# Electrical Engineering

## Celebrating the Past Century and Pondering the Next

In celebration of the centennial of Electrical Engineering (EE) at Caltech, ENGenious sat down with the EE professorial faculty to learn more about them and their vision for the future. Three themes ran through all of our conversations: the opportunities that lie on the boundaries of disciplines; the key role played by mathematics and physics; and the impact made by students.

Our journey into Caltech EE started with the Executive Officer of the Electrical Engineering Department, Professor Babak Hassibi. When asked what makes Caltech EE unique, he replied that compared with other top schools, the Department is much smaller. "We can't cover every area in EE," he said, "so the emphasis has been to hire in strategic areas where we think the impact can be higher. We take a lot of care to ensure that the groups we have in these areas are world class and highly visible," he added. "The small size of the Department gives us more freedom to explore different things. At a bigger school, if I want to go outside my comfort zone and do something else, I'll likely be treading on someone else's toes. Here that doesn't happen, so the faculty can be a lot more flexible. And because the Department is small, there isn't much of a boundary between EE and other areas such as Computer Science (CS), Applied Physics, Applied Math, or Control and Dynamical Systems. In fact, in many cases, these Departments grew out of EE."

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These permeable boundaries are the key to Hassibi's vision for the future of EE. "The next century will be a lot more interdisciplinary, in the sense that much of the exciting stuff will happen at the boundary of the current disciplines," he said. Engineering schools are still structured on the basis of 19th century technology, where there was a clear division between mechanical engineering, electrical engineering, civil engineering, and such, Hassibi pointed out. "If we were to start universities and create disciplines from scratch today, I doubt we would do it in the same way." He sees the next century as one in which disciplines that have become highly specialized begin to talk with one another. "Caltech's students are already open to this mode of thinking," he said. "Every year, we have several undergraduates who double major in things that one would not have thought of in the past—like EE and biology, or EE and economics. I think in the 21st century there will be a lot of opportunities for people with this kind of interdisciplinary background."

Expanding on the key role played by students, he explained that the experience they get at a place like Caltech is different. "We pay attention to the student experience—and I don't think it is just lip service. Each EE faculty, on average, gets 7 or 8 undergraduate advisees, and this year one-fifth of all graduate applicants to Caltech applied to the EE program. So it's a very visible Department and the faculty interact with a large body of the Caltech students. The EE students here get a very solid and broad education." Hassibi went to Stanford for graduate school, where the EE graduate student body alone numbers between 600 and 700. When he was taking classes, the only students he met were other EE students. At Caltech, because it is smaller, there is a much greater mix of students who take the different courses. For example, Hassibi said, if there is a course on optimization for EE students to take, it is often taught by someone who is a non-EE faculty, and there will be students from EE, CS, Applied Math, and even Economics in the class. "So just the fact that students sit next to students with different backgrounds and

# Babak Hassibi

*Professor of Electrical Engineering and Executive Officer for Electrical Engineering, and Associate Director of Information Science and Technology*

> *"My original interest in physics was because it was mathematical, beautiful math that you could use to explain certain phenomena. I've now discovered that there is also beautiful math you can use to design systems and figure out how they work."*

different interests makes the student experience unique."

Asked how he came to the field of electrical engineering, Hassibi replied, "When I was in high school in Iran I wanted to do physics. If I had been able to leave the country immediately after high school and come to the States, that's probably what I would have studied. However, as I could not leave Iran, it seemed more prudent to pursue something I could make a living off, and electrical engineering seemed the right compromise. When I look at it now, I realize I didn't really know what EE was when I came out of high school. I had exposure to parts of physics such as electricity, and magnetism, but I didn't really know how they were used in electronic circuits or signal processing. Over the years, I have had the good fortune of having many outstanding professors who have helped shape my career, and have been able to cut out a niche in control, communication, and signal processing that I find very satisfying, both in terms of educating students and research-wise."

When asked to speak about his research, the conversation quickly turned to his love of mathematics.

# Yaser Abu-Mostafa

*Professor of Electrical Engineering and Computer Science*

> *"EE has become a very versatile discipline and the research culture makes it easy for us to investigate novel issues that are mathematically rich without worrying too much about how they relate to electricity."*

"We're an engineering department, so we care about solving problems, putting systems together, designing things, optimizing performance, and all that. Different people use different tools for that. The tools that my group uses are very mathematical—but they are tools, nonetheless—and actually do help in solving problems that otherwise cannot be solved. My original interest in physics was because it was mathematical, beautiful math that you could use to explain certain phenomena. I've now discovered that there is also beautiful math you can use to design systems and figure out how they work. One of the areas we research is communication over wireless networks without any infrastructure (ad hoc networks). It turns out that these networks are useful not just for communications; they can also sense, or even influence, the environment. As an example, think of a network of cars and stop lights with sensing and wireless capabilities. As your car approaches the intersection it sends a signal to the traffic light, "I am here, turn green," then, the traffic light responds, "Please wait, another car is in the intersection." There are infinite possibilities of how these sensing networks can change and improve our world."

