction with them, and then see how the turbulence as a whole develops. It's deconstructing and reconstructing turbulence, creating "test-tube turbulence," if you will. The novel contribution from us is to say that if you view the governing equations in a particular way, then it does become a set of linear systems, and you can analyze each one of them, work them all back into the system, and over-stimulate one of them and trace the propagation of this disturbance through the system.

Instead of a chaotic field, you can think about turbulence as a very broad array of propagating waves that each have unique wavelengths in the directions parallel to the wall—i.e., in the sense of the main flow and cross-stream directions—and a temporal frequency to them. Because they all propagate at different speeds and they have different scales, it's very hard to pull apart the ensemble of waves. But in our formulation, you can pull them apart, and that changes the game. When they're all together, they interact—for example, one sees a complex, space-filling forest of intertwined hairpin-like vortices in high-resolution simulations, or when smoke is introduced into a laboratory flow. When we pull the ensemble apart, we can see this phenomenon associated with each wave. And, further, we can recreate the essence of the forest with just three of these propagating waves, instead of needing the full field to see this kind of structure. If we know the three propagating waves—and some recent work that we're still doing says that even knowing the form of one might be enough—we can work out how to scale this up and out to other scales. So it really is an idea of pulling things apart and saying that things aren't so hard on a unit-by-unit level. It's just the connection that's very hard, or at least we are not familiar with it.

I said before that we want to understand turbulence as a system so we can talk to it and control it, and we're getting there. What matters in controlling turbulence is the net gain, the savings minus whatever you put in. If a lot has to be put in to make the turbulence do something that it



Software created as part of the Caltech/JPL/Art Center Data Visualization Intership Program gives a unique view into the complex motions associated with the individual subunits of turbulence identified by McKeon and co-workers. The wall is in the x-z plane and flow is in the positive x-directions. Gray arrows represent turbulent velocity and blue particle tails reveal the history of the motion of massless particles released on a uniform grid in the domain.

doesn't want to do, that reduces the net gain. We're saying that turbulence is a collection of very efficient amplifiers—if a very small amount of noise is put in on one side, the same thing always comes out the other side—and we ought to be harnessing this natural characteristic for control. The problem boils down to working out which amplifier or set of amplifiers one wants to tweak to get a big change throughout the system. I describe it as finding which pressure points to tickle, just coaxing the turbulence to do something slightly different from what it wants to do without any input, rather than using a big hammer. And we can see how to do that now. When we're able to use not just the vehicle but the flow around the vehicle as part of the control system, it opens doors to new ways of doing things. It becomes an engineering problem then on how we actually develop and implement a robust control system.

In terms of getting from the lab to practice, this is very much science at this point, so part of the excitement is just being able to explain a little bit about a problem that really wasn't understood. But part of the power of what we do is that we actually demonstrate these things in the laboratory as well, and the world-leading experimental facilities at the Graduate Aerospace Laboratories (GALCIT) really enable this. Together with my collaborator in the UK, Dr. Ati Sharma from the University of Southampton, who has a background in control, we're also interacting with Joel A. Tropp, Caltech Professor of Applied and Computational Mathematics, to use state-of-the-art mathematical tools to interrogate and do this modeling. As well we have been working with John Doyle, John G Braun Professor of Control and Dynamical Systems, Electrical Engineering, and Bioengineering, to complete the dynamical systems description of wall turbulence. This ability to operate at the interdisciplinary boundary is unique to Caltech.

As associate director of GALCIT, I believe it's problems like this that help attract first-class students to Caltech. It is the sort of challenge that drew me, a first-generation college student, away from the dream of flying fast jets in the air force to an academic career interrogating and hopefully mastering the flow over them. It's an old problem, but one with a potentially very significant societal impact. There's a chance to really solve something that has baffled us as humans for a very long time, and the way to do that is to sit between disciplines. That's where we need to be to make real progress. To do so, you need expertise in fluid mechanics and dynamical systems. You need to have some grasp of control, so you can actually use this system description of the flow, and some understanding of materials to know how to modify a surface to control a flow, and you need to have a handle on some applied math techniques so that you know how to do this in the most modern way. You need to be able to reach out to colleagues who have appropriate expertise and frame the problem such that it's interesting for both sides.

It's a pretty exciting area, but it's not the sort of thing that necessarily splashes across the front page because it's not solved yet. And it's not the sort of thing that we build on a bench top in a year. These are long-term problems, and an important part of Caltech's long-term vision is to tackle such slow-burn problems with large potential impact.

Someone congratulated me recently at a conference for getting tenure and said, What are you going to do now? You can do anything. And I said, Why would I want to do anything else? Caltech has afforded me the opportunity to make an impact on this hard problem. Of course, I have diversified some, but really this is where I want to be. And we're on a path toward something really meaningful. E N G

Beverley J. McKeon is Professor of Aeronautics and Associate Director of the Graduate Aerospace Laboratories.

Visit www.mckeon.caltech.edu.

Visit iTunesU to watch the Richard C. Biedebach Memorial Lecture "Taming Turbulence." This lecture is part of the Caltech Watson Lectures. Use the QR code above or visit https://itunes.apple.com/us/podcast/explosion-explosions-april/id422627541?i=114478013&mt=2.

Medical Engineering: A Moral Obligation

They come from diverse backgrounds, have followed unique paths, and do their work in a host of engineering and applied science disciplines, but a common denominator among the faculty of the newly formed Caltech Medical Engineering Department emerged with stunning clarity in *ENGenious*'s interviews with them: These are people with a strong moral compass who are passionate about making a positive impact on society.

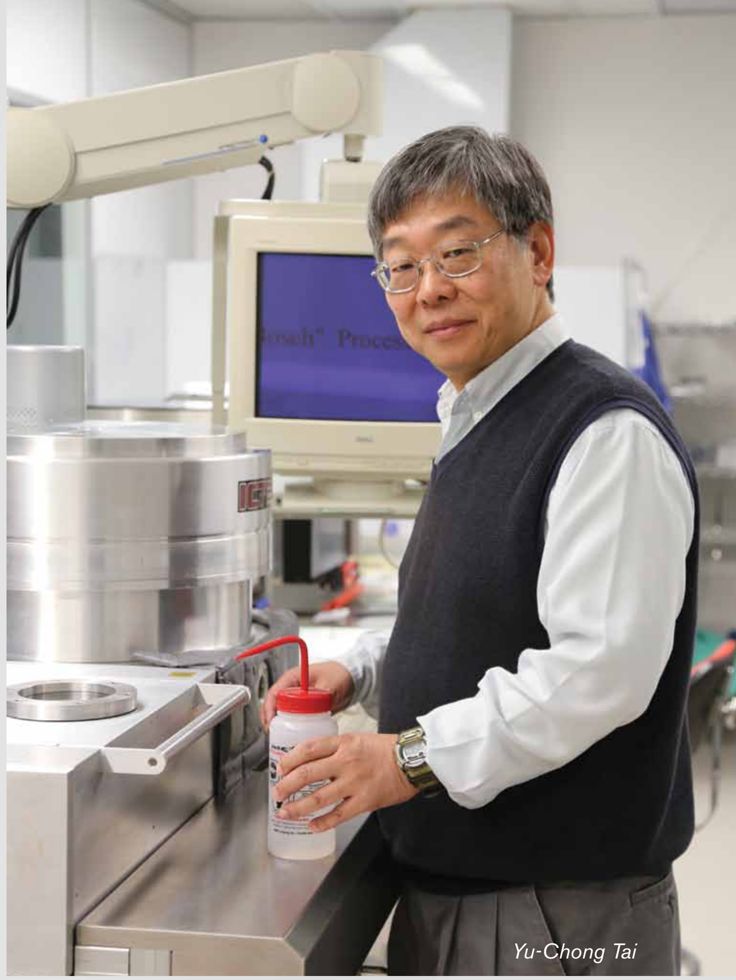
They have been working at the frontiers of translational medical engineering for years, drawing on their expertise in a wide range of fields, including electrical, aerospace, civil, mechanical, and chemical engineering as well as applied physics, materials science, and chemistry. Starting with the fundamentals of basic science and engineering and by potentiating the faculty's individual efforts, the new department aims to more efficiently leverage the research at Caltech to lower the technological barriers to diagnostics and treatment, as well as their cost. The faculty's conversation with *ENGenious* took many directions as the researchers discussed their work and its applications, including reducing patient stress, simplifying devices, and volunteering in a hospital.

ENGenious started the conversation with the Executive Officer of the new department, Yu-Chong Tai, Anna L. Rosen Professor of Electrical Engineering and Mechanical Engineering. "There are more than 60 accredited biomedical engineering programs in the United States, and there are about 100 biomedical programs in various universities and institutes," he notes. "However, from my experience, I think Caltech really has an opportunity. At other institutions they try to cover the entire biology side and take care of the engineering side, but this means the programs are often shallow on both sides. This is an issue because a lot of the work we want to do has to rely on deep engineering. That's our strength at Caltech. Our intention is to build the Caltech Medical Engineering Department in a way that is rooted in really first-class engineering and move toward medical applications."

Several of the faculty interviewed had strong views on how medical engineering at Caltech will be different from similar programs in biology. Many emphasized that the two disciplines are complementary but serve different purposes.

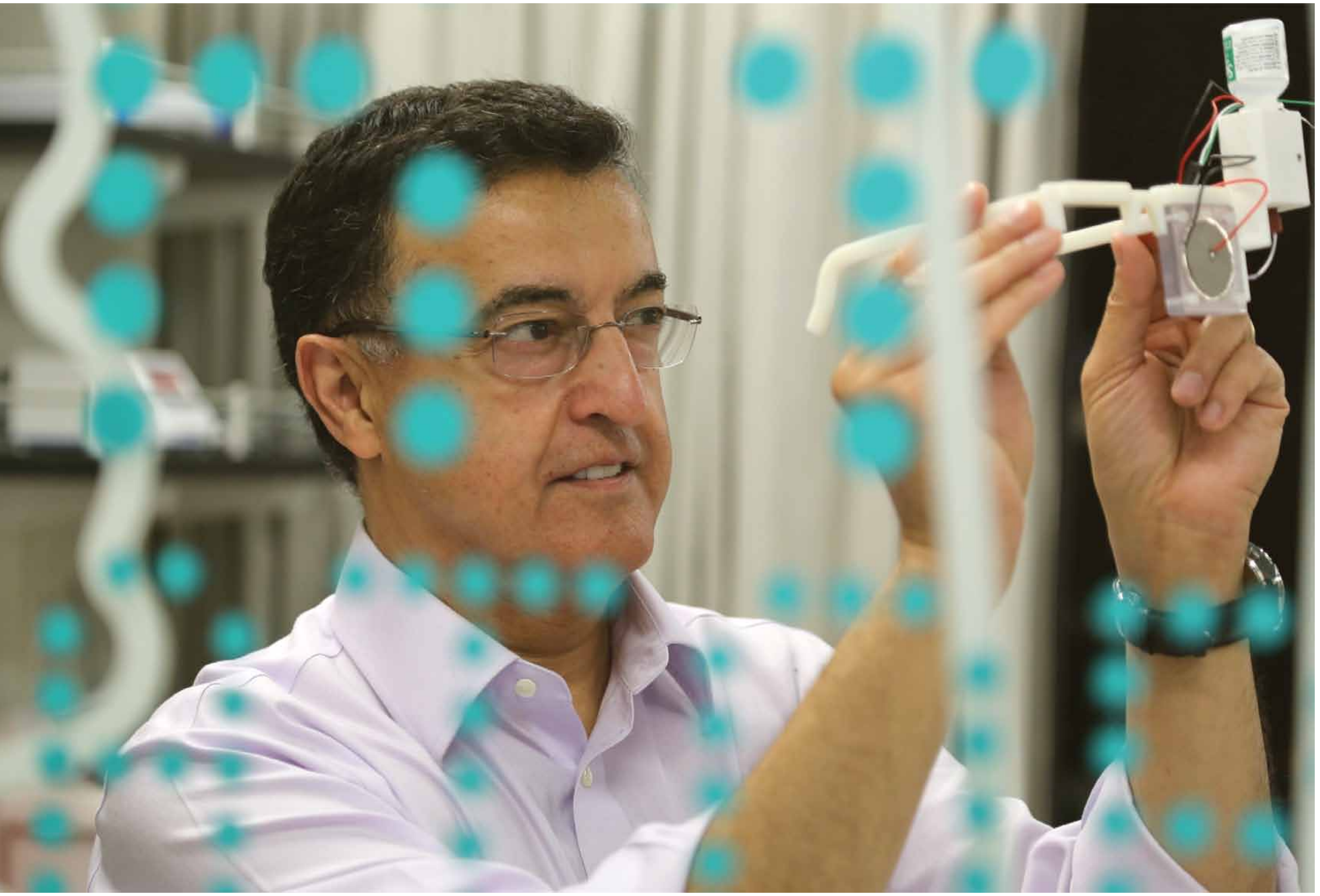
"Medical engineering is top-down," says Morteza Gharib, Vice Provost and Hans W. Liepmann Professor of Aeronautics and Bioinspired Engineering. "We look at the problems that are currently challenging to the field and try to come up with devices and techniques to help clinicians do their job better or make breakthroughs. Biological engineering is bottom-up; it tries to understand how biology works and then builds upon that to get to the point where it can contribute to the field. Basically we're looking at the same wall from two different sides."

