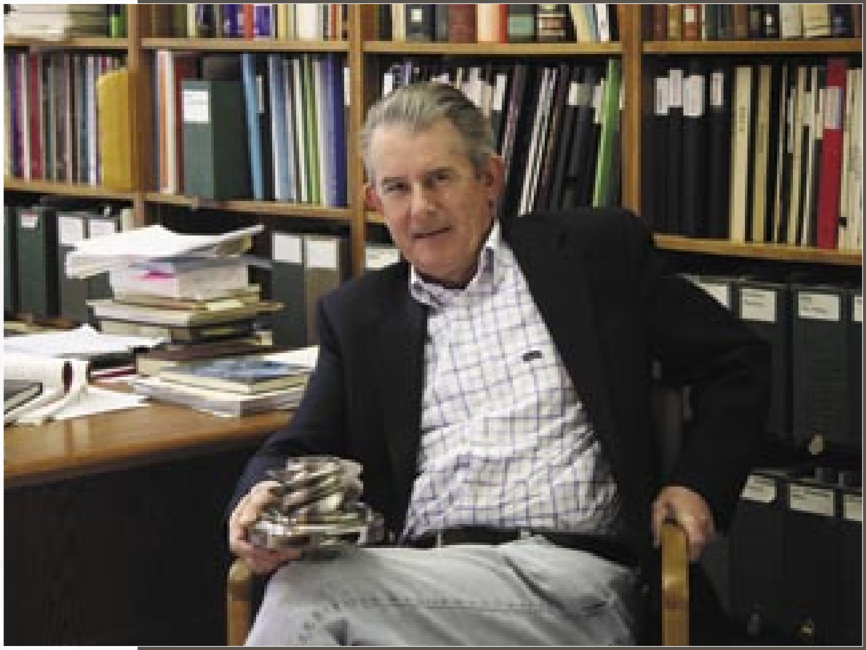
Mechanical Engi

Celebrating 100 Years of Forward Motion in a Constantly Changing Landscape



"We stretch the limits of what is called mechanical engineering," Tim Colonius, Professor of Mechanical Engineering, remarks simply. To see what he means, just consider a sampling of eight research projects by current mechanical engineering faculty: artificial hearts for infants; creating and simulating laboratory earthquakes; active ferroelectric materials; algorithms to process neural information; nanofabrication of high-performance electrodes; modeling of big debris flows; the response of structures to accidental explosions; the creation of genetic algorithms for solving design problems.

This breadth is anchored by the deep understanding and teaching of the fundamentals: thermal sciences, fluid and solid mechanics, mechanical systems, robotics, control, and engineering design. The professors who are capable of this stretch are a special breed, as you will see below in this profile of the current faculty members of the Mechanical Engineering Option at Caltech. We tried to capture the whole gestalt of the group, mostly in their own words. Being engineers, most can tell you the exact day they started at Caltech. For **Joel Burdick** (Professor of Mechanical Engineering and Bioengineering), it was May 3, 1988.

"I was fresh out of grad school. I finished my PhD, took six weeks off to tour the east coast, and then flew out here and started work. I've been on the third floor of Thomas the whole time. My wife says I'm a fossil in training." Burdick's work stretches between several fields. "I think Caltech is a great research environment if you like to do interdisciplinary research, and that's where I like to work: on the robotics side between mechanical engineering,

Chris Brennen

Richard L. and Dorothy M. Hayman Professor of Mechanical Engineering

My grandfather on my mother's side was a mechanical engineer. In fact he was the head of the Belfast College of Technology. But he died five years before I was born. I was always interested in mechanical things. In the small Irish village where I grew up there was a real paucity of mechanical things to play with, especially in the aftermath of the Second World War. But still, I took apart my father's power lawn mower, the only one in the village, but couldn't put it back together. I loved doing things with my hands, and I loved practical physics. I was fortunate that I had teachers at the little Irish high school both in math and in physics that encouraged me and inspired me. And I was very fortunate—because of these excellent teachers, I managed to win a scholarship to go to Oxford University. That was a culture shock of the first magnitude. Somehow I survived and indeed I enjoyed it. I did all my degrees at Oxford. Then I went to work for the British government; I did a postdoc in a lab near London. While I was there, Caltech Professor Ted Wu came to visit; we got into conversation and had a great talk. He seemed very interested in what I was doing. A few weeks later he wrote to me and asked me to come here on a one-year postdoc, and that's what happened. I came here on a one-year postdoc—and that was 38 years ago. Chance has a lot to do with life sometimes.

neering

Kaushik Bhattacharya
Professor of Mechanics and Materials Science

I interviewed here when I was a student. The interview was spread out over three days; you meet great people and you have great conversations. What really struck me was that it was a place where people were very comfortable with themselves. There is not an artificial intensity. That struck me then, and that's what strikes me even now. It's a beautiful campus, great people, and people are very comfortable with who they are. It's not a pressure-cooker—people know you are doing some interesting things and people ask: can we help you? I think that's what's special about this place. Small enough to be personal, informal. You often think of elite places being very intense, high-pressure. Caltech combines very high standards with a very friendly atmosphere; that's what strikes me even today about Caltech.

electrical engineering, and computer science; and in more recent years on the bioengineering side between mechanical engineering, computation and neural systems, and biology. I got started by trying to bring mechanical tools and intellectual tools from robotics to apply to neuroscience, particularly clinical neuroscience." His work in this area, in collaboration with people like Richard Anderson (James G. Boswell Professor of Neuroscience) and Yu-Chong Tai (Professor of Electrical Engineering and Mechanical Engineering), aims to restore capability lost through neural deficits by connecting devices that directly interface with neural signals from the brain to devices to enable function such as arm movement. "We work primarily on animal models, but some of the work is moving towards humans. I am really a tool builder—robotic electrodes, algorithms to process neural data—and while I don't plan to be a neuroscientist, I find myself going deeper into this area and bringing tools to help the biologists understand the underlying neural-biological questions." One of Burdick's strengths is on the mathematical, algorithmic side. "The robotics work has moved from mechanical design and analysis to algorithms and software, because that is where the interesting work is. Everything is run by computers now, and networks are everywhere—and so incorporating how computing and information and networking fits into mechanical systems in increasingly a greater part of what we do."

Richard Murray (BS '85), Thomas E. and Doris Everhart Professor of Control and Dynamical Systems, is an ME professor deeply interested in the ways information and networking are integrated into mechanical—and biological—systems. A sabbatical in the late '90s at United Technologies Research Center initially encouraged his interest in 'smart products.' The idea was to embed information in mechanical systems. "When I came back to Caltech, I got more interested in information systems, and so the next six years or so were spent looking at cooperative control of multi-vehicle systems, for instance, but looking less at the *vehicle*, and more at the *cooperation*, which is more of an information problem. How do they talk to each other? That then led to more interaction with people in computer science, Mani Chandy, Jason Hickey, as examples, and I started to think about the role of formal methods in computer science, improving cooperative behavior, and so on."