Yaser S. Abu-Mostafa, Professor of Electrical Engineering and Computer Science, gave us more insight into the important role of mathematics in EE: "Electrical engineers have always been comfortable with advanced mathematics, and whenever a new engineering discipline arose that required mathematical sophistication, it found its home in electrical engineering even if it had little to do with electricity. As a result, EE has become a very versatile discipline and the research culture makes it easy for us to investigate novel issues that are mathematically rich without worrying too much about how they relate to electricity. The result over the decades is a vast body of knowledge that has a profound impact on society in a wider range of applications than most engineering disciplines."

The journey of Assistant Professor of Electrical Engineering and Computer Science Tracey Ho to EE also started with mathematics, but first she took a detour.

# Tracey Ho

*Assistant Professor of Electrical Engineering and Computer Science*

"I studied EE in college because I liked mathematics and the subject had interesting applications of fun math. After college I worked for a year-and-a-half in the Ministry of Transport in Singapore, but then decided I liked engineering more than writing policy papers and speeches, so I went back to graduate school. I was very happy to find a place as dynamic and exciting, and at the same time as welcoming and supportive, as Caltech."

Currently Ho's group is investigating reliable communication in diverse network scenarios, using analytical tools from information theory and networking to characterize fundamental communication limits, and using coding to approach those limits. She is interested in exploring applications in space missions communications and has had discussions on coding for wireless communications in spacecraft with colleagues at JPL. "I suppose there would be a certain vicarious thrill to have my work make it to outer space," she said.

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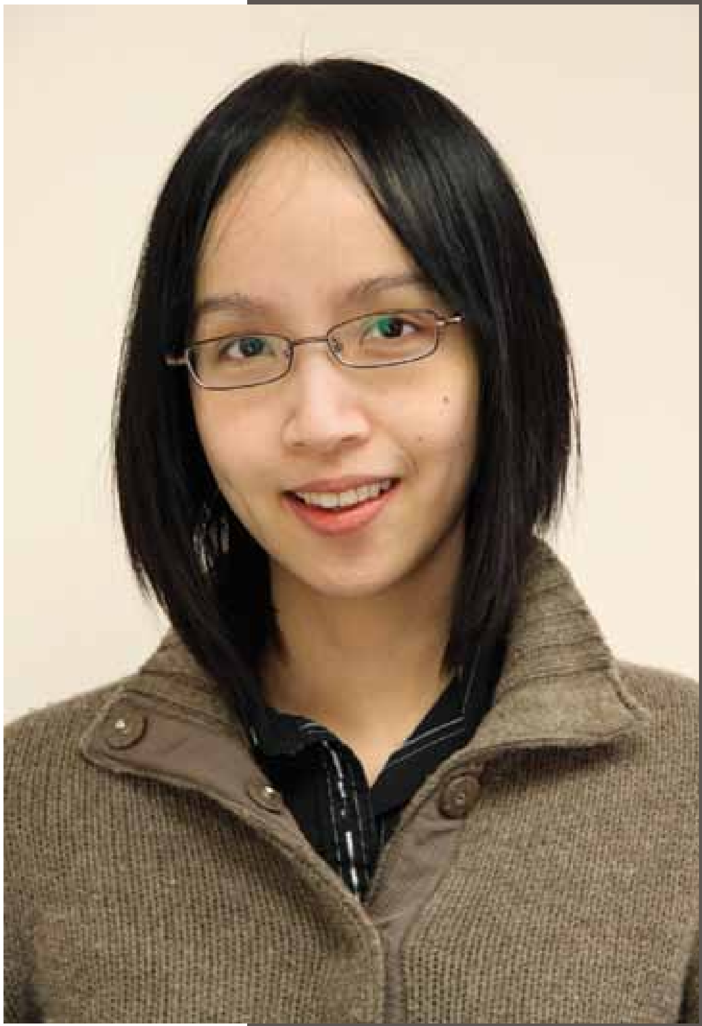
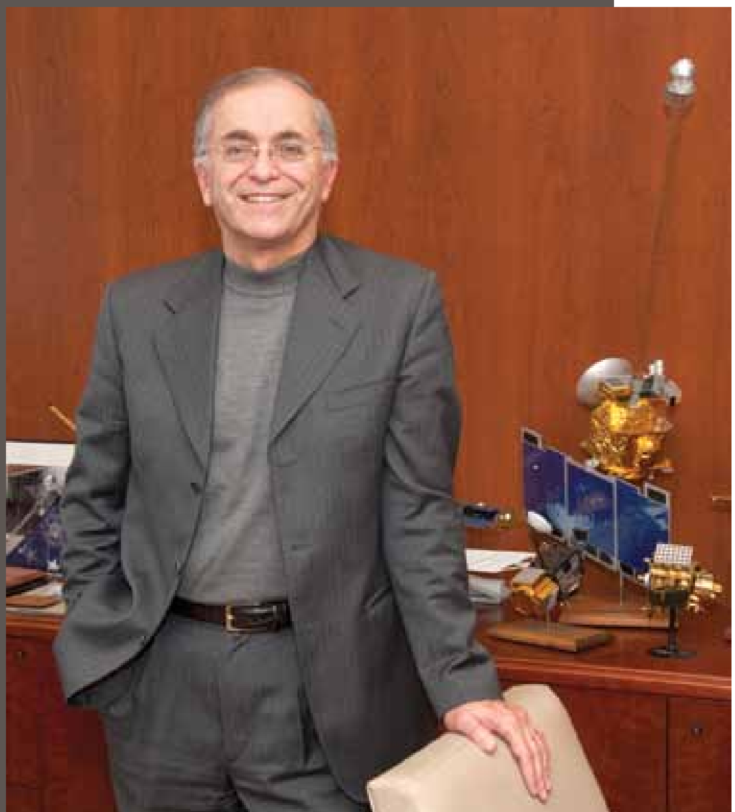