Consolidating the efforts on Caltech's side of the wall creates an


Yu-Chong Tai

> *"We have a cell phone that can do anything, but implantable technology is still in the Stone Age."*
>
> Yu-Chong Tai, *Anna L. Rosen Professor of Electrical Engineering and Mechanical Engineering; Executive Officer for Medical Engineering*

EAS FEATURE



Morteza Gharib

> *We're trying to learn the tricks of nature to come up with new physiological machines that are built out of your own cells, so they're not foreign to you.*
>
> Morteza Gharib, *Hans W. Liepmann Professor of Aeronautics and Bioinspired Engineering; Vice Provost*

opportunity "to combine the technology development that we do in Engineering and Applied Science (EAS), in particular, with a more focused approach on applications than you typically have," says John Dabiri, Professor of Aeronautics and Bioengineering. "This is a chance to apply what we do well to the tools used for treatment in 'the real world.' In many respects, we're going to be providing an outsider's perspective. That can be helpful. For many diseases we just need fresh ideas, and Caltech is well poised to provide them because we haven't been staring at the same problem for 20 years."

Nobel laureate and the Victor and Elizabeth Atkins Professor of Chemistry and Chemical Engineering Robert H. Grubbs also points out the advantages that Caltech engineers could bring to the field of medicine. "Biology today is very attuned to medical problems, which happened naturally," he says. "What hasn't happened naturally is getting engineers and basic scientists involved in medical problems. I see the new Medical Engineering Department at Caltech defining these kinds of medical problems. And there are an amazing number of them. On a somewhat regular basis I recruit seven or eight Caltech faculty and we fly up to San Francisco to spend a Saturday with a group of clinicians who are heads of departments. Every time, it amazes me that these very busy professionals take the time to sit with us and define different medical problems that we can collaborate on."

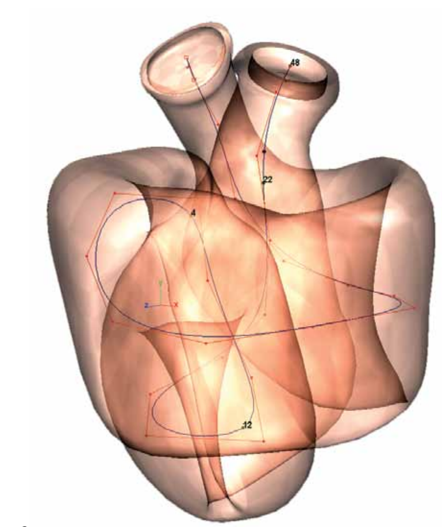
Professor Ali Hajimiri coined the phrase medical engineering at Caltech. "Bioengineering is rooted in biology and chemistry," says the Thomas G. Myers Professor of Electrical Engineering. "The medical engineering side of things is rooted in engineering; it starts from an application and tries to solve the problem using the tools that we have at our disposal. We want to solve medical problems by leveraging our engineering expertise."

For example, "How can we make batteries that can be implanted into the body and power a heart valve?" asks Julia R. Greer, Professor of Materials Science and Mechanics. "To do that, multiple systems have to synergistically work together: the materials have to be biocompatible, the power output has to be just right, there has to be no biofouling, the data acquisition and analysis has to be handled, etc. That's how all of these disciplines work together."

"The difference is whether your endpoint is to understand biology better, or to contribute to medicine," says Professor Tai. "For example, when I work on micro implants, I want to build an electrical device that can stimulate local nerves, and neuroscience is very focused on electrical stimulation. But when we make the device, we need to figure out how it should be shaped and how flexible it should be and how high the voltage should be and how much carbon there needs to be and what's the current distribution? All these are heavy on engineering. Even our colleagues from the biomedical engineering department cannot deal with the depth of these issues like we do."

Professor Tai's work on developing a zebra fish electrocardiography (ECG) device exemplifies both the depth of which he speaks and the urgency he attaches to human applications.

"Our angle is human," he says. "That's why we wanted to study the



Virtual mechanical heart developed in Professor Gharib's research group

In many respects, we're going to be providing an outsider's perspective. That can be helpful. For many diseases we just need fresh ideas, and Caltech is well poised to provide them because we haven't been staring at the same problem for 20 years.

John O. Dabiri, *Professor of Aeronautics and Bioengineering*

John O. Dabiri

zebra fish heart. If you cut off or damage 20% of the zebra fish heart, it recovers 100%. With a human heart, if you have even minor damage, you may die. How does a fish do that? One thing we have to do to understand that is monitor the health of the heart 24/7, so we can see how fast and in which way it recovers. When we first wrote the proposal, nobody had ever measured the ECG of a zebra fish, so we had to figure out how to do it. We had to make really small microelectrodes, place them as close to the heart as possible to get the biggest signal, and do very deep analysis on the metal and the tissue interface, which involves electrical impedance. My students eventually developed a wireless ECG device that we can attach to the fish and it still swims and does its normal activities while we get an ECG."

The significance for humans, says Professor Tai, is that "cardiovascular doctors want a 24/7 distributed ECG device, because cardiovascular problems evolve and move from point to point. It doesn't matter if it's wearable outside or implantable inside; the key word is 'distributed,' so they can detect gradual change in the heart. All my colleagues believe that a small, simple ECG that can be implanted is totally doable. We have a cell phone that can do anything, but implantable technology is still in the Stone Age. If our only focus is to understand the problem, and not to provide devices for a larger population, that to me is a shame. Medical engineering is not about building the first 90 yards and forgetting the final 10. We want to go the full 100 yards in reaching people. It's not okay to say that all I want is to study a problem right out of a paper. That's not biomedical engineering for us."

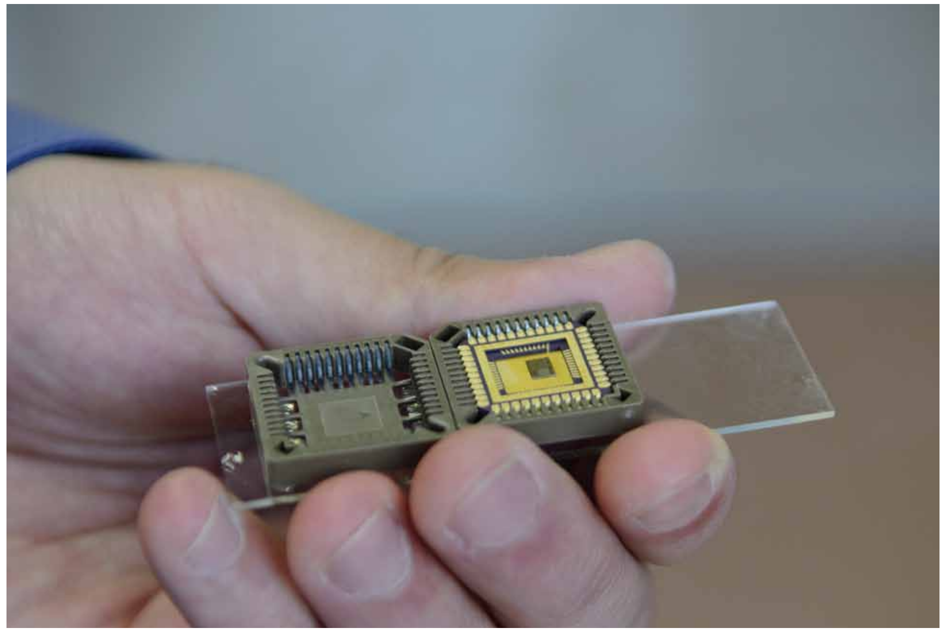
Professor Gharib shares both Professor Tai's perspective and his interest in solving medical problems related to the heart. "My group and I contributed in a very fundamental way to the design of heart valves that are available on the market today," he says, "but at some point I also realized we need to go back and see how nature builds heart valves, so that's how I got into this area of engineering. The heart for me is a special place because my training is in fluid mechanics and life is aquatic. It depends on the transfer of the material from nutrients to oxygen to taking the waste away. Of course, every vessel has flow, but the heart is the most fascinating dynamic entity in that respect. It's still one of the biggest challenges in medicine to have a pump that acts like a heart and that is natural to the human body. That is far from reality, but it's basically a moral obligation for engineers and scientists to look at all these problems and see how they can use current knowledge to contribute to improvements. What we're trying to establish here is a new direction for medical engineering. That's a big challenge, but Caltech has a clear advantage because of the years of research that we have already done. We are trying now to consolidate our gains and train a new generation of students who are going to be better than us. We're trying to learn the tricks of nature to come up with new physiological machines that are built out of your own cells, so they're not foreign to you. We are concentrating on how to create a micro environment like the one that nature provides when the heart grows in embryonic stages."

EAS FEATURE

Imagine when you can buy a reader and then, for about a buck, you can buy a cartridge with the sensor in it that tests for lung cancer, tuberculosis, or hepatitis C. You put it in, it runs the test, and then you throw it away. They would be like apps for your smart phone.

Ali Hajimiri, *Thomas G. Myers Professor of Electrical Engineering*

Ali Hajimiri



Hajimiri's handheld medical diagnostic test cartridges

When working with him as a graduate student, John Dabiri was fascinated by Professor Gharib's application of aerodynamic concepts to the human body. He welcomed the chance to collaborate on what he describes as "probably my first foray into the application of engineering concepts to the human body" after they became colleagues. "When I was just starting on the faculty, he and I published a paper on how you can study blood currents to diagnose heart failure," says Professor Dabiri. "The challenge in many forms of heart failure is to diagnose it at earlier stages than we do now, and to develop techniques that will allow us to make that diagnosis in a way that's less expensive and not invasive. When you have heart failure, the blood flow is one of the first things to start changing, and it's a signature that potentially you can measure from outside the body. Studying the blood flow might tell us earlier than some of the methods that are used today that someone's on the path to heart failure."

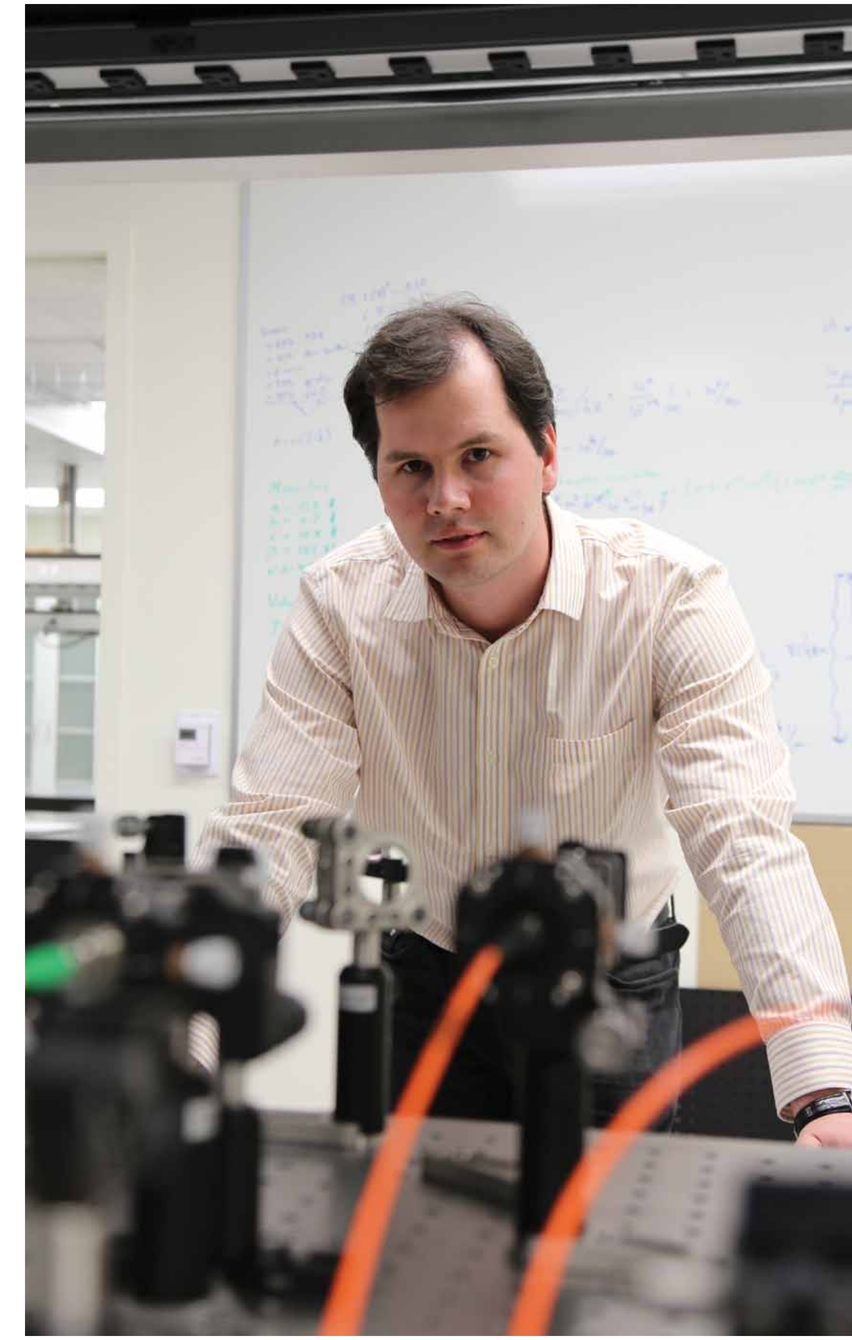
Professor Dabiri paints a vivid picture of the key process. "You have a jet of blood that comes from the left atrium into the left ventricle, two chambers of your heart, on each heart beat," he says. "It creates a vortex like a swirling doughnut of blood, and the shape and size of that vortex is correlated with disease, so you can study that to determine how well the heart is functioning. What is it about a certain shape and size of that blood vortex that leads to healthy function? The immediate goal is simply to be able to tell people that they're sick, because many people don't realize it until it's too late, but a long-term goal is to find a corrective measure that could restore that function. The uniqueness of Caltech is that we have expertise in both fluid dynamics and the types of technologies that will be required to image and measure that blood flow, and we can combine them for the benefit of our clinical partners."

Professor Dabiri finds today's students as excited about the possibilities as he was, and is. "We have students who are really passionate about fluid mechanics, for example, but some of them want to know that the work they're doing has an impact on people's quality of life," he says. "Medical engineering is going to be one of the places where the research we do in EAS affects all of our alumni and friends because, if we're successful, it's going to mean a better quality of life for all of them."