Murray became Division Chair in 2000, so new research was effectively put on hold. "I decided not to get involved in biology, which was obviously extremely exciting; I didn't have time. John Doyle and Rob Phillips both used to say, 'You got to get interested in this stuff—communication, feedback, it's all here.' And I said no, no, no, no, no; but then on more or less the first day of September 2005, which was Day One of not being Division Chair, I said: Yes!" This "yes" has led to Murray to agree to teach a "Physical Biology Boot Camp" with Rob Phillips, Professor of Applied Physics and Mechanical Engineering, in June, 2007. "The whole reason to teach it is because I don't yet know enough to know what the right research problems are. And as Rob is fond of saying, one way to really understand something is to dive in and start teaching it." Murray is exploring biological systems at the level of the ecosystem, the organism, and the cell. Where is the mechanical engineering in all this organic stuff? "The organism and the cell are fundamentally machines. They take in energy in some form or another; they convert that energy into motion; they process information that controls what the machine does; and that information process is part of the machine. There are very few machines anymore that are purely what we might think of as mechanical. They are all combinations of mechanical, electrical, informational, and even biological. So that's the direction I want to go."

Murray is also still very involved in autonomy work as leader of Team Caltech. The Team is fielding a vehicle in the DARPA 2007 Urban Challenge, an autonomous vehicle competition that will take place on November 3, 2007. The latest milestone occurred on March 18: the vehicle demonstrated the ability to drive through intersections, detect an obstacle blocking a lane, and plan and execute a U-turn.

Tim Colonius, Professor of Mechanical Engineering, works in computational fluid dynamics—simulating and predicting complex fluid flow on large computer clusters. He and his group develop algorithms and use them to

Ares Rosakis

Theodore von Kármán Professor of Aeronautics and Mechanical Engineering
Director, Graduate Aeronautical Laboratories (GALCIT)

Interactions with people like Erik Antonsson have always been very rewarding—we have been active in things that have to do with space science due to our respective roles—mine as Director of GALCIT, and his as (former) Chief Technologist of JPL. Of course I also work closely with the other solids professors especially with Ravi with whom I share laboratory facilities. One of the most exciting parts of my current research is doing laboratory seismology, and in this I work very closely with Nadia Lapusta. Since her arrival in 2004, we have already shared one student and we are in the process of getting another to work with us on these earthquake problems. The students are of very high caliber; our new student will actually be carrying out both experiments, from my side, and theory and numerics from Nadia's side.

study the physics of unsteady flows, including turbulence, aeroacoustics, instabilities, and multiphase flows. One area he is particularly excited about is flow control—adding a brain to a fluid flow. "If you want to control the dynamics of a fluid, the turbulent or unsteady motion, you can use sensors, actuators, and a controller to reach flow states that you could not realize in the natural flow." This work has many applications, particularly in aerodynamics—examples including reattaching separated flows on aircraft wings, reducing jet noise, and eliminating the 'whistle' that occurs when flow passes over cavities in an aerodynamic surface.

Colonius derives much enjoyment from working with students. "The quality of the students we get is phenomenal. We have access to the very best students and it makes it so fun to work here. A lot of them take the research to places where you couldn't have taken it, or you didn't think to take it and so it pushes the boundaries of what you know and what you think about." However, for Colonius the real draw is simply the work itself. "As much as I love working with students, I love the luxury of just working on a problem, writing some code and getting results. The nuts and bolts of research. If I can carve out time in the day to do that, it's a happy day."

Nadia Lapusta

Assistant Professor of Mechanical Engineering and Geophysics

In Mechanical Engineering, as in the rest of Caltech, you have this amazing concentration of talented people, both in terms of faculty and also students and postdoctoral researchers. And when you talk to people here, everyone is so excited about their research—and not only are they doing things differently, they are doing something interesting. No matter whom you talk to, you come away with the feeling that if you were not going to continue in your own field, it would be so great to do what they are doing. That's what makes it so successful.

Professor of Mechanical Engineering **Melany Hunt**, currently serving as the Executive Officer for Mechanical Engineering, is one of the professors who also recalls the exact day she started at Caltech: February 1, 1988. "I do a lot of experimental work developing ways to compute large-scale flows—modeling big debris flows or landslide flows. We are looking at liquid flows with lots of particles. These are very complex flows and so we do a lot of experiments trying to understand how you can simplify the particle interactions in a way that would be useful for modeling." Hunt delivered a Watson Lecture last January on the sounds that emanate from sand dunes: low-pitched droning that accompanies the avalanching of sand down the leeward face of a large dune. "People at Caltech have thought about this for years and years. Ron Scott [Dotty and Dick Hayman Professor of Engineering, Emeritus], who passed away in 2005, was the one that got us first interested in it. We've made almost 30 trips out to the dunes and we've gotten better every time in terms of what we are doing and what we are measuring." The internal structures of booming dunes tend to sustain and amplify certain notes, acting like the body of a well-crafted musical instrument. These structures have been computer simulated, and the model's behavior is consistent with years of field observations using seismic refraction, frequency measurements, and subsurface soil sampling. You can compare the music of these booming dunes with the sound of a cello. "In a cello, the musician bows the strings, and the sound is amplified through vibrations of the cello and the enclosed air. In the dune, we excite the system by avalanching the sand on the upper surface, and sound is amplified in a dry, loose upper layer of sand."

Another researcher in complex flows is **John Brady**, Chevron Professor of Chemical Engineering and Professor of Mechanical Engineering. "The research that I do is really in the area of fluid mechanics and transport processes, which has a lot of connections with people in EAS." His work in complex flows extends to electro-rheological 'smart fluids,' that is, fluids which, by an application of an external field, electrical or magnetic, change from a fluid to a solid in milliseconds, reversibly. "The electric field interacts with the particles that are in solution and causes the particles to form chains and solidify, but you can remove the field and the particles all wander off again." He has also been exploring lately 'shear thickening fluids.' "The faster you try and flow them, the stiffer and more resistant to flow they become. Most fluids do not behave this way. Take water: no matter how fast you go, it has the same proportional resistance to the speed. Cornstarch and water makes a nice shear thickening fluid. You can walk on cornstarch. People have made bulletproof vests out of shear thickening fluids. Basically you can take a Kevlar vest with many, many less layers of Kevlar and dip it into a mixture of cornstarch and water (it's a little more complicated than that) and get the same stopping power. The result of that is that the bullet proof vest is now flexible. It's more like a shirt."