Ho's interaction with JPL follows a strong tradition of cooperation. According to Charles Elachi, Professor of Electrical Engineering and Planetary Science, Caltech Vice President, and Director of the Jet Propulsion Laboratory, "The EE Department can take particular pride in providing some of the key leadership at JPL, such as Bill Pickering, who is considered to be 'the mother of JPL.' Although Von Kármán was the original founder, JPL's missions to explore the solar system began during Pickering's tenure. In the last fifty years, we have gone from not knowing how to launch something into space to having twenty spacecraft exploring the solar system and monitoring almost every parameter of our planet to understand the changes that are happening to it. The things that Caltech and JPL have been able to accomplish in such a short time are amazing,



# Charles Elachi

*Caltech Vice President; Director of the Jet Propulsion Laboratory; Professor of Electrical Engineering and Planetary Science*

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and that is something that we can all take pride in.

Elachi then turned his thoughts to the next generation. "I think for young people, EE is a field that will have some very exciting developments in the future, because there will be a lot of innovation in very practical things that will improve our life and strengthen the economy, such as the use of remote sensing to monitor what's happening to our planet."

He added, "Tesla is becoming a cool person. Tesla did a lot of fundamental work in electrical engineering a hundred and some years ago but then he was not as highlighted in his innovation as Edison. But now it seems for the young people, Tesla is becoming cool—the electric cars are called the Tesla car. What is interesting about it is that it's now in the public media; a key electrical engineer is becoming a cool person. That's not very common. Young people are becoming more interested and they find electrical engineering to be a cool business to work in."

Continuing with the theme of inspiring the next generation, when we asked Gordon and Betty Moore Professor of Computation and Neural Systems and Electrical Engineering Jehoshua Bruck about magical moments in his career, the conversation quickly turned to students. "There are many magical moments related to watching students grow," he said. "Training, motivating, and inspiring the next generation is in some sense more important than the actual work we do right now, because they in turn will inspire the next generation and so on. I think the Caltech logo shows the most important thing we do: the two hands aren't holding the torch together—one hand is passing it to the other. It shows the passing down of the light of knowledge." Teaching and learning is not just about the mechanics of how to solve a problem," he added. "You want to deepen understanding."

Bruck's other passion is his research, which combines the design of distributed information systems and the theoretical study of biological circuits and systems. After graduating from Technion-Israel Institute of Technology, he worked for IBM for a few years in Israel before going to graduate school at Stanford. "During my time at IBM, I had my first research results," he recalled. "My wife came to pick me up and I told her that today I had found such a beautiful thing in my research that it's very likely I will never find something of that magnitude again in my whole career." Obviously, it has happened many times since then, he added, "But every day, I feel I've won the lottery because of the work we do here. We're having a lot of fun and yet for some strange reason they keep paying us."

We also spoke about good fortune with P.P. Vaidyanathan, Professor of Electrical Engineering. "The breakthrough that got me into the field of signal processing happened when, back home in India, there was a professor in my master's program who announced a lottery for a project in the application of microprocessors in biological signal processing, and I was lucky enough to get it. I thought this was great because he was the best professor and I wanted to work with him. That professor was a great man, but he didn't have any background in signal processing so I had to more or less learn it myself. In those days, there was only one book on signal processing in my building and I had to take an hour-long bus ride to the Indian Statistical Institute to get hold of other books on the subject, so life was hard in those days."

Before diving into his research Professor Vaidyanathan gave us an overview of the EE Department. "There are the physical layer faculty, people who build things and make them work, and there are people like me who do a lot of theoretical work bordering on information science." These days, he said, the Department has become very information science-oriented, and information sciences itself is very mathematical. This trend will continue; information processing and mathematics are required in digital communications, radar signal processing, image and speech processing, and even in molecular biology. "As

## Jehoshua (Shuki) Bruck

*Gordon and Betty Moore Professor of Computation and Neural Systems and Electrical Engineering*

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a theoretician doing work on computer signal processing, I could find a lot of interesting problems in DNA," he said. "For example, how do you computationally predict the location of a gene? Or a non-coding gene? These questions are very interesting from a signal processor's viewpoint."