Professor Hajimiri also sees the diversity of disciplines in medical engineering and their potential applications as a lure for "students who have strong physics, math, and engineering backgrounds that they would like to apply to a medical problem. This is really a discipline that's designed for them, in the sense that they can take their strengths, combine them with the knowledge of the medical side, and apply them to a medical problem."

His own experience is a model of intellectual diversification. "A few years ago, I got really interested in biology and started going to Caltech undergraduate classes and taking labs with the students," he says. "Then I took some grad-level labs and did several projects, and based on that experience, I made everything in our wet lab. That's really helped us with the biosensors that we develop. Now that we understand both the electrical and biological sides of it, we have a much larger possibility to do research. If we have a problem with the electrical system, modifying the biological side could help. Likewise, if you have something that's very difficult in biology, we can come up with a solution by modifying the electronics. When you do both sides, you come up with things that are much more globally optimum."

Professor Hajimiri describes four medical engineering areas in which he works—biosensors, drug delivery, bioinspired engineering, and terahertz imagers—as "very hot right now." Biosensors can be used "to make a very low cost handheld device for diagnosing a lot of different diseases," he says. "We have actually made the reader, using CMOS (complementary metal oxide semiconductor) transistors, a standard technology, to make it very low cost. We also developed all the biochemistry for making electronic chips into biosensing chips.



Andrei Faraon

> *We are developing tools to deliver light into living brain tissues and to monitor the activity using quantum photonic devices for ultra-sensitive detection of magnetic fields.*

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

Julia R. Greer

> How can we make batteries that can be implanted into the body and power a heart valve?

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

Imagine when you can buy a reader and then, for about a buck, you can buy a cartridge with the sensor in it that tests for lung cancer, tuberculosis, or hepatitis C. You put it in, it runs the test, and then you throw it away. They would be like apps for your smart phone. A lot of these tests now have to be done in a lab. Think about the demand there could be for these readers around the world. The key is that we are leveraging electrical engineering and biochemistry to create this device that has medical applications."

In therapeutics, Professor Hajimiri is using magnetic particles for drug delivery in the brain. "We have developed a sophisticated dynamic magnetic manipulation setup that allows us to 'navigate' magnetic particles any way we want. We are in the process of using this in collaboration with some researchers from City of Hope to deliver drugs to the targeted cancer sites under a National Institutes of Health (NIH) grant. This will significantly improve the efficacy of the drugs and minimize their side effects."

In the field of bioinspired engineering, Professor Hajimiri explains, "we've created systems that are really self-healing. They respond to variations in the system as well as destructive events with no external human interference. We hit them with high-powered lasers that destroy parts of the chip, and the chip finds a way of recovering and still functioning. A chip that's not designed for this purpose would fail if it loses one transistor out of half a billion."

CMOS technology was also used in the Hajimiri group's terahertz imager to keep its cost low. "The behavior of certain kinds of skin cancer is different from regular skin, so you can use this as an early-detection and screening device," he says. "You can scan it across your skin and see if there are any points that need to be checked by doctors. We've also looked at that for other kinds of microscopy and imaging systems. Unlike X-rays, terahertz radiations are non-ionizing, which means that they do not induce chemical change because the photon energy is low. It's a much less damaging kind of radiation for imaging."

Andrei Faraon, Assistant Professor of Applied Physics and Materials Science, is interested in photonics, specifically biophotonics, which he describes as "using photonic devices to learn more about biological systems for diagnostics and to control biological functions." He is collaborating with Michael Roukes (Robert M. Abbey Professor of Physics, Applied Physics, and Bioengineering) in developing nano-scale photonic devices for sensing of biological reactions at the single-cell level.

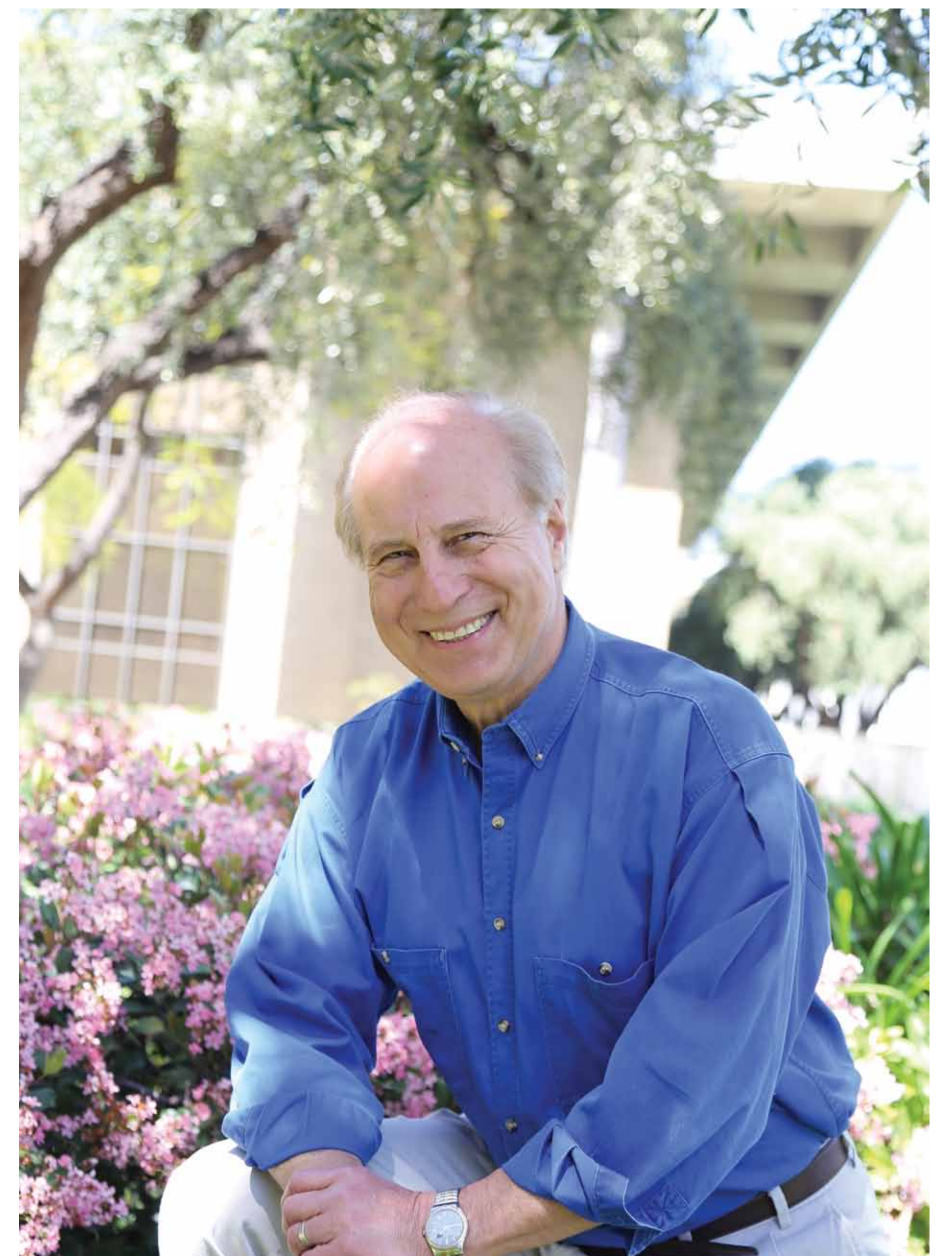
"The neuroscience community recently started to use light to control brain function," Professor Faraon explains, "and currently there is a large nation-wide initiative to map the entire brain and understand how it works. Toward this end, we are developing tools to deliver light into living brain tissues and to monitor the activity using quantum photonic devices for ultra-sensitive detection of magnetic fields."

Working at the same scale as Professor Faraon but toward a different end, Professor of Materials Science and Mechanics Julia Greer has "started interacting with several neurologists in trying to develop submicron- and nano-scale devices for cell or neuron manipulations," she says. "We are making a 3-D platform scaffold for intracellular interrogation by electrical and optical probes. We recently acquired an amazing two-photon lithography tool that allows us to print nano- and micro-structures in three dimensions. This has opened up a rich set of opportunities for biomedical applications."

Professor Greer is also interested in researching "smart materials that can be compatible with the body and help heal and monitor disease." Specifically, her team has been working on creating three-dimensional scaf-

> We're bringing together hospitals, distributors, manufacturers, and clever Caltech design to constantly improve our wheelchairs and make them cheaper. . . . To me, that's the key to great innovation.

Kenneth A. Pickar, *Visiting Professor of Mechanical and Civil Engineering*



Kenneth A. Pickar

Azita Emami

> *As electrical engineers, we can have a huge impact on medical engineering. . . . That motivated me to think about building minimally invasive, high-performance implants, drug delivery systems, and wearable devices that can adapt to our body both electrically and mechanically.*
>
> Azita Emami, *Professor of Electrical Engineering*

folds for cell growth and migration, using magnesium, a biocompatible metal, and hydroxyapatite, a mineral that comprises up to 50% of bone by weight. "These scaffolds will help us understand the processes of bone formation," says Professor Greer. "We can then learn how and why bones break and maybe figure out a way to delay and prevent failure. Once we have studied these phenomena at the fundamental level, we will be able to create artificial bone scaffolds that the natural bone will grow through and around, and strengthen it without having to take the scaffold out."

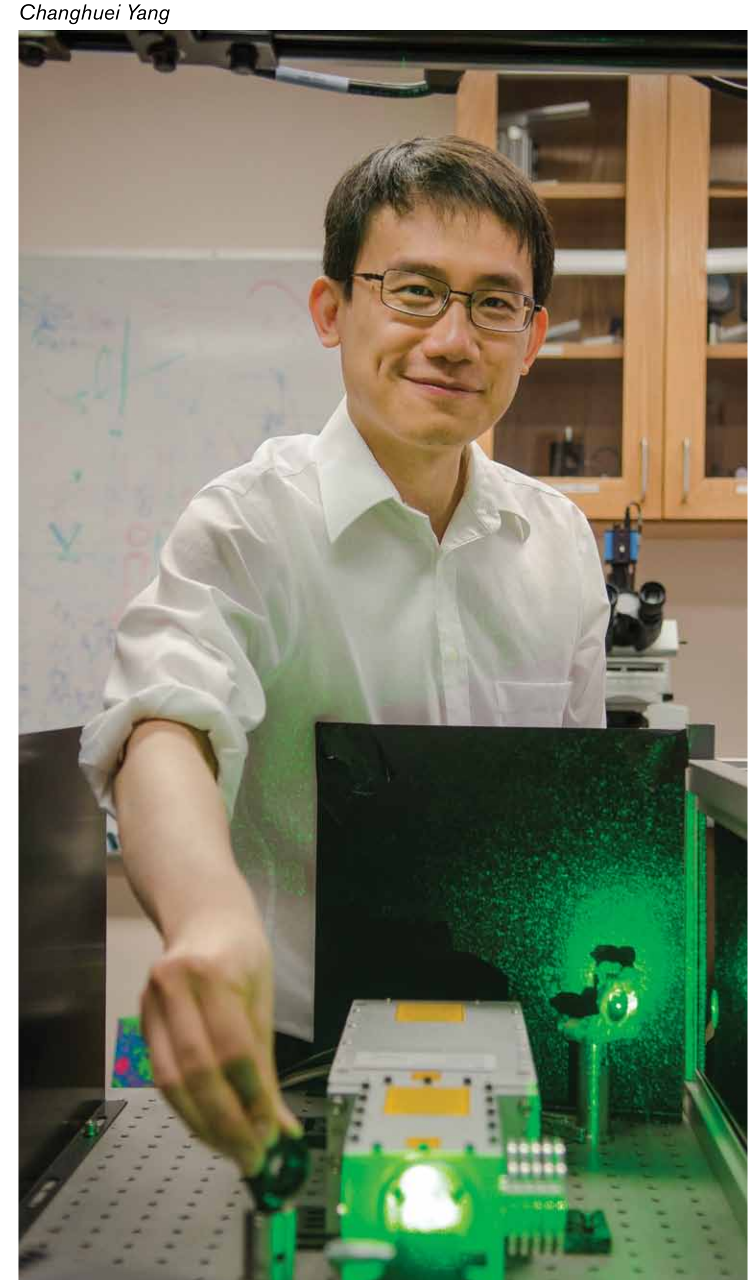
In addition to working with researchers such as Professor Greer, students in the new Medical Engineering Department would have the opportunity to take a unique Caltech course called Product Design for the Developing World taught by Kenneth A. Pickar, Visiting Professor of Mechanical and Civil Engineering. Professor Pickar's medical engineering interest is in "rehabilitative devices that either help people recover from serious injury or enable them to function to the best of their abilities."

Professor Pickar, who has many years of experience in taking students to developing countries, explains that "it was pretty obvious that there were big gaps in Guatemala and India on things that we take for granted here, which my students have attempted to fill by observing actual problems and then working backwards from that. For instance, their wheelchairs were very poorly designed for the environment, were flimsy, and were either free or way too expensive."

The problem is making affordable wheelchairs that are adapted to the environment. "We're scaling our wheelchairs so we can make them cheaply, employing bicycle parts in the critical regions," says Professor Pickar, "and we're bringing together hospitals, distributors, manufacturers, and clever Caltech design to constantly improve our wheelchairs and make them cheaper. Uniting engineering and the delivery of medical care gives us a better chance of becoming problem-centered and coming up with new technologies. To me, that's the key to great innovation."