The newest assistant professor in Mechanical Engineering is **Nadia Lapusta**. She arrived in late 2002. "It's a wonderful place. It's a very unique place in the sense that it is much smaller than what you would expect based on

Tim Colonius

Professor of Mechanical Engineering

At the end of the day, engineering is about making tools to solve real-world problems. So research in Mechanical Engineering is either research into the tools that are going to be used to create things in the future or research into the things you are going to build. We mechanical engineers are very much in demand: we have a skill set that is very much in demand. Collaborators from across campus find us, and we in turn have intentionally been very broad in our focus. For these reasons we have been very successful with lots of different activities at Caltech.

the impact it makes. In ME, as in the rest of Caltech, you have this amazing concentration of talented people, both in terms of faculty and also students and postdoctoral researchers. And the research is very multidisciplinary. My primary interest is the mechanics of solids but I am applying that mostly to earthquake processes, their physics and modeling. So I have a joint appointment with GPS [the Division of Geological and Planetary Sciences] and my students come from ME, Aeronautics, and Geophysics."

Lapusta is interested broadly in friction laws, fracture, and earthquake mechanics. "Earthquakes and earth movements are very interesting phenomena. A whole variety of behaviors is possible. For example, if two plates slide slowly, the frictional heat produced has time to dissipate. But imagine what happens when they slide really fast: you deposit heat where you slide. The solid materials then heat up, and at certain depths, there is melting—and that of course changes the behavior. When the earthquake stops, the material hardens producing something like a glass. Some people think that those melts should be preserved—they have found some, but not enough to account for all the heat that should have been generated. So there are other theories being proposed, many ideas. We try to formulate laws based on theories, and then test them in our models. For example, Yi Liu, a PhD student in ME, works with me on developing computational methods that would allow accurate simulations of earthquake cycles with different laws applied on the sliding interface or fault. The results of simulations can be compared to seismic and geodetic observations. I also collaborate with Professor Ares Rosakis on modeling high-speed frictional and fracture experiments done by our joint student, Xiao Lu. We use modeling to devise new experiments."

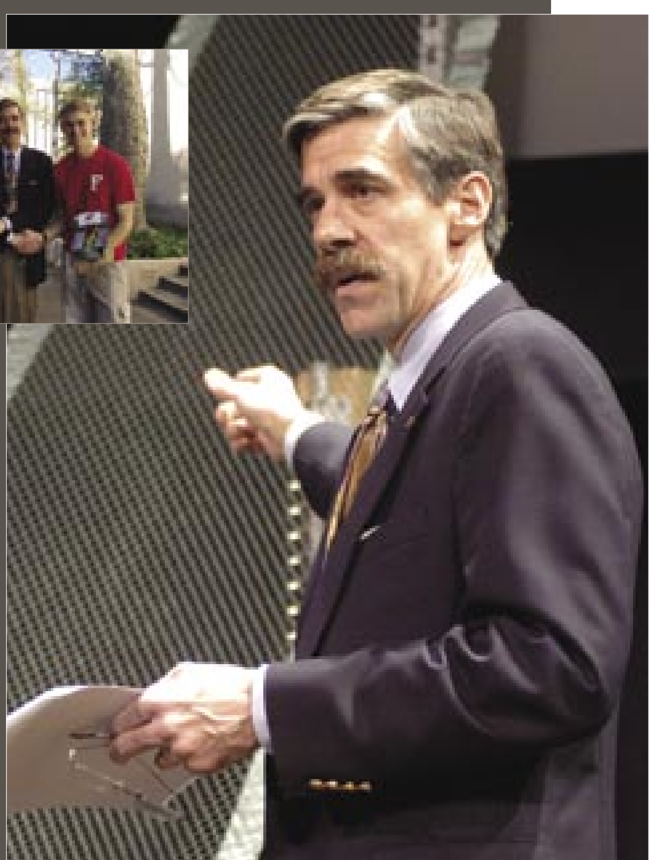
Lapusta observes that "a lot of people here have some practical applications for their work, but really the emphasis is on fundamental research. But that means the importance of the work is only felt much later. So supporting research in ME is really supporting the future. The impact of Caltech ME is disproportionate to its size. ME at MIT has roughly 90 faculty—but we have 18, less if you consider that some of us have primary appointments in other options or divisions."

The newest full professor is **Sandra Troian**, Professor of Applied Physics, Aeronautics, and Mechanical Engineering, who first came

Erik Antonsson
Professor of Mechanical Engineering

After this year's contest, I was walking back to my office from the auditorium and I ran into Mike Ikeda and Ghyrn Loveness. Their feet were not yet on the ground, they were just still aglow. And we had a wonderful conversation. They made comments much along the lines of "this is why we came to Caltech" and they were just so excited. I think they came in second place.

After all the nice words had been said and I was still enjoying their high level of excitement, they wanted to get a picture. So we posed on the walkway near Spalding in a nice spot, and a young lady took the picture of the three of us. I am shaking each of their hands like this [demonstrating]. And they sent the picture to me. And it's just wonderful. The glow on their faces is just priceless.



to Caltech in 2004. "The most wonderful year of my life had to be the one I spent here as a Moore Scholar. It was by far a most intellectually invigorating time. I interacted with many people and when it came time to leave I was sad to go; I felt that the environment here fit me like a glove. I was very happy when I heard after returning to Princeton that I would have the opportunity to come back for good."

Troian joined Caltech as a member of the faculty in the fall of 2006, and in particular joined the ME faculty because of their expertise in fluid and thermal sciences and the burgeoning emphasis on MEMS and microfluidics. "The confluence of MEMS devices and micro/nanofluidic flows is a rather new area in mechanical engineering. Some fundamental scientific questions as well as new technologies become possible in the study of liquid flow with interesting material properties inside or around small structures. One can also build intriguing optical structures by shaping liquid interfaces—part of a new field called optofluidics. For example, one can induce thermocapillary instabilities to shape and then solidify a nanofilm of molten polymer, thereby creating MEMS structures, photolithographic masks, or diffraction gratings. This 'topology on demand' may provide an inexpensive method for generating large-area arrays of photonic crystals."

Troian has spent the last 10 years working in traditional areas of fluid dynamics with emphasis on free surface thin films and their stability behavior. "Here at Caltech I plan on exploiting the beauty and power of interfacial stresses induced by electric, magnetic, and thermal fields to modulate the shape and response of small liquid-like structures with an eye toward micro- and nanodevices."