Another EE faculty member who is exploring the boundaries of EE and biology is Ali Hajimiri, Thomas G. Myers Professor of Electrical Engineering. "There are tremendous opportunities on the boundary between EE and bioengineering," he said. "We can make sophisticated systems such as integrated circuits that can have a significant, tangible impact on people's lives. It's very important for me to see that."

One of Hajimiri's research areas is self-healing systems and circuits. Biological systems, he explained, have a lot of resilience built into them. For example, if we cut our hand, we don't die, we heal. His group is trying to engineer systems that also heal if there is a failure. "The self-healing is done in multiple layers: at the circuit, at the device level, and at the system level, and all of these things have to work together," he explained.

Hajimiri described the EE Department as "a collection of centers of excellence that allow faculty to work closely with each other, as evidenced by the kind of creative things and tangible results that have come out." He then sent a message to the alumni. "Caltech can only remain as influential as it is by maintaining a very high level of quality. We would like alumni to be involved in our activities, contribute to them, talk to us, give us feedback, and provide an environment where we can exchange ideas and thoughts and receive the benefit of their experience."

This invitation to alumni to get involved was shared by many of the EE faculty, including Amnon Yariv, Martin and Eileen Summerfield Professor of Applied Physics and Professor of Electrical Engineering. "The message I would like to transmit to our alumni is that in spite of our great

## P.P. Vaidyanathan

*Professor of Electrical Engineering*

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achievements in EE we are a very vulnerable organism, chiefly because of our small size. Our success depends critically on attracting the best possible faculty and graduate students. As a matter of fact, without top students the best faculty will not come here, and vice versa. If I had to limit myself to one area where our alumni and friends can be of assistance, it would be to help us attract, by personal involvement and financial help, the best graduate students in the world."

Its open, welcoming, and interdisciplinary nature is one of the unique features of the EE Department, Yariv said. "The ability to have students in my group from other departments, especially Physics, enabled me to follow research directions that were not traditionally EE." He finds it exciting to see graduate students pushing at and even crossing the boundaries of various fields. "Maybe the single most exciting moment in my career occurred back around 1970, when after two years of trying, one of my first graduate students, David Hall, succeeded in demonstrating the possibility of guiding and modulating light in a semiconductor p-n junction. This helped launch the field of optoelectronics and much of our own subsequent work." Currently, the Amnon group's research aims at developing "the new technologies that will be mandated by the seemingly endless appetite for optical bandwidth." Specifically, they are working at extending, to the field of laser optics, some key ideas that form the foundation of the microwaves and the radio frequencies fields.

Axel Scherer, Bernard A. Neches Professor of Electrical Engineering, Applied Physics, and Physics, also emphasized the key role played by students. "The

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*Thomas G. Myers Professor of Electrical Engineering*

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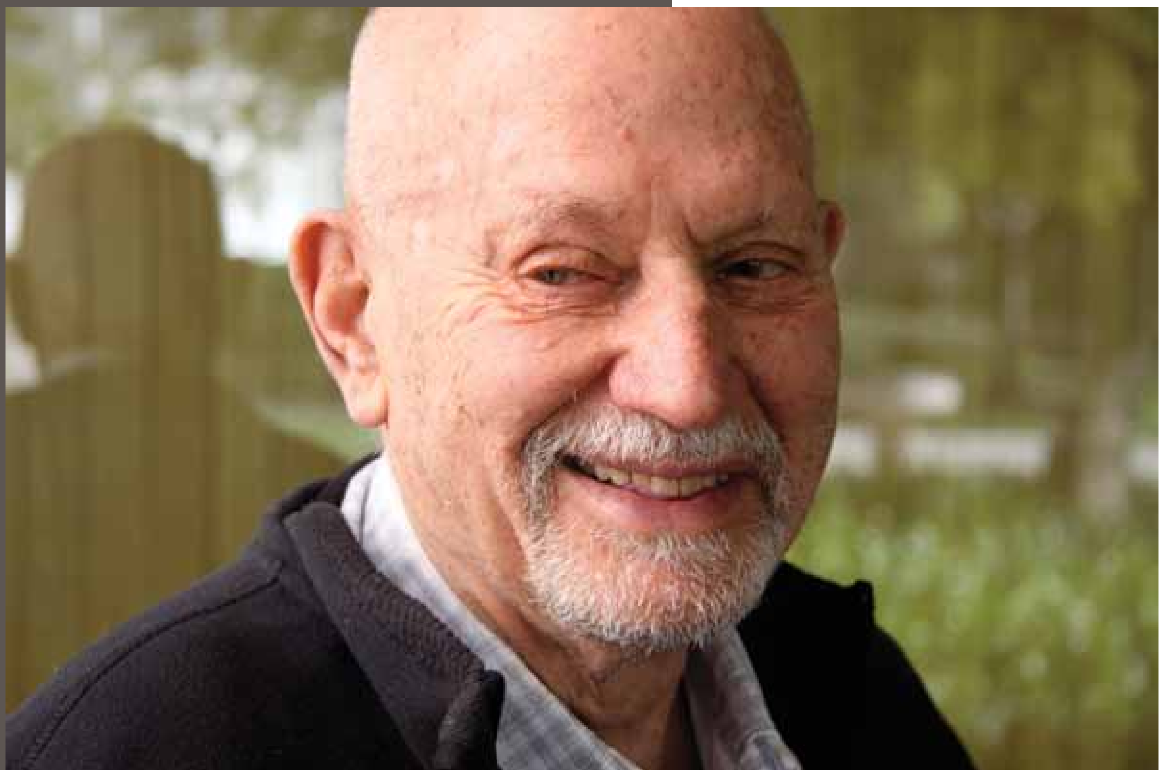