"Problem-centered" is also an apt characterization of Azita Emami's work on implants. "As electrical engineers, we can have a huge impact on medical engineering," says the Professor of Electrical Engineering, "because any system you want to build that monitors or actuates or senses needs electronics to process the information or provide the data for the system. The challenges are very similar to those in other high-performance electronic systems, in terms of trying to make your system energy-efficient, accurate, and able to transfer

Changhuei Yang



> *I especially love it when I sit down with a clinician who starts complaining about a specific problem he or she has. Then, 30 minutes into the conversation, I am finally able to parse it into a sufficiently detailed engineering problem. From then on, the conversation usually becomes a series of light-bulb moments.*
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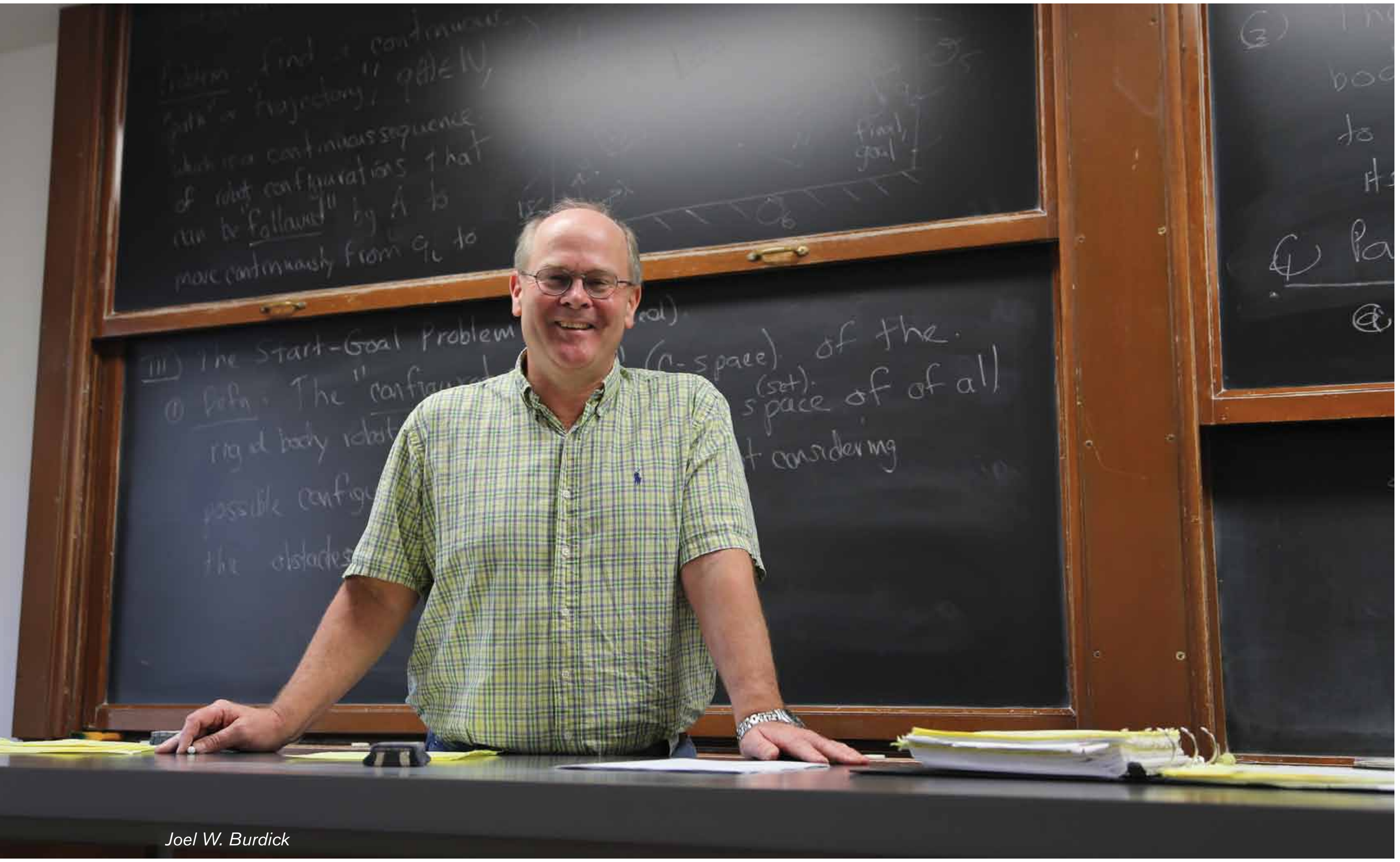
> Changhuei Yang, *Professor of Electrical Engineering and Bioengineering*



Joel W. Burdick

"We're interfacing with the human nervous system, which communicates and processes data based on both chemistry and electrical impulses. The big pharmacology companies have done a great job of pushing the chemical end, but there's a variety of other nervous system disorders that may benefit from more sophisticated implantable devices that modulate the electrical activity in nerves."

Joel W. Burdick, *Richard L. and Dorothy M. Hayman Professor of Mechanical Engineering and Bioengineering*

and communicate information. I started working on implants for neural stimulation and neural recording, in particular the retinal implant project, when I came to Caltech, and that motivated me to think about building minimally invasive, high-performance implants, drug delivery systems, and wearable devices that can adapt to our body both electrically and mechanically."

The products she envisions would be modular, low cost, and easy to use. "We want to come up with novel techniques to connect and integrate smaller components efficiently and use origami folding and unfolding techniques," she says. "We want to attack problems with an engineering angle that is exciting and difficult. Also ones that lead to strong PhD projects. The electronics in these modular and adaptive systems are extremely challenging, so we'll have interesting problems to solve."

Changhuei Yang is especially gratified when he aims his expertise at a medical target. As the Professor of Electrical Engineering and Bioengineering puts it, "I like to work on pretty much anything for which my group's optical and microfabrication expertise can significantly address medical needs."

He is currently pursuing two major lines of research with his group. One is a self-imaging petri dish that can stream microscopy images of cell cultures out of the incubator. "The ePetri is an exciting technology that can cut down on labor and contamination risks in diagnostic labs," says Professor Yang. By redesigning the petri dish to incorporate an inherent imaging capability, this technology opens up opportunities to perform diagnosis and experiments in ways that were previously impractical. For example, the ePetri has an inherent field of view that is orders of magnitude larger than that of standard microscopes. This makes it easy to keep highly motile cells in sight with the ePetri, while a standard microscope would have a hard time following those cells.

The other line of research in Yang's laboratory is cutting through the foggy nature of human tissues. "We appear opaque to light, not because we absorb light but because we scatter light. If we are able to switch off the scattering, we would be able to see right through the human body. That is useful because light can be used to extract biochemical information where X-ray and ultrasound fall short." Yang's group has been working on using the time-reversible nature of light to 'turn off' tissue scattering. Recently, they were able to focus light with an unprecedented sharpness and depth through tissue. Besides

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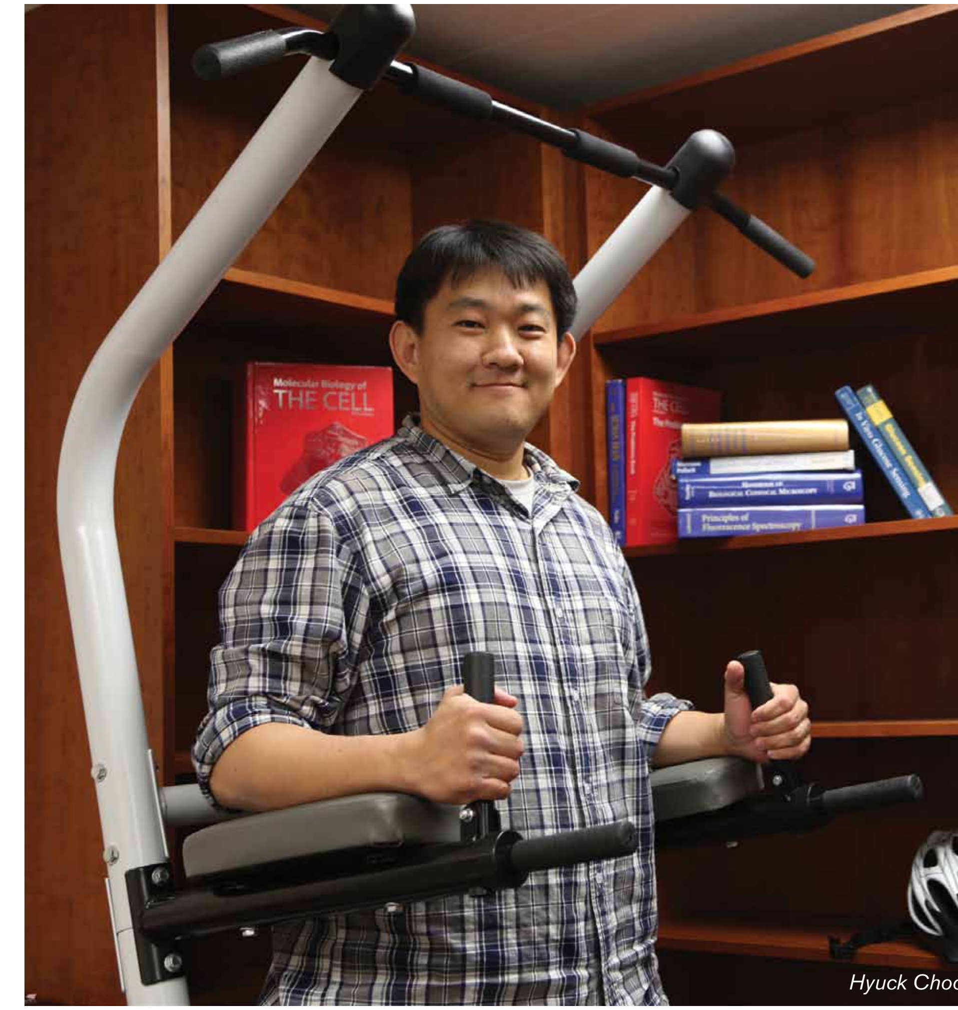


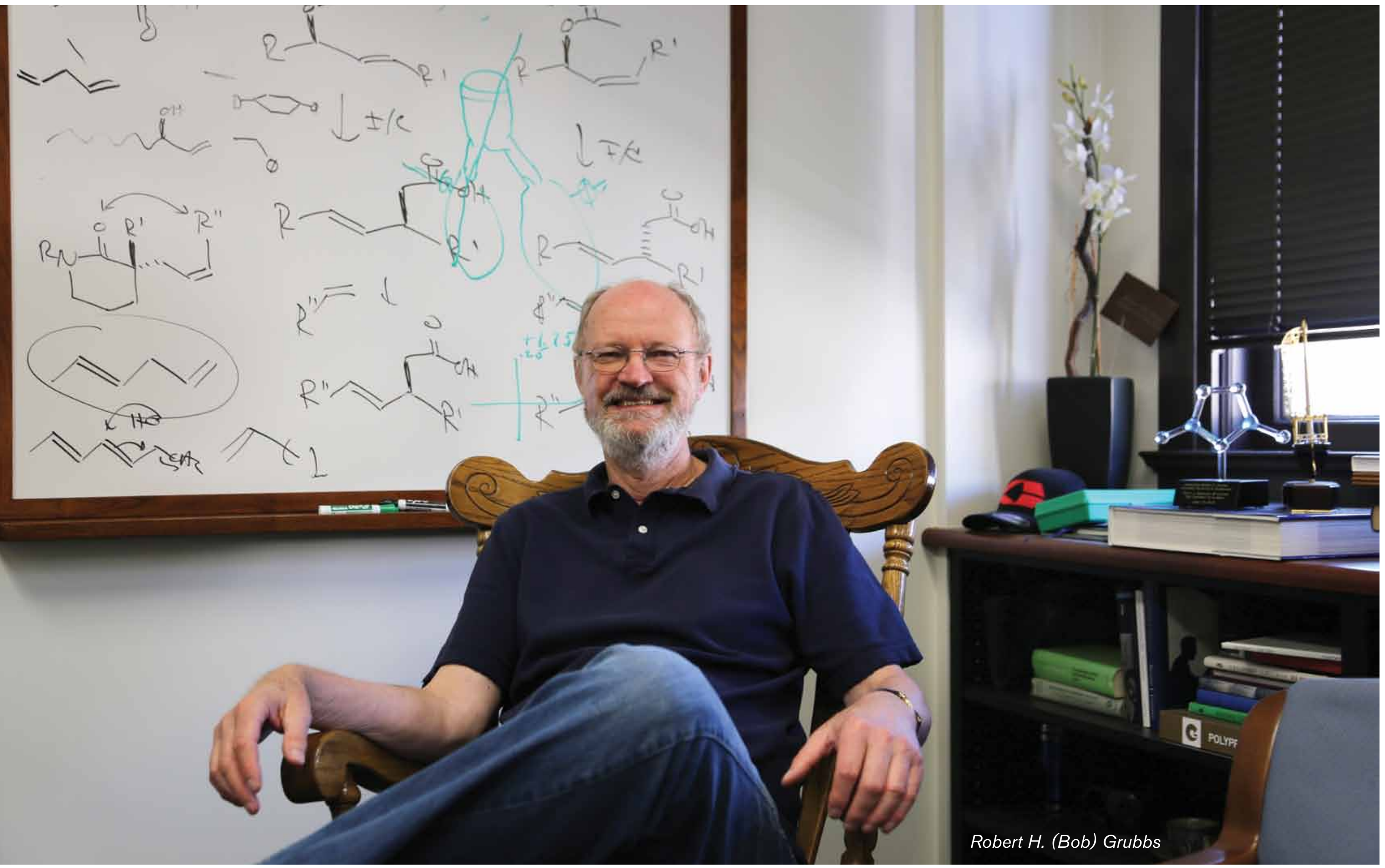
Hyuck Choo

"People deserve to be well and free of disease and live a long life in a happy manner. . . . We're in an era where we can bring together our accumulated technology and experience, as well as our talent and creativity, to finally provide a solution to these long-lasting challenges for the human race."

Hyuck Choo, *Assistant Professor of Electrical Engineering* extracting biochemical information, this technology "may also allow laser surgery without creating an incision, which means faster healing time and lowered infection risks."