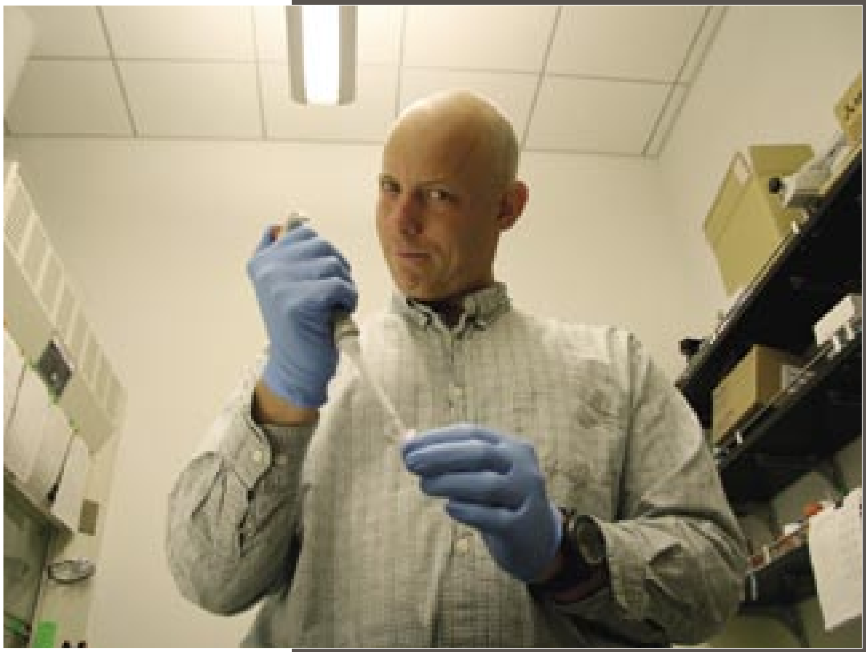
Ken Pickar, Visiting Professor of Mechanical Engineering, has been here for nine years, and during that time he has developed three outstanding courses for ME and the Division, E102 Entrepreneurial Development, E/ME103 Management of Technology, and E/ME105 Product Design. "Outside my family, Caltech is the core of my ex-

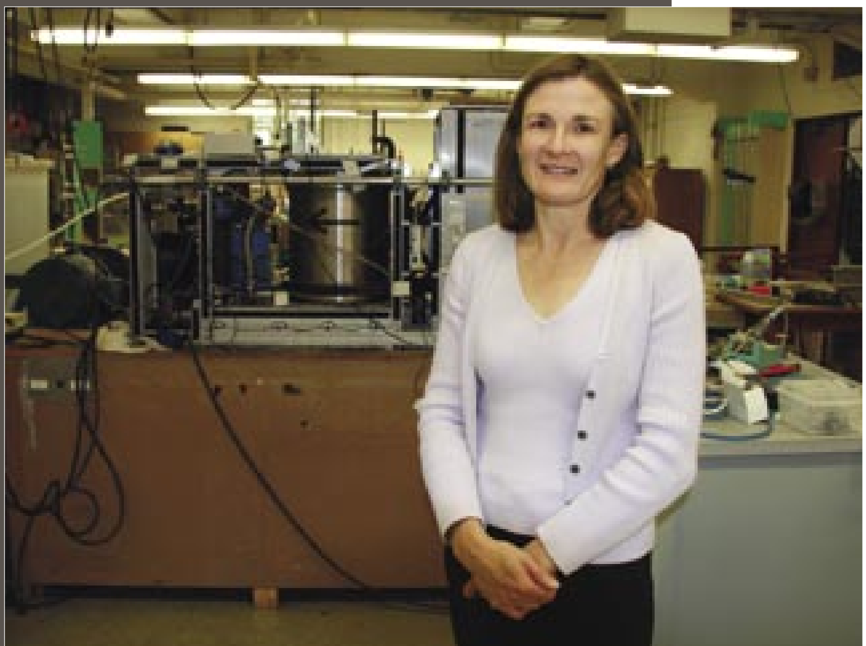
Rob Phillips

Professor of Applied Physics and Mechanical Engineering

In my heart I'm more of a physicist—which is what I am trained in. What I like is the application of mechanics to various things. Before I came to Caltech, I was working on how mechanics applies to materials. But I really have fun here working on how mechanics applies to biology.

What really changed everything for me was this one particular experiment by a group at Berkeley. What they did is grabbed onto a single virus, and they held it while the virus was packing its DNA. I was so impressed with that; I thought it was such an incredibly cool example of applying mechanical ideas to something in the biological realm. I said—honest—I've got to work on that, no matter what, and I've got to bail on my former life. Which is what I did.





Melany Hunt

Professor of Mechanical Engineering
Executive Officer for Mechanical Engineering

Caltech ME is still a special place—we still very much worry about how to educate students. What is the best way to get students interested not only in science, but interested in contributing to society? We aim to educate students in a way that results in building their confidence and their abilities so that they feel they are qualified to do a whole bunch of different things. Caltech does that in a unique way that is hard to find elsewhere—we pay close attention to the students and focus on fundamentals.

What I really love is hearing about what students do with their Caltech degrees—the range of things they do and the challenges they overcome using the tools of their engineering backgrounds. They don't feel limited by their engineering—they can and do find success in many different things. That's a great testament to Caltech.

istence right now. It has become the overriding factor in my professional life. What do I do? I teach three courses that are somewhat linked. All of them were driven by my reading of student demand."

"The Product Design course has evolved most profoundly. The course now is focused on the developing world, particularly rural Guatemala. The concept here is to take Caltech students, and all of our local brainpower, and apply them to a real-world problem that affects the over one billion people in the world who live on less than a buck a day. This kind of effort carried out in many universities over a long period of time is not characterized by a high success rate. You are building a product—that's tough for starters—for people you likely have no understanding of: their culture, what drives them, their living conditions."

"So what we've done is attempted to bridge this huge cultural and geographic gap by working with students from a Guatemalan university. All the teams have a student from Guatemala who is resident in Guatemala and free to travel on weekends into rural areas. They are the ones who are helping inform our work—that is, they are the ones who are helping to define the product, helping in the design, and testing whatever prototypes we are able to build in the very short 10-week sequence that we have for this. The students meet on Skype, an internet telephone service, several times a week, so there is bonding as a team. All my lectures are put on streaming video on the web. For the final exam the Guatemalan students are flown up here, partially paid by the Moore-Hufstedler Fund, for a period of 4 or 5 days. It's a new way of busting barriers between countries, cultures, and universities."

"We just finished the first semester where we had this close collaboration—and it has not been easy, but I would say it's been successful enough so that we are going to do it again and try and see if we can improve it." Pickar plans to take the class to a new level: in partnership with a professor at MIT he is applying for various grants to see if this model of having cooperative teams with people in-country and our own students is a good way of improving the "hit rate" of projects.

The desire to change the world for the better often marks a student's desire to go into mechanical engineering. **David Goodwin**, Professor of Mechanical Engineering and Applied Physics, was one such inspired student, and remains dedicated to solving both scientifically interesting problems, and those with more near-term application. "When I was a senior in college, there was an energy crisis in the U.S., and at that point I decided I wanted to do energy-related work. I found that at Stanford the energy programs were in Mechanical Engineering, and so I applied to that program. Shortly after I started, in about 1979, the nation's priorities changed, and funding for energy projects declined. Oil prices declined. I did finish my PhD on energy related projects, but during my postdoc positions I ended up working on other things entirely. Now, however, energy is once again a popular topic. I think we are at the point that while prices may fluctuate a little bit, they are never going to go back to being so low we can forget about it. Now there is an essential difference—we realize what we are doing to the environment through global warming. There's added motivation to develop new energy techniques that we didn't have in the '70s and '80s. A lot of my current work has applications to energy. In the last few years I've reentered the energy arena and over half my program is working on solid-oxide fuel cells. In that work I collaborate quite a bit with Sossina Haile [Professor of Materials Science and Chemical Engineering] in Materials Science, and colleagues at other universities."