# Amnon Yariv

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students are what makes EE unique. They are the people who drive the research in my group and the energy that makes things work. This generation of students will learn the vocabulary, not only of electrical engineering, but of biology and other sciences that apply to the work. For the past 18 years I have taught a freshman class co-listed in Applied Physics and EE that encourages people to make real devices early on in their undergraduate career. When I started teaching it, there were mainly electrical engineering and applied physics students. But now geologists, biologists, and astronomers take this class because they're interested in how small things get made. I tell my students that chemistry, physics, biology, and engineering all come together at the smallest scale, and we're headed into a world where the traditional boundaries are shrinking. The tools of electrical engineering are being adopted by many other disciplines and it's a good sign."

Asked about his own group's research, Scherer said, "My students and I are building systems that can be used to increase the capabilities of medical care without increasing the cost." They recently developed an inexpensive method of identifying whether pathogens are viruses or bacteria, so that the correct treatment—antibiotics or not—can be administered promptly, at a cost of about $100 instead of the $50,000 it costs now. An interesting byproduct is that the process is also more efficient; the results of the analysis are available within minutes rather than hours. "That's a big difference," Scherer said, "because you can tell the patient the answer within a couple of minutes, and they don't have to come back later."

To further investigate how the use of technology is unifying efforts across disciplines we spoke with Yu-Chong Tai, Professor of Electrical Engineering and Mechanical Engineering. "About 10 years ago, it struck me that bio implants were really in the stone age. I decided that this offered me a wonderful opportunity to keep busy for the rest of my career. Think about shrinking a cell phone down to the size of a rice grain, then adding sensors, wireless communications, and other functions, and putting it in the

## Axel Scherer

*Bernard A. Neches Professor of Electrical Engineering, Applied Physics, and Physics; Co-Director, Kavli Nanoscience Institute*

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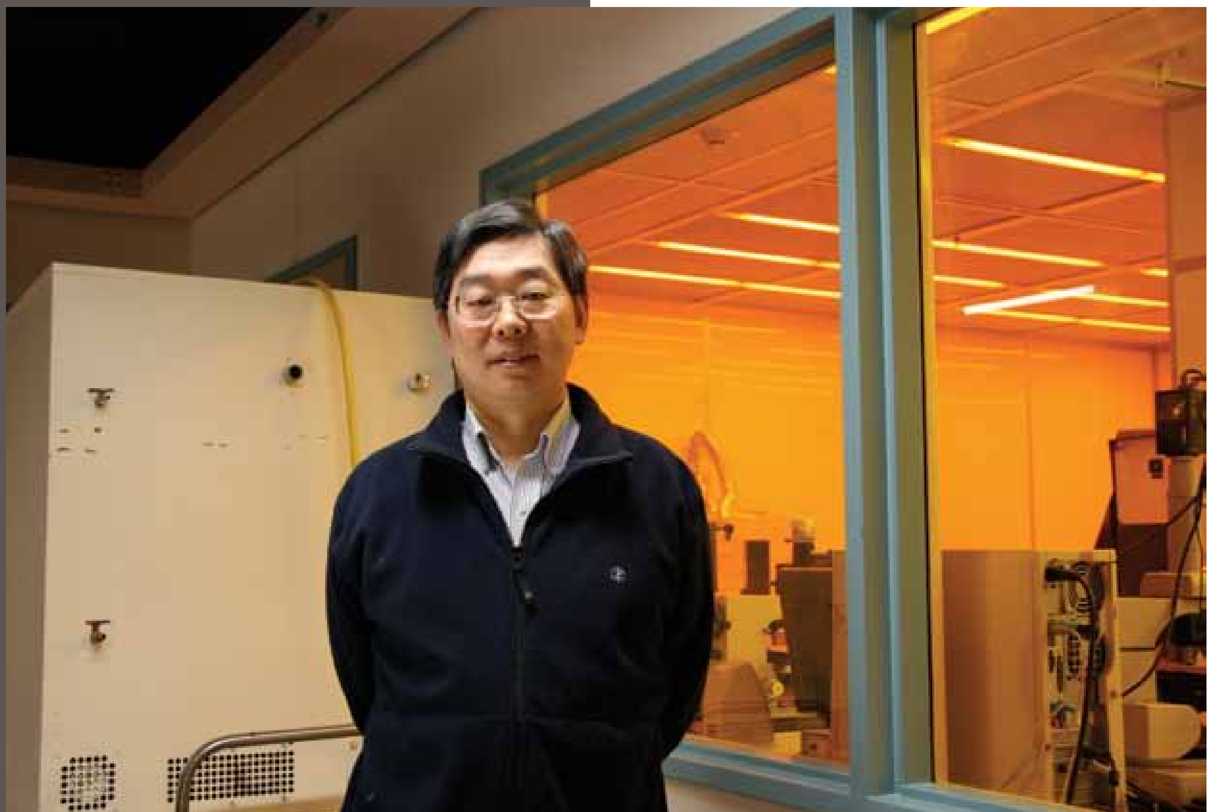