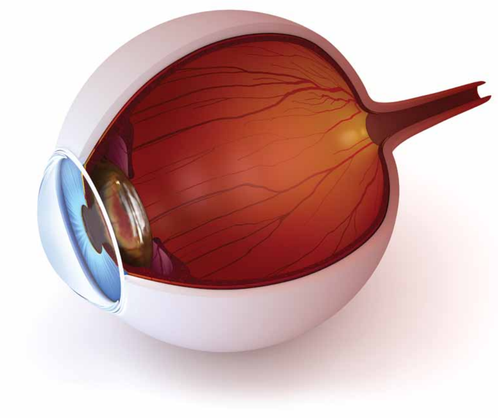
Besides these two major research directions, Professor Yang is also engaged with clinicians and biologists on a number of other projects. Most of his projects were spawned from spontaneous discussions. He even has a favorite scenario. "I especially love it when I sit down with a clinician who starts complaining about a specific problem he or she has," he says. "Then, 30 minutes into the conversation, I am finally able to parse it into a sufficiently detailed engineering problem. From then on, the conversation usually becomes a series of light-bulb moments."

Joel W. Burdick and his team have also had many light-bulb moments while working on technology



Robert H. (Bob) Grubbs

> *I have been pursuing some lines of research for 45 years, and I see the Medical Engineering Department opening up a whole set of new problems for me to work on. I think we have a real opportunity if we do it right and can make the right connections outside of Caltech to clinicians.*
>
> Robert H. (Bob) Grubbs, *Victor and Elizabeth Atkins Professor of Chemistry*



to help patients paralyzed by spinal cord injuries. "After they're implanted with the stimulating electrodes and electronic package, they're typically in the clinic for anywhere from three to six months, recovering and getting daily training," says the Richard L. and Dorothy M. Hayman Professor of Mechanical Engineering and Bioengineering. "But after they go home, we want to provide the patients with the same kind of physical therapy that they get in the clinic. So we've been working on prototypes of what we call a home stand frame. Currently, patients are pinned into a frame that just holds them upright. But with our patients, they're able to stand independently under the influence of the electrode array, and we want them to be free to move around because it helps the recovery process. However, we also want to be able to catch them when they start to fall or at least allow them to fall in a way so they aren't harmed."

It is also desirable for the clinicians to track the patient's progress remotely. "In the clinic, there's a whole suite of sensors trained on the patient to gather data which help us improve the therapy," Professor Burdick says. "We want them to have these devices at home so we can monitor how they're doing. After every daily training session, all the data gathered by the sensors built into the frame will be transmitted to a clinic and preprocessed by algorithms, and a summary is presented to the clinicians so they can assess the patient's progress. Currently, the patients have to come back to the clinic every few weeks, but if you're able to monitor them effectively at home, you have more of what we call an event-based approach, where you call them into the clinic when they reach the next threshold."

Professor Burdick envisions a host of other medical applications for his research. In his team's spinal cord work, "we're interfacing with the human nervous system, which communicates and processes data based on both chemistry and electrical impulses," he says. "The big pharmacology companies have done a great job of pushing the chemical end, but there's a variety of other nervous system disorders that may benefit from more sophisticated implantable devices that modulate the electrical activity in nerves. There's a broad field called neural modulation, which includes back-pain devices, our spinal cord stimulators, deep brain stimulators for Parkinson's, and cardiac pacemakers. We think there are more pathologies out there that would benefit from such modulation, and that we can do a better job in the areas that we're already working on."

Professor Grubbs also sees many opportunities for medical applications relating to his research. "I have been pursuing some lines of research for 45 years, and I see the Medical Engineering Department opening up a whole set of new problems for me to work on. I think we have a real opportunity if we do it right and can make the right connections outside of Caltech to clinicians. We have to have a reality check from clinicians and surgeons saying, 'I can go into the operating room and I can do this, but I can't do that.' For example, one of my research areas relates to the inner ocular lens. This research involves making a material that can be adjusted externally. So after the lens is implanted and the patient is healed, the clinician can go back and change the refractive power. This research required us to go through human trials and has been a really interesting exercise. But it also provides a model for how we're trying to do things: a clinician or a scientist identifies a potential solution, and the next step is that the clinician has sources of funding so we can hire postdocs to improve the concept. Then, once we do a proof of concept, we form a company, that takes it the rest of the way."

After almost 40 years at Caltech, its culture might be a given for Professor Grubbs, but Hyuck Choo, Assistant Professor of Electrical Engineering since 2011, is still in awe of his fellow faculty members' "extraordinary creativity and their ability to work with and support their colleagues. I think these two things will make medical engineering at Caltech unique."

Professor Choo's path exemplifies not only those qualities but also his own determination to make a difference in the world beyond the academy. He was working on his PhD project on optical micro systems when he had an epiphany. "I started thinking about why do we do engineering," he says. "The answer is that we are

Rustem Ismagilov

> *"Often the bottleneck in going from an idea to impact is actually figuring out all the engineering aspects. One competitive advantage that Caltech has is having smart people who are going to come up with new engineering principles to go from ideas and scientific discoveries to impact."*
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> Rustem F. Ismagilov, *Ethel Wilson Bowles and Robert Bowles Professor of Chemistry and Chemical Engineering; Director of the Jacobs Institute for Molecular Engineering for Medicine*

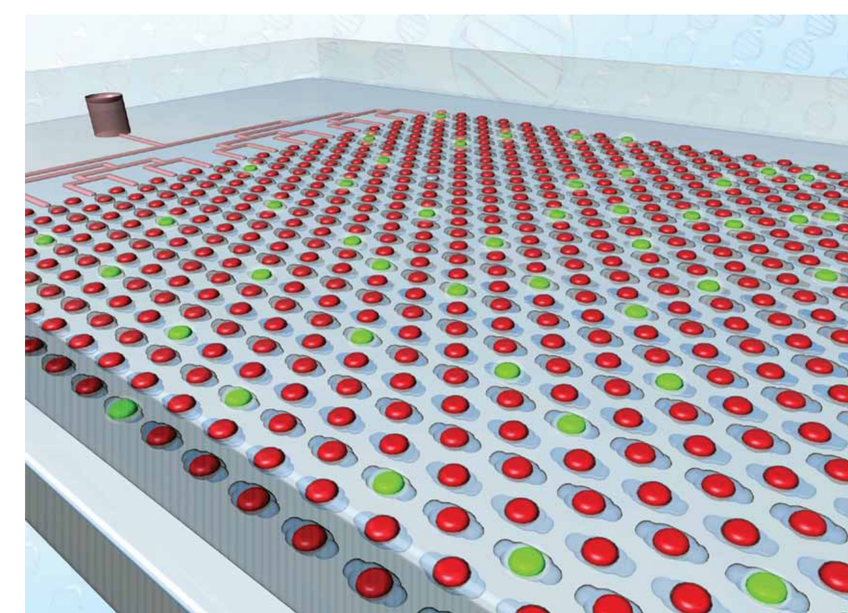
trying to improve the quality of human lives by means of technology. I figured that solving medical problems would be one of the best ways to do that."

After finishing his doctorate, he literally knocked on researchers' doors at the University of California, San Francisco, in search of one who would work with him on medical applications. "And I came across my present collaborator, Dr. David Sretavan, who specializes in glaucoma research," Professor Choo says. "I was looking for a particular case of keratoconus where the cornea develops into an abnormal shape. Dr. Sretavan said he would be interested in characterizing optical aberrations through an ocular cornea but also in measuring pressure inside the eye and monitoring pressure-regulating ocular structures at high resolution. Fast-forwarding to today, we are building an intraocular pressure sensor for glaucoma research. Glaucoma is a leading cause of blindness in the developed countries, and the increased level of intraocular pressure is the major risk factor for the disease, but medical researchers cannot say that it's a cause, because they do not have the technology that can measure the pressure inside the eye. Our ultimate goal is to optically monitor the pressure and observe the pressure-regulating system in the human eye to understand what causes glaucoma. It requires quite a feat of optical engineering to do this without damaging people's eyes."

The call that Choo heeded wasn't only intellectual or compassionate; it had a spiritual dimension, one that he sees in medical engineering as a whole. Echoing Professor Gharib's belief in engineers' "moral obligation" to improve health care, he says that "people deserve to be well and free of disease and live a long life in a happy manner," citing a passage from the American Standard Version of the Christian Bible. "In Matthew 11:5, it says, 'The blind receive their sight. The lame walk and the lepers are cleansed. The deaf hear and the dead are raised up and the poor have good tidings preached to them.' I think we're in an era where we can bring together our accumulated technology and experience, as well as our talent and creativity, to finally provide a solution to these long-lasting challenges for the human race. It's already happening, too. The blind receive their sight: Professors Tai and Emami are working on retinal implants. The lepers are cleansed: if the pharmaceutical researchers bring out a better medication, we can come up with a device to deliver it. People who lost their hearing can regain it: we have the micro machining technology to design and create an artificial structure inside the auditory system that would work. And the dead are raised up: I don't know if we can do this one. But good tidings for the poor might be that we can create an economic engine from using our technology that would help people enjoy a better quality of life. It's all about helping people. That's the long-term goal of Caltech medical engineering."

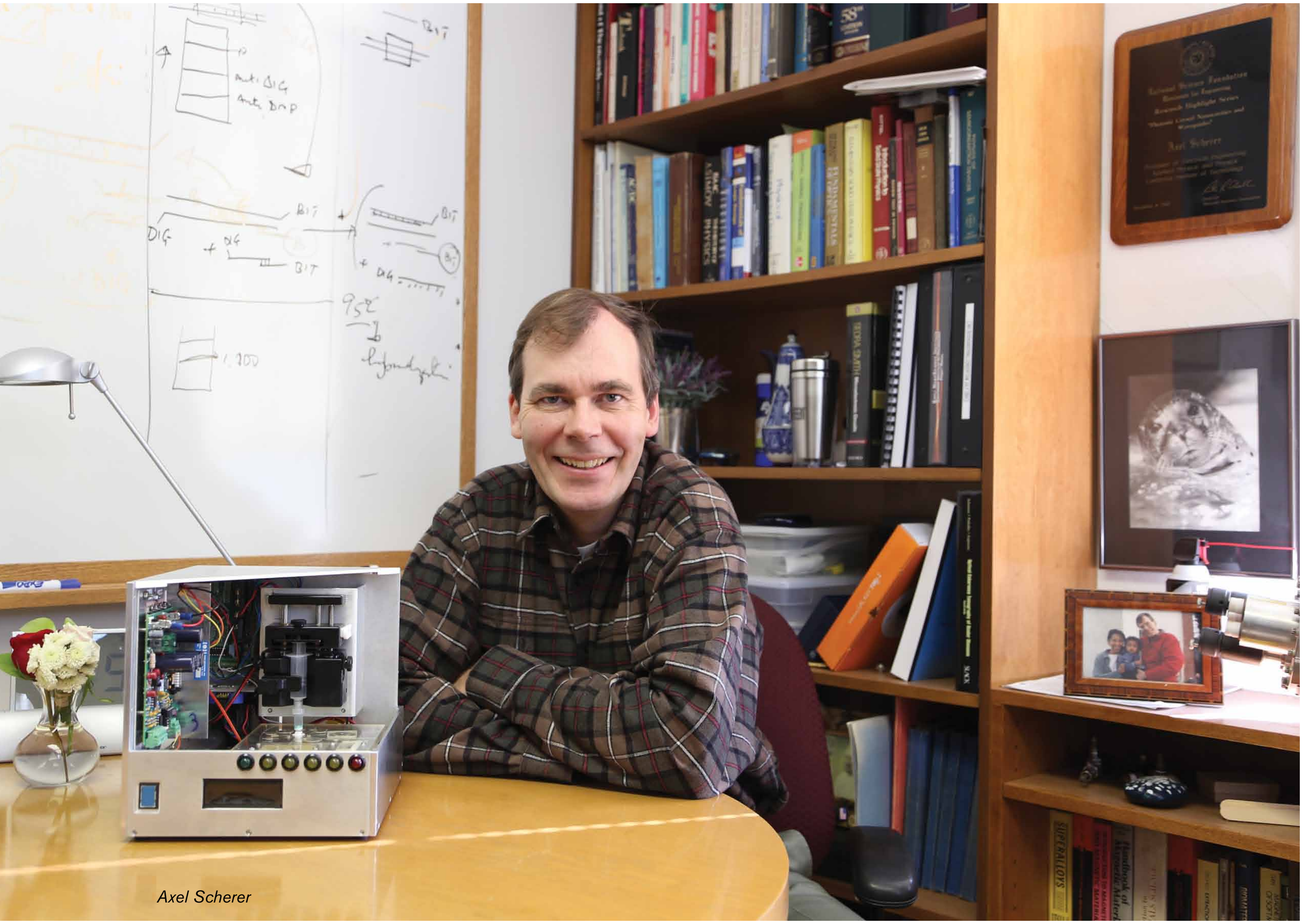
Similarly, Axel Scherer is concerned with what he describes as the moral problem of how we take care of the weakest amongst us. "If we decide to just give the best medical care to the rich and forget about the poor, that sort of defines us as a culture," says the Bernard Neches Professor of Electrical Engineering, Applied Physics and Physics. "Then the question becomes, What can we do at a university? We've been supported by the Bill and Melinda Gates Foundation for the last year and a half to build instruments that are available for the developing world to do medical diagnostics. They're primarily interested in diseases that occur in tropical countries, like malaria, tuberculosis, AIDS, and sleeping sickness. These diseases require testing that usually has to be done in the field in very rugged conditions. The way it's done now, samples are taken and then transported to some central location. By the time the results come back, it may be weeks or months later, and the patient is gone. The solution is to build a set of inexpensive, automated tools that allow us to identify these diseases without any lag time. You push the button and then you do the test. These tools also have to work in very demanding environments: high humidity, high temperatures, lots of dust. In metropolitan city centers, we have many of the situations that exist in the developing world. If we can build instruments that work in these rigorous conditions, then they will also work in the Western world."