"I've always done a lot of numerical modeling and simulation. There was an opportunity in the fuel-cell world: a lot of people are doing good experiments, but there is a need for better numerical simulations. It turns out that many of the things that you want to measure inside a fuel cell are very hard to measure, so numerical calculations can give you some idea of what might be going on—or help you to design better experiments. With the renewed awareness of energy issues, there is a lot of interest among the students, so I am fortunate to be getting a lot of student interest in my projects."

John Brady

Chevron Professor of Chemical Engineering and Professor of Mechanical Engineering

I am interested in complex fluids. Complex fluids are, for example, personal care products, printing inks, polymers, polymer solutions—all kinds of 'gunky' stuff. More formally, we call them multi-component materials in a fluid-like state. Often they are in the form of colloids—small particles dispersed in a liquid—and I try to understand their static properties. Can we form interesting structures? More importantly, I like to ask: How do they move? How do they behave? How do they flow?

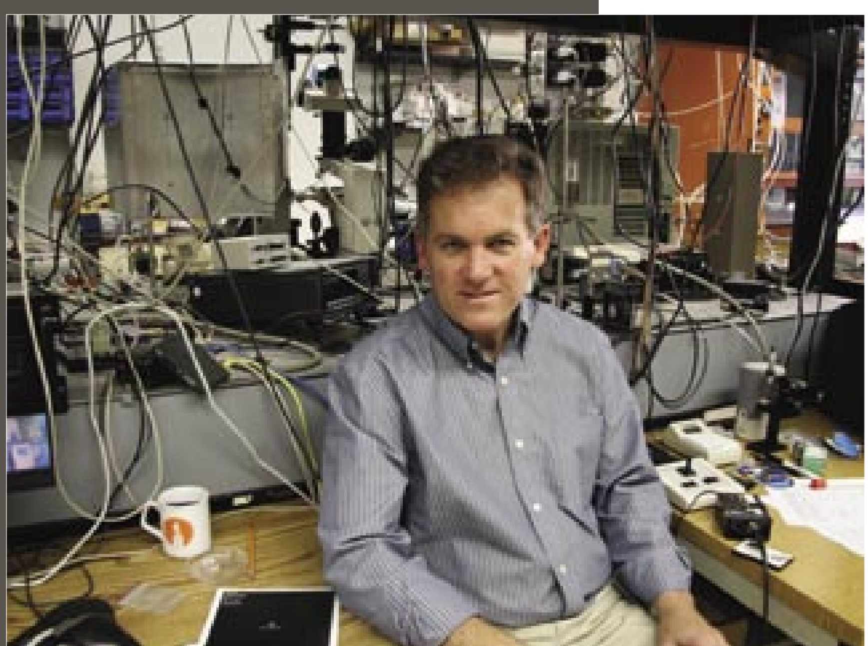
I've been doing fluid mechanics for a long time and have served on a number of thesis committees in ME, so joining the option, which I did in 2005, was a natural thing to do. I wanted to make my association more formal, and I wanted to become more involved in what goes on in Mechanical Engineering.

David Goodwin

Professor of Mechanical Engineering and Applied Physics

I think ME at Caltech is a little different than ME at other places. Our strength is at the interface of engineering and science. We don't do a lot of very applied and practical things that some other schools do—our unique niche is at the scientific end of the engineering spectrum. I was struck earlier this term when our new graduate students were here for orientation. We went around the table and asked them what they are interested in doing for research. And essentially every one of them said "micro-" or "nano-" something. Partly it's because we are interested in engineering at small scales, and we admitted those students. But I also think that illustrates one of our major directions: small things.

Within my own work, I think there's quite a potential for using some of the recently developed nanofabrication methods to develop much higher performance electrodes. Electrodes now are made from a random mish mash of powders that are baked to sinter the particles together. But I think that a more engineered approach, less random, would lead to higher performance. I am very interested in exploring how new nanofabrication methods can lead to higher performance fuel cells. And I think that we can make structures that just a few years ago would have been impossible to make.



The student side of the equation in Mechanical Engineering is tremendously important. **Joseph Shepherd**, Professor of Aeronautics and Mechanical Engineering, a recent joint appointment, has worked with ME students for a long time. "The nice thing about the ME program is that it is a very flexible program and gets students involved in research early on. The program attracts excellent students and I have worked with a number of them over the years. My joint appointment began in 2006, but one of my very first graduate students was actually an ME student. Since I arrived at Caltech in 1993, I've always had one or two ME students in my group."

Shepherd is interested in how structures respond to explosions. "We are working with Los Alamos right now—they have some metal cans that are used for special purposes, and we are studying the bending of these cans due to accidental explosions. In addition to solving their particular problem, we are trying to form rules in a very general way so that we'll have a set of ideas that we can use on other problems. We'd like a way to estimate the results for any mixture and any size pipe and any kind of explosion event—then we'll have something we can provide to the engineering community and the results will have widespread use."

Shepherd has joint projects with several ME faculty. "Dave Goodwin has developed a really great set of software tools called Cantera—this software allows you to do calculations on kinetics—and we've picked up on that and use it quite a bit, especially in a class on combustion that I teach." He also works with Tim Colonius, looking at problems concerned with the interaction of fluids and structures, and he has a program with G. Ravichandran, sponsored by the Navy, exploring the interactions between shock waves, bubbles, and solids in water.

Students are tremendously important to the work of **Yu-Chong Tai**, Professor of Electrical Engineering and Mechanical Engineering. "I have 17 PhD students and 3 undergrads. In my field, the job market is really good, so when students graduate, they are immediately stolen away.

We don't have that many postdocs! My students have to master all the theory, all the math and science, but they also have to master their hands, like a surgeon. They are able to operate many difficult machines and make devices beyond what conventional machining technology can do. That kind of student is attractive to so many technology sectors. My students have really broad backgrounds. I think that's really wonderful. That's actually the kind of group that I envisioned working with when I was young. They help each other, they teach each other." Tai and his students are inventing devices, particularly in the bio-implant area. "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 then putting it in the 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's low-power devices use micro and nano technologies. He and his colleagues have developed retinal implants that can allow a blind person to see a real-world image, not just light. "We are hoping that in less than two years, the devices that we designed here in the lab—that we have spent the last 10 years developing—will go into the human eye. That will be the biggest moment of my career."

Kaushik Bhattacharya, Professor of Mechanics and Materials Science, is one of the mechanical engineering students that passed through the Indian Institute of Technology, Madras in the 1980s, a time when two very influential professors were teaching there: Alwar and Ramamoorthy. "Anyone who went through IIT Madras in that era would know these guys. Phenomenal teachers. Many of the mechanical engineering students went into solid mechanics because of them, myself included."