# Yu-Chong Tai

*Professor of Electrical Engineering and Mechanical Engineering*

> "*Think about shrinking a cell phone down to the size of a rice grain, then adding sensors, wireless communications, and other functions, and putting it in the human body.*"

human body. If I can live 50 years longer, I think I will see this realized. Biology has done a great job of providing clues of where we need to go, but now we need technological breakthroughs."

Tai and colleagues, including Azita Emami-Neyestanak, Assistant Professor of Electrical Engineering, are working on retinal implants. Emami-Neyestanak's group, which works on microelectronics, is currently building very low power micro-chips to implant inside the eye of people who have lost their retina, but still have functioning neurons. They will then wirelessly send the information about the image to the implant, which will in turn stimulate the neurons in the eye to transmit the image to the brain's visual cortex."

In addition to microelectronics, Emami-Neyestanak is passionate about bringing more women into engineering and conveying to them that engineering is a field that has a lot of human components to it. Some female students think that electrical engineering is about sitting behind a computer and being isolated from the world, but actually, she said, engineering in general and electrical engineering specifically is a very interactive area of research that is very rewarding. "Caltech is a very good environment for female students," she added, "and the question of whether you are a man or a woman never comes up. Everyone just does what they are passionate about."

Emami-Neyestanak's path to EE started in Iran. "I went to a girls only high school, which was for exceptionally talented students. We were the only school that had the freedom to do things differently. I got very interested in hardware design, and that's how I ended up coming to the field of EE. For me it was the best choice, because I like physics and math, but at the same time I liked to build things that can eventually be used to change the world."

# Azita Emami-Neyestanak

*Assistant Professor of Electrical Engineering*

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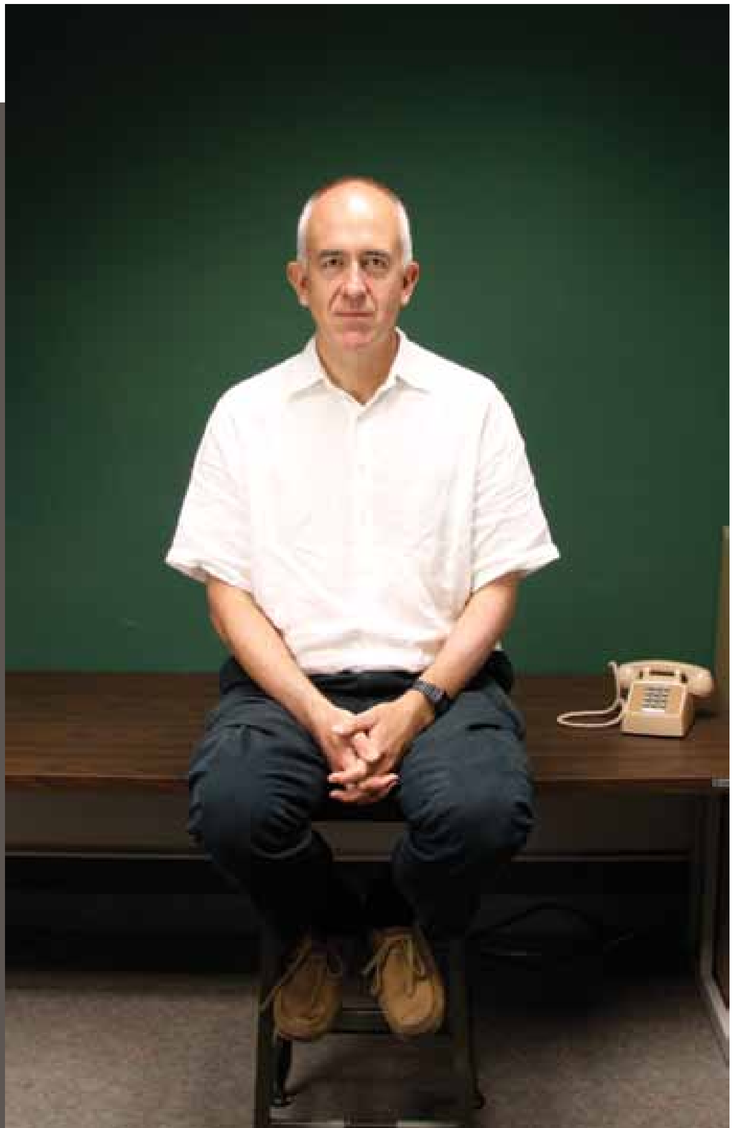

# Pietro Perona

*Allen E. Puckett Professor of Electrical Engineering*

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Several of the EE faculty commented on how the impact of the Department is out of proportion relative to its size. Pietro Perona, Allen E. Puckett Professor of Electrical Engineering, explained that "the quality of both faculty and students is incredible, which means that our work is, on average, the most innovative and useful. The quality of interpersonal relationships is also exceptional. We seem to be very lucky in that we have a harmonious group that gets along really well, with respect for each other. And we are exceptionally good at what we do."