A collaborator of Professor Scherer's who is also committed to solving the problem of diagnostics in the developing world is Rustem F. Ismagilov, the Ethel Wilson Bowles and Robert Bowles Professor of Chemistry and Chemical Engineering. When asked about his medical engineering research interests, Professor Ismagilov explains, "I'm interested in three aspects. One is understanding how nature works. Another is creativity and thinking of new things that people haven't thought about before. And finally, there's making an impact. I derive the greatest satisfaction from



The single-molecule and single-cell diagnostics paradigm

EAS FEATURE



Axel Scherer

“Let’s focus on reducing the amount of suffering in the world and use technology to bring medical care closer and closer to the real point of care, which is the patient.”

Axel Scherer, *Bernard Neches Professor of Electrical Engineering, Applied Physics and Physics*

my work if I can see how it makes an impact in the short term or I can see the path to making an impact in the long term. I think often the bottleneck in going from an idea to impact is actually figuring out all the engineering aspects. One competitive advantage that Caltech has is having smart people who are going to come up with new engineering principles to go from ideas and scientific discoveries to impact.”

For instance, Professor Ismagilov explains, “We have found that using microfluidic devices and chemistry to take diagnostic measurements out of the traditional kinetic paradigm into the single-molecule counting paradigm simplifies the process. The argument we have is that in the single-molecule paradigm, the diagnostic measurement would actually be much more robust to changes in assay conditions such as temperature or imaging accuracy. Therefore, we can reduce or eliminate the need for equipment infrastructure currently used to control assay conditions or provide high-quality imaging, making the process more accessible. As an analogy, think about the spread of communication technologies. People used to have landlines for phone service. In the developing world and rural areas, you just couldn’t afford that infrastructure, so you just didn’t have phone service. Then cell phone technology appeared and people in these developing or rural areas leapfrogged straight to those better technologies. I argue that in these developing countries, home testing will also bypass building traditional diagnostic infrastructure and leapfrog directly to digital single-molecule measurements.”

Professor Scherer explains another motivation for this research: “The most important thing is to manufacture the technological capabilities that we have available in medical applications at the lowest possible cost. That’s sort of an unusual thing for a professor to say. I’m not supposed to think about cost. But hopefully we can build tools for the medical world the same way that we build consumer electronics. The DVD player has a huge amount of complexity, and I can buy one for $50. A medical instrument costs $50,000 for similar complexity. It’s an engineering challenge to shrink the cost. As a society, I think it’s a moral obligation to focus our efforts on making the capabilities that we are technologically able to provide available to everyone.”

Some of Professor Scherer’s core concepts came from his volunteer work at a hospital in Southern California. “If you work in a hospital, you realize that lots of suffering occurs needlessly because we don’t have the right tools at the right place,” he says. “I saw all the frustration on both the nurses’ and the patients’ side. I realized that technologically, there was a huge challenge that could be met by the capabilities we could develop. Let’s focus on reducing the amount of suffering in the world and use technology to bring medical care closer and closer to the real point of care, which is the patient. Once we build these kinds of systems, there’s a whole other kind of medical engineering that becomes possible—for example, implanting devices in the brain that allow us to control prosthetic devices, implants that detect our intention of, say, picking up a glass of water and have some robotic system do that for us. We could argue that that will replace the spinal cord with a Bluetooth connection. Let’s make a difference, which is what Caltech is good at.” ENG

Learn more about medical engineering at mede.caltech.com.

Move Bits not Watts:
Algorithms for Sustainable Data Centers

By Adam Wierman, *Professor of Computer Science*

I was a latecomer to computer science. When I started as an undergraduate at Carnegie Mellon University, I was a civil engineering major. Then I went to psychology, statistics, math, and finally I found what I was really passionate about: computer science. There was an amazingly engaging professor, Steven Rudich, who got me excited about the fundamental challenges in the area, and the perspective of "focusing on the fundamentals" has defined my work since.

These days, my primary focus has been on finding places where computer science can help to address the problem of burgeoning energy consumption. Computer science can play a major role in this area, but it's also a major part of the problem.

Research in this area puts me at the boundary of several fields, such as economics, electrical engineering, and control, because one ends up using tools from many different areas to gain a clearer understanding of these concerns.

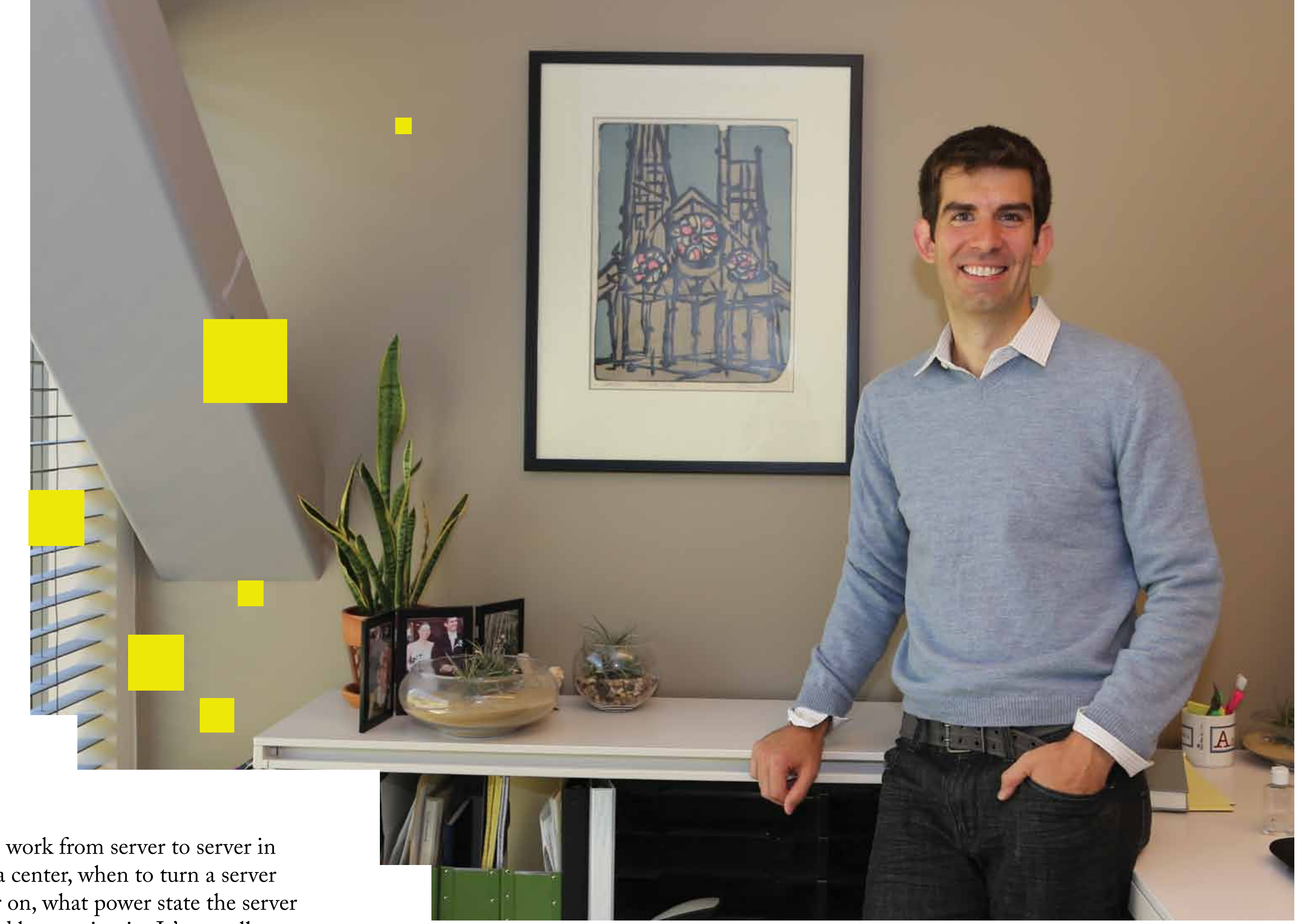
I'm particularly interested in the effects and potential of cloud computing, where so much of our lives seem to have migrated. The data centers that make the cloud work the way it does are huge energy users: there are about 2,000 medium to large data centers in the United States, and those 2,000 buildings make up 2 to 3% of the country's energy usage. That's still a small percentage today, but energy usage in data centers is growing at about 10% a year, while the energy usage of the United States as a whole is growing at about 1% a year. The problem is that their servers are basically always on. There are 10,000 or 100,000 servers sitting there idling at 10% capacity most of the time.

My students and I started out just thinking about how we could make data centers more efficient. Can we use renewable energy in powering them? Can we make them more efficient at using renewable energy?

A key observation that guides our research is that not all the work that the cloud is doing is email, search, and other such things where an immediate answer is required. A lot of it is "delay-tolerant," like scientific computing, where if it's going to take a week to do a simulation, what matters to the user is that it's done in about a week, not that it's done in a week and a minute versus a week and ten minutes. That affords the flexibility to run the computations when it's sunny out or when it's windy out, or when the grid sends a signal that there's a huge demand because it's a hot day.

But this approach requires a lot of dynamic control of the workload, of the servers, and of the cooling for them. That's a big challenge, and it's terrifying to the data center operators because they care about reliability. If Gmail or Netflix or Flickr goes down for 10 minutes, that's a disaster. One has to be very careful not to sacrifice reliability, which makes getting flexibility out of the services a really challenging problem.

What we're doing is designing the algorithms that determine when to move work from server to server in a data center, when to turn a server off or on, what power state the server should be running in. It's actually a very dangerous decision—the costs involved in turning something off are nearly the same as the cost of leaving it running for an hour or two. One way to think about this is as a rent-or-buy problem. If there's not enough workload to keep it busy, the server should be turned off to take advantage of the savings in cost and energy. But if the server is uncertain whether it might be needed, great care must be exercised in turning it off. So, keeping it on is like renting and turning it off is like buying. Since the cost of "buying" is so high, it becomes essential to make the choice carefully. And, in reality, it's not just a binary decision of renting or buying. One has very fine-grained control of which servers to turn on, where to keep data depending on which servers are kept on, which cooling systems are kept on—and everything's correlated over time, so things have to be in certain orders for certain jobs to work. It becomes a very complicated decision about which things to turn off and when.



Our goal is to design algorithms that we can take to HP and Apple and Google and say: Using this algorithm will manage your capacity in a sophisticated way so that when you have a solar farm next to your data center, you can take advantage of that to save money on the grid, and be net zero, or close to it, by using renewable energy as much as possible.

In fact, we've been working with HP for three years, and they're now pretty convinced. They have our algorithms implemented as part of their "net-zero data center architecture," and so the ideas have made the initial transition from academia to industry.

There's no way we could have made that kind of progress if my Caltech students hadn't connected with HP. That was pivotal, and it's been great to have the Caltech community really help in making those connections. Our work is quite mathematical, and so it took a lot of effort from the students to convince HP that the algorithms we had developed actually made sense for their system. Having students go onsite was what made the transition out of academia possible, because there's nothing we can do here that will convince them that for their data center, something like this can work. They need to see that even though it's their architecture, their design, and the things they do are specialized, the models still apply.

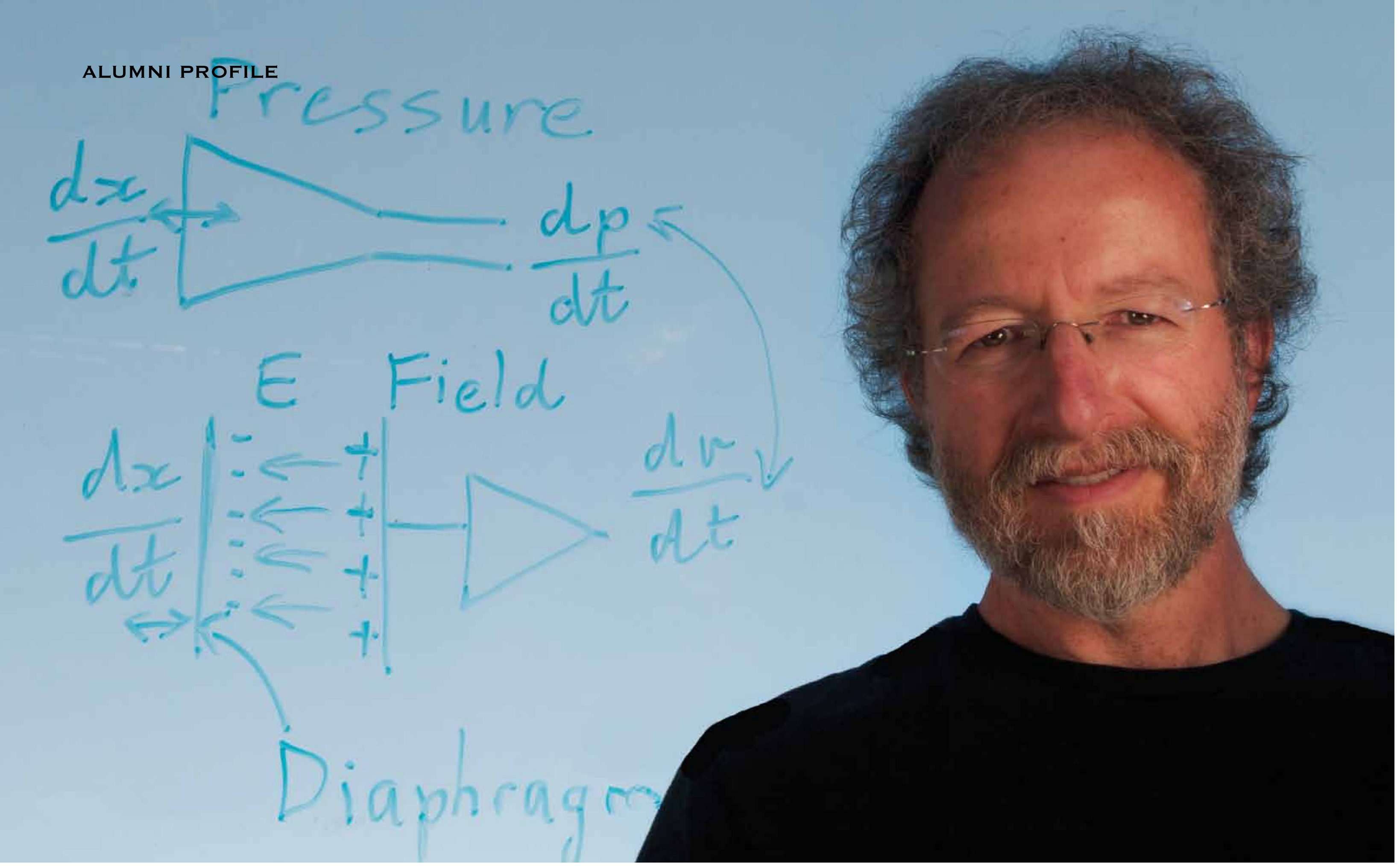
Going forward, there's still a lot to do. We think that data centers can actually be a key to helping integrate renewable energy more efficiently into the grid itself. The problem with renewable energy is that it fluctuates. In a grid, you have to match demand —which you basically don't have any control over—with supply at every given instant, and that's really hard if you can't predict the availability of wind energy and solar energy. But data centers, if they're sophisticated in the way we've been talking about, can give you some control over demand, because you can say to a data center, we need an adjustment of demand of a megawatt to help balance our energy sources. According to HP and some smaller companies that we're working with, they can very easily give 10 to 25% flexibility in their energy usage at any given point during the day, which means that in a 20-megawatt data center, you basically have two to five megawatts of storage. That's like having a two-megawatt battery that grid operators could just plug and play and control, if the market is set up so that it makes sense for the data center to provide this flexibility to the system. And this is where economics comes in: How can we design markets to extract this flexibility? So, at this point, we're working on both the control schemes for the data centers and market design for demand response to try to understand how they can work together.