Bhattacharya works on problems somewhere between mechanical engineering and materials science. "When people think about mechanical engineering, they usually think about designing machines—cars, robots, devices. What I think of is the *materials themselves* in that same spirit. From a traditional mechanical engineering point of view, a material is some homogeneous blob of material. But

Michael Ortiz

Dotty and Dick Hayman Professor of Aeronautics and Mechanical Engineering

First and foremost, the aptitude, enthusiasm, and devotion to science and technology of Caltech's students are unparalleled. Caltech's student body is a national resource that feeds top talent into academia, industry, and the national laboratories. Another aspect that is increasingly rare and that particularly appeals to me in connection with my current focus on predictive science is Caltech's commitment to experimental science. As experimental programs at other elite institutions dwindle or are terminated outright at an alarming rate, Caltech's strength in experimental science becomes increasingly prominent. As a theorist, the opportunity to collaborate closely with leading experimental scientists is a luxury available at few other places and makes the Caltech experience unique.

if you look at it in some subscale, you will find that there are interesting features within the material and that's what gives us the macroscopic properties that we use. Materials scientists traditionally try and understand the substructure of materials. The difference is that today I can start understanding, analyzing, manipulating the substructure using a mechanical-engineering-like language. The material acts as the machine."

Along with one of his collaborators on the experimental side, Professor G. Ravichandran, Bhattacharya has worked for a long time on 'active materials,' piezoelectric or ferroelectric materials that do work based on some change in their structural qualities. "What is very interesting about these materials is that if you go to very small scales, scales of microns, the polarization is not uniform. Distinctive patterns are formed based on regions of polarization—and every material has distinctive patterns. The questions we are interested in are: Why does a particular pattern form and how can I manipulate it to get specific properties? That's our activity in active materials."

"One of the things that I am very excited about currently is a collaboration with Michael Ortiz and a group of students starting with Vikram Gavini. We're doing quantum mechanics, but at macroscopic scales." No material is perfect: materials have defects. Most of these defects are in parts per million or parts per trillion. So to compute them you need then to consider millions or billions of atoms. "We are developing methods to do these calculations at these levels. We ask the question: what aspects of this fine-scale behavior are important at the macroscale? Then we try and compute that directly. We write the down the detailed theory for everything, and then systematically coarsen the grain, shedding the information we don't need. We don't make assumptions or use multiple theories. We are just using one theory and computing it on a hierarchical scale. If you know that in a region the structure was nice and ordered, you only need to sample that area, you don't need to compute all the details. Near the defects, you need to get all the information. Our technique throws out a lot of redundant information."

Solid mechanics is very well represented in ME by Nadia Lapusta and Kaushik Bhattacharya, but through a process of 'mergers and acquisitions' in 2000, three joint appoint-

Joel Burdick

Professor of Mechanical Engineering and Bioengineering

I owe a great debt to a lot of the senior faculty—mentors like Chris Brennen, Allan Acosta, Frank Marble, Jim Knowles, Tom Caughey, and Ed Zukoski. When I was a young faculty member, they set the tone that you should be a gentleman and a scholar. They believed by their actions that people worked together and pushed the department forward. And this theme persists today: the faculty of the department really get along well. There are no politics. I actually enjoy going to ME faculty meetings. The faculty here have responsibility, but also feel ownership of the place. In larger schools you can feel more like just an employee.

ments of professors strongly associated with aeronautics and GALCIT—Ares Rosakis (Theodore von Kármán Professor of Aeronautics and Mechanical Engineering and the Director of GALCIT), G. Ravichandran (John E. Goode Professor of Aeronautics and Mechanical Engineering), and Michael Ortiz (Dotty and Dick Hayman Professor of Aeronautics and Mechanical Engineering)—took place. This brought enormous experimental expertise into the ME mix, as well as additional theoretical and computational acumen.

Professor **Michael Ortiz** comes to mechanics from the theoretical side. "The importance of modeling and simulation in the design and certification of complex engineering systems—traditionally based almost exclusively on testing—has skyrocketed in recent years, and this is likely to continue to become increasingly central in the future. For want of a better descriptor, the term 'predictive science' is used to describe this emerging field. As the complexity of engineering systems increases, our ability to test those systems thoroughly enough—and base their design solely on testing—steadily decreases or becomes impossible altogether. The resulting challenge is to develop our physical models and codes to a degree of fidelity such that we can reduce the number and complexity of integral tests required for certification. Of course, predictive science does not in any way diminish the role of experimental science, it enhances it. Carefully designed tests, tightly coupled to modeling and simulation, are more important than ever in order to validate models and codes and make code-based certification possible. The grand challenge of developing rigorous and reliable predictive science methodology combining modeling, simulation, experiment, and uncertainty quantification is one of the most interesting endeavors that I'm involved in at present."

Professor **Ares Rosakis** comes to mechanics from the experimental side, and at present is very excited about his collaborations with Nadia Lapusta in "experimental seismology," or laboratory earthquakes. "This research started about six years ago with Hiroo Kanamori [John E. and Hazel S. Smits Professor of Geophysics, Emeritus] and myself. We were looking at certain unusual earthquake

Richard Murray

Thomas E. and Doris Everhart Professor of Control and Dynamical Systems

I see very interesting feedback problems in biological machines. And we are now at the point at the organism level that we are able to probe into things like insects and other organisms much more deeply to understand how the machine works. There are applications, but I think it is interesting on a sheer scientific plane. At the cellular level, similarly, we are now able to probe in ways that we never were able to before, and therefore, we are able to design. So we can actually take the principles that we learn about how it works, and then design a new system using those principles. Synthetic biology is one of the areas I am interested in where Caltech is taking a reasonably early lead. My colleagues and I are interested in how to build things out of molecular machinery and to do so in a way that illuminates the biology that is going on. In the long run, the work may also be useful for developing therapeutic systems, detecting disease, and curing disease.

Guruswami Ravichandran

John E. Goode, Jr., Professor of Aeronautics and Mechanical Engineering

The ME department at Caltech is a very strong department, engaged in quite fundamental engineering science, with an eye toward application. It is also a very cohesive group that cares very deeply about undergraduate and graduate education. Students are provided with the opportunity to work on real-life problems and they have excellent classes. Programs like Erik Antonsson's ME72 class and the DARPA Grand Challenge with Richard Murray—these have really energized the students. And they also draw deep inspiration from the robotics program. There are all sorts of opportunities that are very attractive, very appealing to the undergraduates. They know the faculty cares about them. There is a sense of family.

ruptures that featured very high rupture speeds—speeds that were much higher than the shear wave speed of the material, in this case crustal rock. There was no direct proof that this could be happening—the seismological records were very unusual. We hired a student and constructed the experiments that mimic the rupturing earthquake in a laboratory setting. Kanamori provided invaluable guidance in designing these experiments with me so that they are relevant to seismology, and we produced miniature earthquakes in the laboratory. We demonstrated that highly unusual speeds of rupture are possible in nature, and we described the conditions leading to such unusual behavior. These experiments use high-speed photography, photoelasticity, and infrared thermography as diagnostics. This type of work is continuing now with both Kanamori and Lapusta. We are concentrating on the study of the 'crack-like' or 'pulse-like' nature of laboratory ruptures and their behavior when they encounter fault complexity such as forks, kinks, and jogs."