Perona has also joined those with a growing interest in biology, and is researching the application of machine vision to measuring the behavior of laboratory animals. "This is very exciting because it allows me to explore what 'behavior' is," he said, "and it is enabling unprecedented experiments in genetics and in ethology." He is also studying how humans allocate their visual resources to optimize their performance in a given task. "It appears that humans are surprisingly optimal."

Another faculty member who works on the boundary of disciplines is Changhuei Yang, Associate Professor of Electrical Engineering and Bioengineering. On the subject of crossing boundaries he explained, "Caltech faculty can freely expand to different areas and that may not be as easy to do in bigger schools in which you can't really expand too far before knocking into somebody else's research area. Another good thing about Caltech EE and Caltech in general is that it's relatively easy for a new professor to come in and try to explore different research areas."

Yang tries to focus his group on developing practical technologies that can significantly impact medicine. One area is doing biochemical assessment on tissues without any invasive chemical or physical process. Human tissue is opaque and scatters light very strongly. What we have found is that this scattering process, even though it looks random, is actually deterministic in nature. This means that if you take all those scattered lights and time reverse them you can actually force them to retrace their path through the tissue and recover back what was originally sent into the tissue. You don't get the complete set of information back, but you get a pretty good subset of it." This work can potentially lead to deep tissue optical imaging that will give biochemical information, something that ultrasound or X-rays cannot do. For example, he said, cancer cells might express biochemicals before they become a tumor, and if we could image that, it would be very useful.

Whether it is cancer, devices, theory, or systems, EE faculty take delight in the fact that they can work on whatever they are passionate about. When asked what he would like to work on, David Rutledge, Kiyo and Eiko Tomiyasu Professor of Electrical Engineering, replied, "I have always worked on what I wanted to work on. I have only one project now, assessing future fossil-fuel supplies and the possible climate impacts. It has everything: geology, engineering, atmospheric science, politics, and scandal."

The path Professor Rutledge took to EE also involved mathematics, but in a slightly different way. "I was an undergraduate major in mathematics at a liberal arts college, and I had a summer job at Rensselaer Polytechnic Institute (RPI). The main thing the job taught me was that I was not going to make a living at mathematics. However, my roommate was in EE, and I became interested in his circuits textbooks."

Professor of Electrical Engineering Michelle Effros's path to electrical engineering was anything but direct. "If asked, as a high school senior or even a college freshman, to list my top 20 or 30 potential majors, engineering would not have appeared on the list," she said. "I didn't know what engineers did. I didn't have any friends or relatives in engineering, and I recall quite distinctly that engineering didn't 'sound good,' though I knew almost nothing about it. My first engineering class at Stanford was called 'visual thinking', and it was taught in the Mechanical Engineering Department. It was one of those classes where you do all kinds of crazy projects—building devices out of a short list of allowed supplies to solve very particular problems, like popping a 3-foot-diameter balloon in the middle of a pond without the use of projectiles.

## Changhuei Yang

*Associate Professor of Electrical Engineering and Bioengineering*

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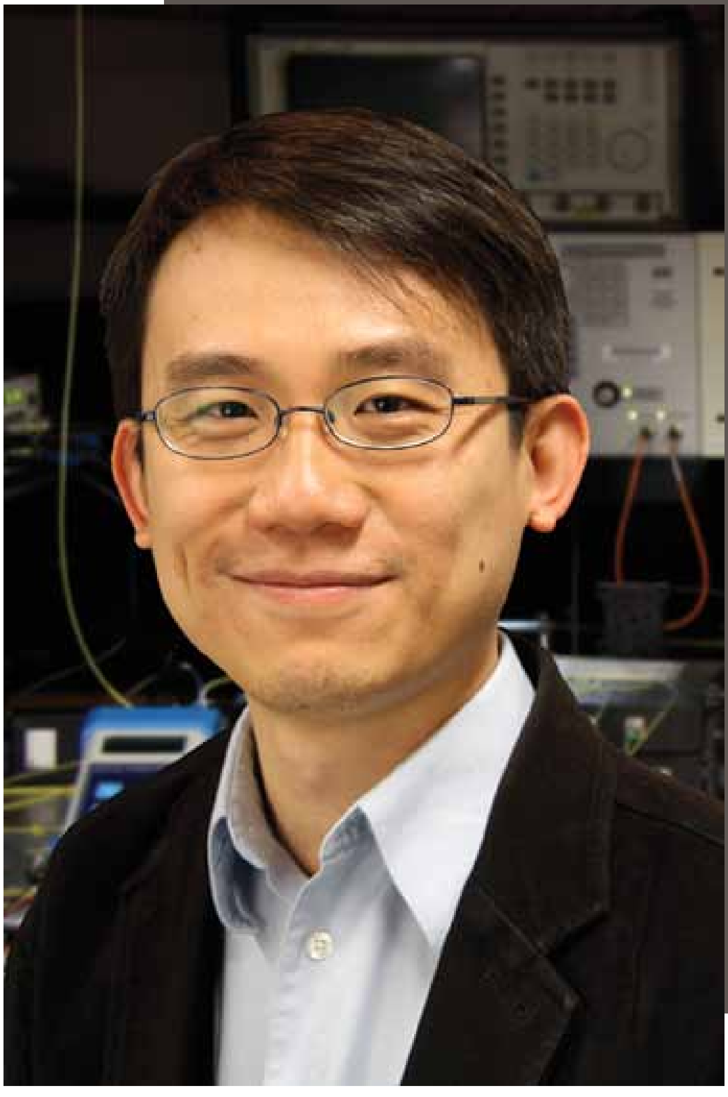