One of the harshest realities of going from the data-center world to the electricity-market world is the difference between talking to engineers about how to design a system and trying to have a policy impact on how markets are regulated. There is just a complete difference in how changes are realized. In the data center, a test bed can show that things are working, but there's no parallel to this in the policy arena.

But the outcome, as I tell the students when they start, is that if we can make it possible for data centers to provide such services for the grid, that would basically save a few power plants. That's a very different form of impact than a computer scientist typically has. It's not just that people will use your system, but you can have an impact on a crucial challenge facing society. E N G

Adam C. Wierman is Professor of Computer Science.

Visit rsrg.cms.caltech.edu.



Clive Smith is a Caltech electrical engineering alumnus (MS '84) who was inspired by Professor Rob Phillips's article in the last issue of *ENGenious* entitled "Calculations in the Sand: Random Walks in Physical Biology." He decided to start a dialogue with Professor Phillips about the key points of the article, including using mathematical models in conjunction with experiment. *ENGenious* approached Smith to learn more about his Caltech experience and how it has shaped his professional pursuits, including reinventing the stethoscope.

Clive Smith:

Using Mathematics to Reinvent the Stethoscope

***ENGenious*: Tell us about your undergraduate experience in South Africa.**

Smith: I educated myself out of textbooks. On my first day at Wits University, the dean, Costa Rallis, made a speech telling us, "We will educate you to educate yourselves." He meant that technology moves so fast that we have to be autodidacts. I later came to interpret it to mean that lectures were pointless. After the middle of sophomore year, I only showed up for exams. I decided that dull education shouldn't kill my love of engineering. But I've never forgotten the dean's message. Technology has only accelerated, and we have to be lifelong learners. As my favorite Bob Dylan line goes, "He not busy being born is busy dying."

***ENGenious*: How did you come to Caltech?**

Smith: We had conscription in South Africa, so before I could do graduate studies I went into the South African air force. I didn't want to use my engineering education to design weapons for an apartheid regime. So I got myself into a medical unit to avoid doing anything militarily useful for a political system that I abhorred. Toward the end of my service, I decided that I wanted to go to America for graduate study. I was fixated as a kid on the moon landing. So I grew up with a feeling that anything that matters in science and technology happens in America. Caltech was on my radar because of the Jet Propulsion Laboratory (JPL). I applied to Caltech and was very honored to get in.

***ENGenious*: What was your Caltech experience like?**

Smith: In great contrast to my South African educational experience, I missed two lectures in my entire Caltech master's degree program. In terms of the teaching, every single one of the professors was absolutely incredible. My biggest regret is that I didn't take a unique course that Richard Feynman, John Hopfield, and Carver Mead were teaching called The Physics of Computation. I couldn't fit it into my curriculum. There were other subjects I wanted to study, but that was a huge mistake.

***ENGenious*: What made the Caltech professors so incredible?**

Smith: First example: Professor Robert Middlebrook, who was the chair of the Caltech Electrical Engineering Department during my time as a student. The grade in his class was based exclusively on homework—one long assignment a week. More importantly, the homework grade was not based on whether one got the right answer, but how. If we used pages and pages of rote mathematics, Middlebrook would guarantee not more than a 20% grade. But if we used judgment and insight, applying math and circuit theory more judiciously in one page, we could get 100%. That was his teaching style—develop judgment and insight to simplify a model by eliminating unnecessary complexity and only then apply mathematics. His approach produced solutions that revealed a kind of "truth" about circuits, by which I mean identifying which parameters most affect system behavior and how to use that understanding to synthesize a better design. You can get answers by rote, but you have to model a problem in a way that the mathematical result becomes useful. This was, perhaps, the most important lesson I ever learned at Caltech, and pretty much every professor taught that philosophy in one way or another. It wasn't about textbook teaching. You can learn that anywhere. Fundamentally, what they taught at Caltech was how to mathematically model the world and use that insight to improve the world.

Another example of an incredible professor was P. P. Vaidyanathan, who was an assistant professor at the time. I remember a take-home exam that I did for him where I flipped over

> *"Technology has only accelerated, and we have to be lifelong learners. As my favorite Bob Dylan line goes, 'He not busy being born is busy dying.'"*

Laennec stethoscope, invented 1816

The Thinklabs next-generation stethoscope the page and sunlight shone through the back of the page so I could see the problem upside down, and that's where the solution to the problem lay. That was the kind of thing he used to teach—sometimes you need to flip a problem upside down and look at the inverse problem. I was a paid teaching assistant for P. P., which was invaluable for me. One year at Caltech was 2.5 times more expensive than my entire bachelor's degree in South Africa. Which was true for most international students. So my job with P. P. made Caltech affordable.

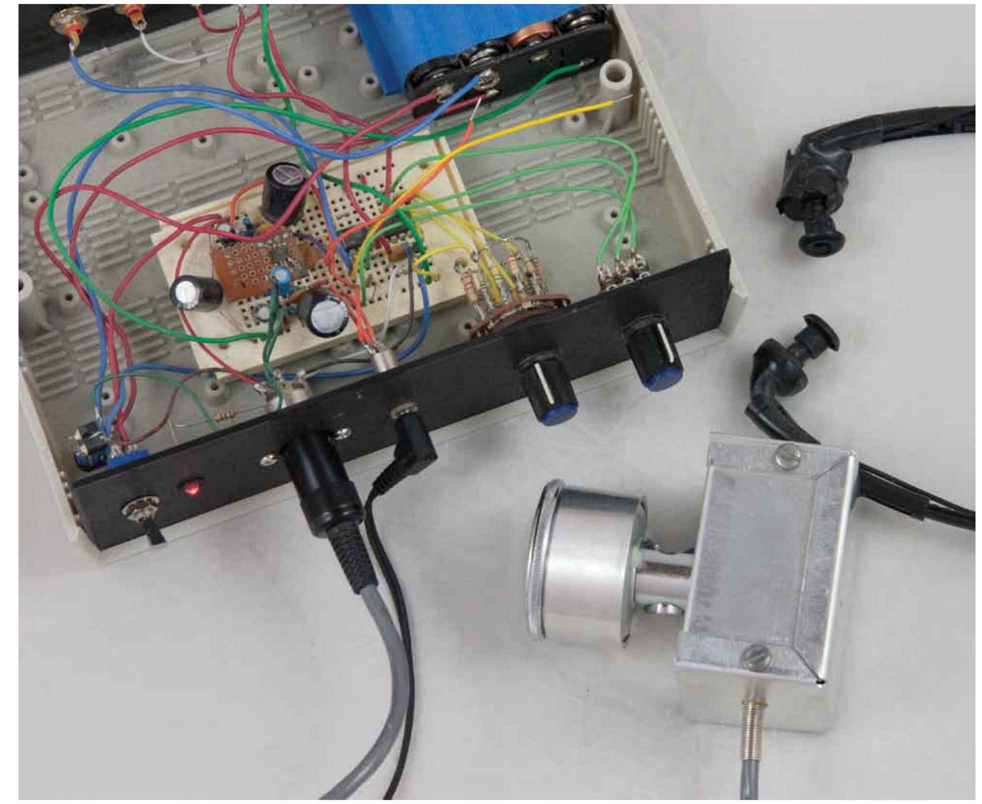
ENGenious: Can you expand on your ideas to use mathematical models in conjunction with experiments to educate students, including kindergarten to grade 12?

Smith: I'm still a firm believer in mastering fundamentals. "Creative math" without core skills has been a disaster. But widespread negative attitudes are largely due to people not understanding math's relevance to their lives. So give kids real design and open-ended problems to figure out. Let them start by using intuition and reason, and then show them the beauty of arithmetic methods in the early years and algebraic or calculus solutions later on. Students will care more when they understand the potential power and elegance of mathematics in their own lives. Teaching Newton's laws in a course called The Physics of Car Accidents would be more valuable to teenagers than dry advanced placement physics. We engineers take mathematics and physics and translate it into the real world. But what everybody should be doing every day is translating the real world into even basic mathematics and physics to better understand what's going on around them and potentially make more informed choices. Quantitative reasoning is all too rare. It doesn't have to be complicated, just rooted in valid fundamentals—Richard Feynman dropped material in ice water and we all understood how the Space Shuttle exploded.

ENGenious: How did you get into the medical device business and start Thinklabs Medical?

Smith: I was doing some research and stumbled across a cardiology paper about the acoustics of modern stethoscopes. The author also built a replica of the original stethoscope from 200 years ago, and he found that stethoscope acoustics were essentially unchanged in two centuries. So I thought, "I did analog circuit design and signal processing at Caltech. I should have the keys to solve this problem!" My goal was to keep the sound as natural as possible for the physician trained with the old stethoscope, but with the benefits of electronic amplification and signal processing. The key creative leap came when I asked a simple question: What is the mathematical and physics model of the mechanical stethoscope and how can I create an electronic model that has the same mathematical and physical behavior? Solve that, and electronics can replace acoustics but the sound should be analogous. It took years for me to be satisfied with the sound, and I ended up solving the problem by inventing a new type of transducer. The solution was to replace air pressure with electric field intensity. I turned a pressure-based diaphragm into a capacitive diaphragm that senses voltage instead of pressure. Quite simple, really. Just ask the right question and develop a good mathematical model. Being obsessive about audio quality paid off. People in esteemed medical schools tell me it has the best sound quality of any stethoscope they've ever heard. Framing the right question was key—the foundation of good engineering. Asking the right question and turning it into a useful mathematical model was a Caltech perspective.

Thinklabs stethoscope



Hidden workings of an early Thinklabs prototype stethoscope

ENGenious: How did you get your stethoscope from bench to bedside?

Smith: When I started experimenting, there were essentially no electronic stethoscopes in the market. Then Hewlett Packard (HP) Medical private-labeled a Canadian electronic stethoscope. I had benchmarked it against my technology, with favorable results. I called HP, now Agilent Technologies, and they agreed to a meeting, warning me that every aspiring stethoscope disrupter had walked through their doors. They listened to the sound and asked what complex solution was hidden in the "black box." What was hidden inside my prototype was an ugly breadboard circuit that only an analog geek could love. I explained the thought process and the physics and they promptly dispatched an engineer to my home to do due diligence on what seemed like a too-elegant solution, especially from a guy working alone in his garage. Agilent then funded my engineering effort. Philips later acquired Agilent Medical, and by the time we were done, Philips decided to exit the stethoscope market. I was a one-person company with intellectual property, a complete design, and results from a Harvard focus group that validated the performance. I decided to produce it under my own Thinklabs brand. I put on a marketing hat and went to a major cardiology conference in Orlando with one working stethoscope. I rented a condo with my brother, who's a cardiologist, and did an all-nighter building more demo models. I'd once spent 44 hours straight finishing a chip design to meet a deadline at Caltech, so the all-nighters I do as an entrepreneur aren't a big deal. Caltech teaches stamina. By sunrise I had three working stethoscopes. The conference opened, and I stood sleep-deprived in my small conference booth, looked at the big companies that had booths half the size of a football field, and I thought, "I'm going to spend three days people-watching. What was I thinking?"

ENGenious: Did people come to your booth at the cardiology conference?

Smith: People lined up! We're usually one of the busiest booths at medical conferences. We've reinvented the stethoscope. My new design is a complete departure from the 200-year-old icon of medicine.

ENGenious: What is next for you?