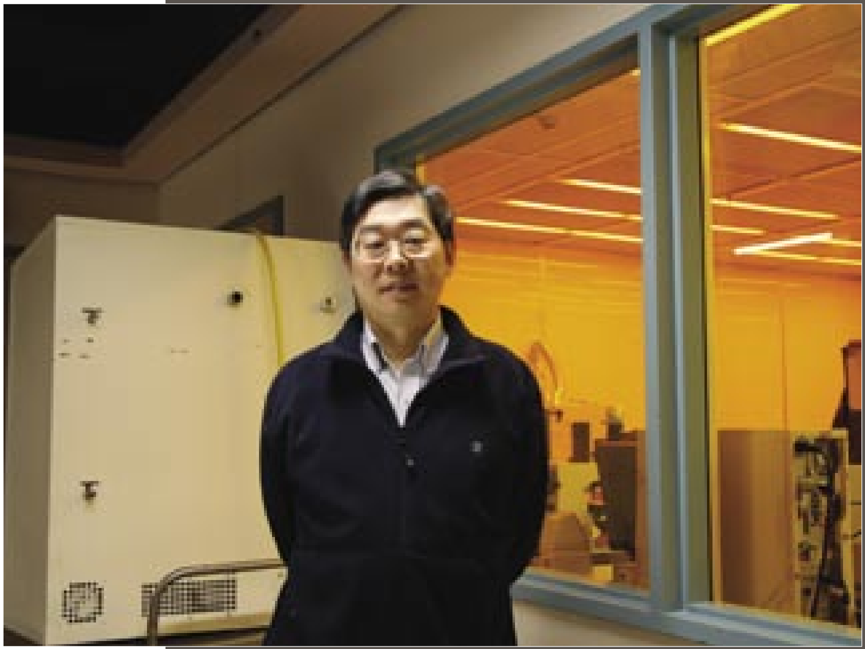
The fifth member of the ME "solids consortium" is Professor **G. Ravichandran**. As an experimentalist, Ravichandran determines if what the theoreticians say is possible is actually possible. "I work with a lot of ME students, and with Kaushik Bhattacharya. He's a theoretician, and I do experimental work, so we complement each other. He has made a number of predictions, particularly regarding active materials. People were very skeptical about this, but we have shown in the lab that in fact the behaviors Kaushik predicted are possible."

True to Caltech form, Ravichandran's collaborations extend across divisional boundaries, and he is now working with a group in Chemistry and Chemical Engineering on developing biomaterials based on protein engineering. "I have gotten very excited about that—cells can be thought of micromachines, at least in my very simplistic view." Ravichandran is working with David Tirrell, Ross McCollum - William H. Corcoran Professor and Professor of Chemistry and Chemical Engineering. They are jointly exploring cell-surface interactions, 3D cell migration in artificial extracellular matrix (aECM) proteins, assembly, and the mechanical properties of biomaterials. The goal is to move towards a comprehensive understanding of biological structure-function relationships in soft materials.

Rob Phillips, Professor of Applied Physics and Mechanical Engineering, has migrated over to the biological side. In fact, he is the one member of the ME faculty who now resides in the Broad Center for the Biological Sciences. His conversion is so complete that he serves as Option Representative for Biochemistry and Molecular Biophysics. Yet, many of his methods are still firmly rooted in mechanical engineering. "Our research uses physical approaches to understand the structure and function of living organisms and the macromolecular complexes that make them up. We are focused on the physical biology of the cell." Phillips is interested in a number of different phenomena involving the mechanical response of cells and the machines within them. "How do cells sense mechanical forces? That's a basic question. We know the mechanism of mechanosensation in bacteria is mediated by a protein known as Mechanosensitive Channel of Large Conductance (MscL). But how does MscL sense tension in the membrane? How do the elastic properties of the surrounding lipids affect the function of the channel? For that matter, how do the elastic properties of the lipids affect the function of any channel or transmembrane protein?"

To help bring students and colleagues deeply into the subject matter, in 2005 Phillips initiated "Physical Biology Boot Camps" and will be running his fourth camp this summer (with Richard Murray). He is also organizing a summer school and conference called "Nanomechanics: From Cells to Solids" that takes place in July 2007.

ME72 is a Caltech tradition, not just a class. Cheerleaders, the National Anthem, the final showdown in Beckman Auditorium… ME72 epitomizes many of the best qualities of Mechanical Engineering at Caltech. The course has been taught 22 times, and for 18 of those, **Erik Antonsson**, Professor of Mechanical Engineering, was presiding. "I was born a mechanical engineer. My father is a mechanical engineer. My mother's father was a mechanical engineer. My father's father did everything under the sun—never had the education to be engineer—but he certainly had the insight to be a mechanical engineer. He taught me a lot about the way things worked in the world. My mother's brother was a mechanical engineer. My older sister married



Yu-Chong Tai

Professor of Electrical Engineering and Mechanical Engineering

When I was a grad student at Berkeley, I saw a yellowed paper on a lab bulletin board announcing an EE search at Caltech. It was drafted by Dave Rutledge. It had been on the wall for at least two-and-a-half years. Then I did one thing right. I actually emailed Dave Rutledge asking if the position was still open. He said yes. We did not know each other at the time. He invited me to send in my information, and I did. Dave invited me for an interview almost instantly. So I came. I liked the people here. Paul Jennings, the Division Chair, told me "Tai, you come here, and we'll build you a lab." When I talked to faculty, basically they told me I could do anything I wanted. Less than one week after the interview they called me to ask me to come for another interview and offered me the job. From the time I saw the yellowed paper to the offer was less than a month. No regrets!

Kenneth Pickar
Visiting Professor of Mechanical Engineering

From everything that I can see—and I have talked to professors who have been here much longer than I have—ME is as strong as ever, is as well-positioned for the future as ever. This great array of talent here has kept the flame alive. When you are on top of so many areas, and when you do it for so long, there is only one way for you to go, which is down! But we haven't done that. The faculty here has kept the faith, and they have continued the tradition of Caltech excellence.

We are going to change—you can expect that ten years from now the things that people will be working on will be significantly different than the things that people are working on today. You can already see that beginning. Mechanical engineering as a profession has changed significantly over the last 20 years and it will continue to change. This is the only way that makes any sense; the word mechanical engineering has been around for a long time—it's been around for 100 years at Caltech. We've been able to maintain this discipline in a way that doesn't compromise the past, and yet doesn't get stuck in the past.

a mechanical engineer."