# David Rutledge

*Kiyo and Eiko Tomiyasu*
*Professor of Electrical Engineering*

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I enjoyed it, so that got me thinking about engineering."

Now that she is on the path of EE, Effros finds that "Information theory is full of magic, with results that seem almost impossible yet are true and can be proven using only a few simple tools. Some of my favorite moments at work are when I am giving a talk or teaching a class and I can feel the concentration and intensity in the room. I also love the moments when you understand something for the first time. In an instant, something difficult that you have fought with and struggled against becomes clear, almost like a part snapping into place. Somehow, it's surprising every time."

Effros and her group study the theoretical limits of communication networks. "Communication networks play such a central role in our society. These days everything from entertainment to health services, government operations, and the economy relies, in critical ways, on our cell phone networks and the Internet," Effros noted. "It's surprising that almost nothing is known about how much information these networks can carry." She is building mathematical and computational tools for bounding network capacities. And she explained, "These tools are important because they will allow us to compare competing network designs and build better networks in the future."

Steven H. Low, Professor of Computer Science and Electrical Engineering, also puts mathematical tools to work in the study of network systems. As he explained, "There seems to be a very strong and coherent underlying set of mathematical tools and mathematical perspectives that apply to a whole set of applications whether it is social networks, the Internet, or power networks. These associated sets of tools cut across Applied Math, Computer Science, and EE, so we're trying to pull together the underlying core that will support all the different applications that are emerging."

Low has pioneered development of mathematical theory of Internet congestion control that brings rigor and elegance to the Internet research and impacts the practice

## Michelle Effros

*Professor of Electrical Engineering*

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# Steven Low

*Professor of Computer Science and Electrical Engineering*

*"In the next couple decades the electricity network will go through the same kind of architectural transformation that the telephone network has gone through in the last fifteen years. I'm trying to understand the theories and algorithms that Caltech can design to facilitate and guide this transformation."*

of congestion control. His team has helped break world records of data transfers and the technology based on his research is powering the world's second largest content distribution network. Low predicts that "in the next couple decades the electricity network will go through the same kind of architectural transformation that the telephone network has gone through in the last fifteen years. I'm trying to develop theories and algorithms that can help us understand and guide this transformation. This transformation is going to dramatically change how power is generated, transmitted, and consumed, and we want to understand not only the engineering of power networks and how they will evolve in the future but also the economic and even regulatory structures that go with it. A new thinking will be needed to really exploit emerging trends, and also to best capture the opportunities and manage the risks. I think this is really exciting."

Another EE faculty member who is working on developing a new way of thinking is John C. Doyle, John G. Braun Professor of Control and Dynamical Systems, Electrical Engineering, and Bioengineering. "I'm not interested in how we build functional systems. That's easy. How do we build systems that are robust, sustainable, and don't do unexpected things."

Asked to reflect on the EE centennial celebration, Doyle commented that the boundaries that are being celebrated are a hundred years old and a little out of date. "But we don't know how to redraw those boundaries yet," he said. "I'm working on the Internet, smart grid, microbes, intensive care units, wildfire, earthquakes, which have theoretical foundations in physics, but are so complex that physicists have a hard time with them. On the one hand I'm eager to try to describe it but at the same time what I end up saying doesn't hold together very well. It's just a bunch of seemingly disconnected things. Not as disconnected as it sounds, but the connections are hard to explain. I'd love to continue to try."

When we asked Doyle to predict the theme for the next century of EE, he said it would probably be massive extinction. "If we avoid massive extinction, it will be because of less technology. We're already committed to such heavy use of technology that I don't see how we can retreat from it, but it needs to be much lighter on the environment. The twentieth century gave us the capacity to build anything we can imagine, but it didn't give us the capacity to make it sustainable and robust. Can the twenty-first century be the century of sustainability and robustness or will it be the century of extinction?" ENG

*Visit:* *http://ee.caltech.edu/people*

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