Smith: This market is moving toward telemedicine—examine a patient in Africa and send sounds to America or India for diagnosis using mobile platforms. Novel technologies will be proven in Africa and Asia. They lack resources, so they have to be creative and may leapfrog over our stuck approaches. In America, technology contributes to medical costs more than it improves efficiency. Healthcare is now unaffordable everywhere. Low-cost mobile medicine has been on my radar for many years. We now have amazing technologies with which to innovate, design, and manufacture. I'm a bit of a control freak and perfectionist when it comes to product design—I do the electronics, software, and industrial design, and I'm now using 3-D printing to manufacture in the USA. I'm also exploring low-cost robotic manufacturing. Beyond medicine, I have ideas ranging from audio products to new musical instruments to new Internet applications. There has never been a better time to be an engineer, and I've never had more fun being a designer. Hopefully I'll never stop learning.

Clive Smith is founder and CEO of Thinklabs Medical.

Visit www.thinklabsmedical.com.

Therapeutic Bubbles

Some people might think about a glass of champagne after a long day at the office when they hear the phrase "therapeutic bubbles." But the phrase has a very different meaning to Professor of Mechanical Engineering Tim Colonius, who leads the Computational Flow Physics research group at Caltech.

***ENGenious*: How would you describe your group's research?**

Colonius: We try to simulate turbulent flows on the computer, and then we use those simulations to understand the physics. An example is trying to understand how a particular flow might be unstable to small disturbances. Perhaps one wants to enhance an instability in order to better mix two fluids, or control an instability to reduce noise or vibration. We would do a computer simulation that would try to isolate the physics behind that instability. We mainly work in three application areas. One is aeroacoustics, which is how sound waves are generated by or interact with flows. The second is flow control. How do we put sensors and actuators into a flow and make it do something that it wouldn't do on its own? And the third area is cavitation and bubble dynamics, and that's where biomedical applications of bubbles come in.

***ENGenious*: How did you come to research treatment for kidney disease?**

Colonius: The late Brad Sturtevant, who was a professor in aeronautics here, had an experimental program on lithotripsy when I first got to Caltech. Lithotripsy is a non-invasive procedure for breaking up kidney stones. Brad saw the models of bubble dynamics that I was developing at the time and said, You should come and work with me because we need this kind of analysis to better understand lithotripsy. The lithotripter creates shock waves and then focuses them to where the physician believes the stone to be. It is fired over and over until the stone is broken into tiny bits. Lithotripters have been around since the 1980s, but there was hardly anybody studying the physics behind how the machine works until a group led by Andy Evan at the Indiana University school of medicine started the project with Brad and Larry Crum. One of Brad's great contributions was to make an experimental lithotripter to see how it worked under controlled laboratory conditions. That started a line of research on how kidney stones break under the action of shock waves that continues today. Understanding the mechanics is important because we need to know how the lithotripter can be used efficiently and safely, and ultimately design more effective ones. But almost immediately the question also became, Why is there sometimes injury? Hemorrhage and other kinds of acute effects can result from the treatment.

***ENGenious*: What has this line of research revealed?**

Colonius: We think there's sort of a two-step process when a kidney stone is pulverized. First, the stone gets broken up into big pieces through the action of the shockwave, like taking a brittle material and hitting it with a hammer. As smaller pieces are made, there's no way for the shockwave itself to break them further, but a second mechanism then pulverizes the stone into fragments so small that they can be passed naturally. What's thought to occur is that cavitation bubbles, tiny bubbles of gas completely surrounded by liquid, are created by the expansion that follows the initial shockwave. When the bubbles collapse, they make their own shockwaves that further break the bits of stone.

***ENGenious*: Has your research had any effects on medical practice?**

Colonius: One of our team's findings regarding lithotripsy is that bigger and faster is not better. A lower amount of energy delivered at the proper rate is going to lead to a more effective process with less injury. We developed a model that describes how this works, and it predicts that there's an optimal pulse repetition frequency of a little less than one hertz. Because the physicians and medical professionals I work with have been effective at putting out this message, there's beginning to be a trend of running lithotripters more slowly and also going to lower shock energies, and even designing new lithotripters with broader focal zones. Even if we're just working behind the scenes to understand the physics, it's gratifying to me to see that understanding reflected in practice.

***ENGenious*: How is the engineering contribution to this field unique?**

Colonius: Well, there are lots of applications that involve bubble dynamics, and we are providing specialized techniques to predict these flows. We're not quite there yet, but we would eventually like to understand in greater detail and be able to predict how biological materials respond to acoustic waves and cavitation. All the micro-structural aspects play a role in whether and how tissue gets damaged. There are problems like sonoporation, which is getting bubbles inside cells to deliver drugs. We don't have good simulation models for how these soft materials respond to mechanical stresses. Right now we have to homogenize the material to make a model of it. But we would like to start to get to a more realistic description.

***ENGenious*: What are some other medical applications of your research on bubbles?**

Colonius: One application is in the area of cancer treatment. Histotripsy, as it is called, uses focused ultrasound to create a cloud of cavitation bubbles that melt or ablate cancer cells. Lithotripter-type devices have also been used for other conditions, like tennis elbow or planar fasciitis. If a lithotripter is fired at a bone that was broken and it's basically healed but not attached, it can re-damage the area and re-initiate the body's own healing process. Finally, in the area of therapeutic bubbles, if one coats a bubble with a drug, for example, and excites it with ultrasound, it can go into cells and deliver the drug right into the cell. Understanding how waves create bubbles and how those bubbles interact with tissue and biological materials is, I think, a key to a lot of biomedical technology. ENG

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Asking the Tough Questions:

Caltech Center for Teaching, Learning & Outreach

In August of 2012, the Caltech Center for Teaching, Learning & Outreach was formed by the Office of the Provost to support university teaching and learning, along with K–12 and public educational outreach, under a unified umbrella. *ENGenious* interviewed the Center's director, Cassandra Horii, to learn more about its activities and her vision for the future.

***ENGenious*: Why was the Center created?**

Horii: When we think about Caltech, naturally we think about cutting-edge research. But our scientists and engineers also think long and hard, and care deeply, about their role as educators. You would not believe how some professors go into the classroom to practice, writing everything out on those boards and erasing it, to hone their lectures before students get to class. And, despite the fact that they've taught the course many times, others rewrite and rethink their notes every time they teach. Still others give of their time and expertise to reach out and work with students and teachers in public schools with limited access to research labs. These actions speak to the depth of commitment of our people. The Center for Teaching, Learning & Outreach was created to support the initiative of the faculty and to help make the educational part of Caltech's mission as exceptional as the research.

***ENGenious*: What is the role of the Center and whom does it serve?**

Horii: We bring the latest research in education and findings on new tools and technologies to three main groups: our faculty, our graduate students (who almost all serve as teaching assistants, TAs, at some point), and our undergraduates, many of whom also work as peer tutors, mentors, and TAs. Caltech doesn't have a school of education, so the Center also consults on institutional and policy structures related to teaching. Wherever teaching is happening, we are here to help!

***ENGenious*: How do you work with the faculty?**

Horii: Oftentimes we work with faculty in individual consultations. Teaching is a very personal act. In addition to one's unique perspective on the subject matter, it involves the self, the voice, and the whole person. We look for a match between what research suggests is effective and what will really work for the individual faculty member. That's why consultations are tailored; they're driven by particular goals, a point in the curriculum, what students are capable of, and the personalities involved. First, a Center representative such as myself would want to know what's going on. What are their teaching and learning challenges? What have they observed? Are they looking to change parts of a course or try a new type of assignment? Are they seeking a different way of involving or interacting meaningfully with students? Faculty also seek us out when writing proposals for new education-related endeavors—often in conjunction with their research proposals. In those instances, we provide models of what has worked well, both here and elsewhere. We can also help find a good "fit" between their research and local schools.

***ENGenious*: Do you attend their classes?**

We won't come to a class unless the instructor has requested it. But we absolutely can visit and give feedback on specific things. We have to remember that during class the instructor is attending to a great deal of information: the big ideas of the course, the specific class plan, details like handwriting or operating technologies in the room, plus the students' faces and reactions—for larger courses, dozens of them. It can be really helpful to have another set of eyes in the classroom. For example, we can take a look at how students are taking notes or observe how they direct their attention and thinking, in ways that are difficult to detect from the front of the room. This service has been quite helpful for the faculty we've worked with. The students can be a little intimidated by Caltech faculty, who are pretty amazing people. Students may not always speak up with their questions, or the instructor may hear from the outliers in the class and might not know if they represent the median or the wings. We at the Center can also survey students neutrally and give faculty an action-oriented summary of how students are learning and what they perceive in class, which the instructor can put together with how they see the students performing on problem sets. Then we work on specific strategies to help all of our students (who are also pretty amazing) to learn more effectively.

Cassandra Horii (left) with Mitchel Aiken and Melissa Dabiri

***ENGenious:* What are some of the challenges you have faced, and how are you overcoming them?**

Horii: The demands on Caltech faculty are immense, especially in their early career years, and they do not have a lot of extra time. To overcome this, we try to be very practical and emphasize that we want teaching to enrich their experience, to be as rewarding and nourishing for them as possible. We bring small groups of faculty together around common interests like teaching in the core curriculum. A short-term commitment might be a seminar or a workshop on a particular topic. It is well defined in time and space, lasting only 45-60 minutes, and provides a quick, useful introduction to new teaching methods. We also record some seminars and make them available after the fact so that they have a lasting impact beyond the 30 or 40 people who attend. I've even given a ten-minute talk to a group of faculty and TAs on the "top three things about learning" that they needed to know in order to effectively redesign a course. We don't always have to spend a lot of time to have an impact.

***ENGenious:* How do you help Caltech graduate students in their teaching roles?**

Horii: The vast majority of our graduate students serve as TAs at some point, if not for several terms. In addition to recitations and labs, they hold office hours and have a lot of direct contact with undergraduate students. But they're often teaching for the first time, in front of very accomplished undergraduates who can be a bit intimidating—or at least perceived as such. One way we are helping is by partnering with the Graduate Studies Office to redesign the teaching orientation for graduate students to better serve their needs. On their way toward full-fledged academic and research careers, we also support graduate students in their leadership efforts on teaching by advising and co-sponsoring events with the Caltech Project for Effective Teaching (CPET), a grad student committee that plans seminars and programs. CPET paved the way for the Center—they started over five years ago and are still going strong. For graduate students who want a more in-depth experience, we've developed Engineering 110: Principles of University Teaching in STEM. By the end of this course, with some mentoring from the Center, they'll be well prepared to answer questions about the fundamentals of evidence-based teaching when they go on their faculty interviews and launch their careers.

ENGenious: **Do you also work with Caltech undergraduates?**

Horii: Yes, our undergraduate students are frequently teaching as well, so we do a separate orientation for them as TAs three times a year. We help them practice expanding on ideas that may be obvious to them in order for their audience to understand, and we address the unique concerns that arise when teaching one's peers. Our Center also works closely with the Academic and Research Committee (ARC) of the undergraduate student government—the Associated Students of the California Institute of Technology (ASCIT). With ARC, we've implemented new training for undergraduate Course Ombudspeople, who are house-based student liaisons to faculty teaching larger courses, and continue to collaborate with ARC on other new ideas. We're excited to work more closely with Student Affairs to offer more support to Caltech peer tutors as well.

ENGenious: **How is the Center different?**

Horii: Many research-intensive universities have centers for excellence in teaching and learning, some with 50 years of history in the field. The Caltech Center is unique because we don't limit our scope to higher education. We dedicate attention to effectively partnering with local K–12 schools and teachers beyond Caltech. For instance, Mitch Aiken, the Center's Associate Director for Educational Outreach, recently worked with a Caltech professor with a vision for working with local schools as part of a research program. The goal was to make sure that high-school and middle-school students have exposure to Caltech's cutting-edge science and engineering at the right time. The professor also recognized that graduate students in his lab needed to practice talking about their research: he didn't want a major research conference to be their first experience trying to explain fundamental concepts to a broad audience, so he wanted to get them involved. At the Center we get very excited about outreach, not just as a way to give back to the community but also as part of students' professional development and future careers, whether they are going into industry or into government labs. Scientists are increasingly public educators. One of our biggest hopes is that the Center's work not only improves teaching but makes teaching part of how Caltech students develop and prepare for their roles as public educators while at Caltech.

ENGenious: **Where do you see the Center in five years?**

Horii: There is a tremendous potential here, just because people are used to being skeptical and asking tough questions. When it comes to Caltech, we dial it way up. We're far more technical. We can move much faster. Our pace could be completely different from any other institution's. I'm convinced; I've watched it happen already. I would never have predicted what we could do in the space of that ten-minute talk on the "top three things about learning." The whole group—graduate and undergraduate TAs included—got it instantly, and were soon giving each other sophisticated feedback based on the talk.

In five years, I would love to see it as commonplace for faculty and students to exchange ideas about how they are learning and teaching their science, alongside their research, so that it's not a secret piece of our identity. Our educational mission doesn't take away from the important research that we're doing; it fosters a conversation that is more public and helpful to our people and our community.

I would encourage Caltech teachers to continue to bring their scientific questioning and skepticism to the table, to think with us at the Center about evidence that will be convincing to them and to their students, and not to worry that the mystery of good teaching will disappear when we talk about it and understand it. Like they do with their research, they can be both passionate and knowledgeable about teaching and it will just get even more magical. ENG

Cassandra V. Horii is Director of Teaching and Learning Programs at Caltech.

Visit teachlearn.caltech.edu.

The Franklin Thomas Laboratory of Engineering, the home of the Department of Mechanical and Civil Engineering as well as the office of the Chair of the Division of Engineering and Applied Science, is being upgraded to serve changing research and teaching needs. The renovated building will house state-of-the-art research and teaching laboratories that reflect the evolving focus of the department toward engineering a sustainable physical environment. The building will also include a new auditorium and will have an open layout that brings in natural light, integrates the building with the courtyard, and promotes collaboration. The architects, AC Martin, have incorporated many design features that reflect the innovative research that will be conducted within. The building will also recognize the generous support to the Institute of both the Gates Frontiers Fund, in memory of former Caltech trustee Charles Gates, and alumnus Jim Hall (BS '57) and his wife Sandy.

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