Antonsson has been the public face of the Mechanical Engineering Option over many years due to the magic of ME72—magic that extends off-shore, even beyond the boundaries of campus. He served as Executive Officer of the option from 1988 to 2002, catalyzing and provoking discussions, growing and inspiring the faculty. The ME undergraduate degree program was reestablished during this period. "This was important because it identifiably establishes our program and our students. It was a topic of considerable debate—and healthy debate—because it meant that we were making a long-term commitment to teaching the undergraduate program."

These activities were, of course, always accompanied by his research work. Antonsson and his group have been using genetic algorithms as a way to develop design solutions. "That's not unique—lots of people are doing that. But during the last couple of years we have recognized some of the fundamental limitations to this approach. We've realized that biology uses genetic information in a way that is very different from the way it is used in artificial evolutionary methods. And the difference is that the information in our genes is not a description of us, it is a recipe for us to grow and develop." This realization has led Antonsson to explore a new approach. The algorithms evolve sets of rules, and then the rules are handed to a simulation environment where individuals grow and develop. "At the end of that process we evaluate how well they performed. This more closely parallels evolution in the natural world, and is quite a radical difference in the way these methods are used and particularly the way they are used for solving design problems."

"We'd like to expand to attacking design problems where the designs have intrinsic complexity and therefore are difficult to solve by manual methods." Applications to environments like space offer complex challenges, for example. Solutions must perform at a very high level. "Now you start thinking about structural materials that change character or properties along their length—they might be flexible in some regions, stiff in other regions, and lightweight and hollow elsewhere. Bones—structural elements in biology—have exactly that character. They are not shaped like the rectilinear pieces you see in chairs and buildings—they are weird and complex. And they are also complicated from a materials standpoint. A long bone has an outer sheath of cortical bone that is very dense and stiff, and that sheath thins down at the ends. The hollow region of the long bones is filled with a kind of spongy bone that is almost like a closed-cell foam that takes up the space and provides other properties, but is lightweight. And they are hollow in the center. Bones are really quite complex. So we've thought about how to develop rules sets that would evolve in such a way that we could make things that would look like biological structures, like bones. What would we learn from that? That's the work that I am truly, deeply excited about."

Professor **Chris Brennen**, Richard L. and Dorothy M. Hayman Professor of Mechanical Engineering, has been closely associated with the lives of students on the Caltech campus far beyond his academic teaching and mentoring activities—which are prodigious by themselves. He has won three teaching awards, including in 2005 the Richard Feynman Prize, Caltech's most prestigious teaching honor. He was Master of Student Houses (1983-87), Dean of Students (1988-92), Executive Officer for Mechanical Engineering (1993-97), and then Vice President for Student Affairs (1997-2002). "I spent over 12 years in the administration of student affairs. Probably the most challenging job was the first one, Master of Student Houses; there was no staff in those days to deal with student problems. I had to deal with all kinds of things in the middle of the night. But particularly as you grow older you look back at those human moments—what you were able to do for particular students and students in general. I remember Richard Murray when he was an undergraduate. Richard was even faster then!"

"I'm at the age now where I don't have to worry about whether my research is respectable, or good enough to get tenure. I work on what I like to work on and I've always been interested in a very wide range of things. I've always worked on cavitation. It's such a pretty, visual subject. There are many applications of cavitation. Cavitation is a serious problem for artificial hearts for infants or adults. I am working on an NIH project trying to develop artificial

Joseph Shepherd

Professor of Aeronautics and Mechanical Engineering

I think the ME program is a very good program for the undergraduates because it gives them an exposure to actual mechanical things—they get to work on bits of hardware. I think the reason students like to come to a place like Caltech is because they imagine that they are going to be doing things with their hands. They are going to be building things, measuring things—doing something other than sitting in front of the video screen. So much of modern education has become very passive. ME at Caltech provides an outlet for students who are interested in working with technology in a hands-on way. And that is something that I hope we can continue as a tradition.

You can go anywhere and sit in classes—and you can argue that the classes here are better than those anywhere else. But I think the key point is that students have this wonderful opportunity to have interactions with the faculty who run these research labs. It's a fantastic opportunity. You learn so much working in a laboratory—not only learning about that specialty, but also learning how to be in a research group and what it's like to be on an exciting research project. That's where the tremendous advantage of Caltech lies.

hearts for infants, which is a big challenge. None of the artificial hearts work very well. I am working of course with Melany on booming sand dunes. I still do work on rocket engines. Cavitation is a big issue in rocket engines because the turbo pumps that are a key part of the engines cavitate like crazy. You have to manage that cavitation and make sure it does not become unstable and create serious problems."

"In ME, we have always striven to be at the very forefront of the new engineering—of the engineering of the future rather than working over the engineering of the past. I think we are very committed to teaching, especially the undergraduates. I fear that the commitment to the educational mission of this Institute has declined significantly, and that depresses me. ME has always had a tradition of marvelous teaching, and I learned a lot from my predecessors, such as Allan Acosta [Richard L. and Dorothy M. Hayman Professor of Mechanical Engineering, Emeritus], Rolf Sabersky [Professor of Mechanical Engineering, Emeritus], Ted Wu [Professor of Engineering Science, Emeritus], and Milton Plesset [Professor of Engineering Science, Emeritus], all of whom were devoted to students and great teachers.

"The *esprit de corps* among the ME graduate students is something I value. I think it is beneficial to them—they have tremendous pride in being part of ME. I guess I am a believer in what the social scientists call *social capital*—that is to say, you need to invest in your relations between people. And once you accumulate some goodwill, you have to be very careful not to squander it. It's harder to measure so scientists don't tend to believe in it. I have always believed in it because of my background. The benefits that accrue from social capital are in the end of tremendous value to the institution and to the department."

"I feel enormously fortunate to have been able to live out my career here at Caltech. Enormously fortunate with the colleagues I've had—seniors and juniors. I've had misfortune in my life, but I've also been very, very fortunate. And it's been a fantastic adventure being at Caltech. Hard to imagine I could have luckier in that regard. So I try to give back, as my mother, Muriel Maud Brennen, taught me I should always." ENG

Stay in touch with ME at: http://www.me.caltech.edu

Sandra Troian

Professor of Applied Physics, Aeronautics, and Mechanical Engineering

My office was in the Thomas building the year I was on sabbatical at Caltech as a Moore Scholar in 2004-2005. I spent many wonderful hours discussing topics like non-normality and stability of fluidic systems, Brownian motion, and quantum dot assemblies with the faculty there.

What I enjoy most is the strong emphasis on experimentation coupled with the fact that ME has some of the finest mathematicians around. One of the most important characteristics that attracted me to ME—and it is something that the ME departments everywhere should strive hard to maintain—is the basic focus on building structures of all kinds, from nanodevices to jet wings. Doing this job well requires passion and skill in understanding the fundamentals and the willingness and agility to learn the use of new tools and methodologies. Caltech knows how to do this right.