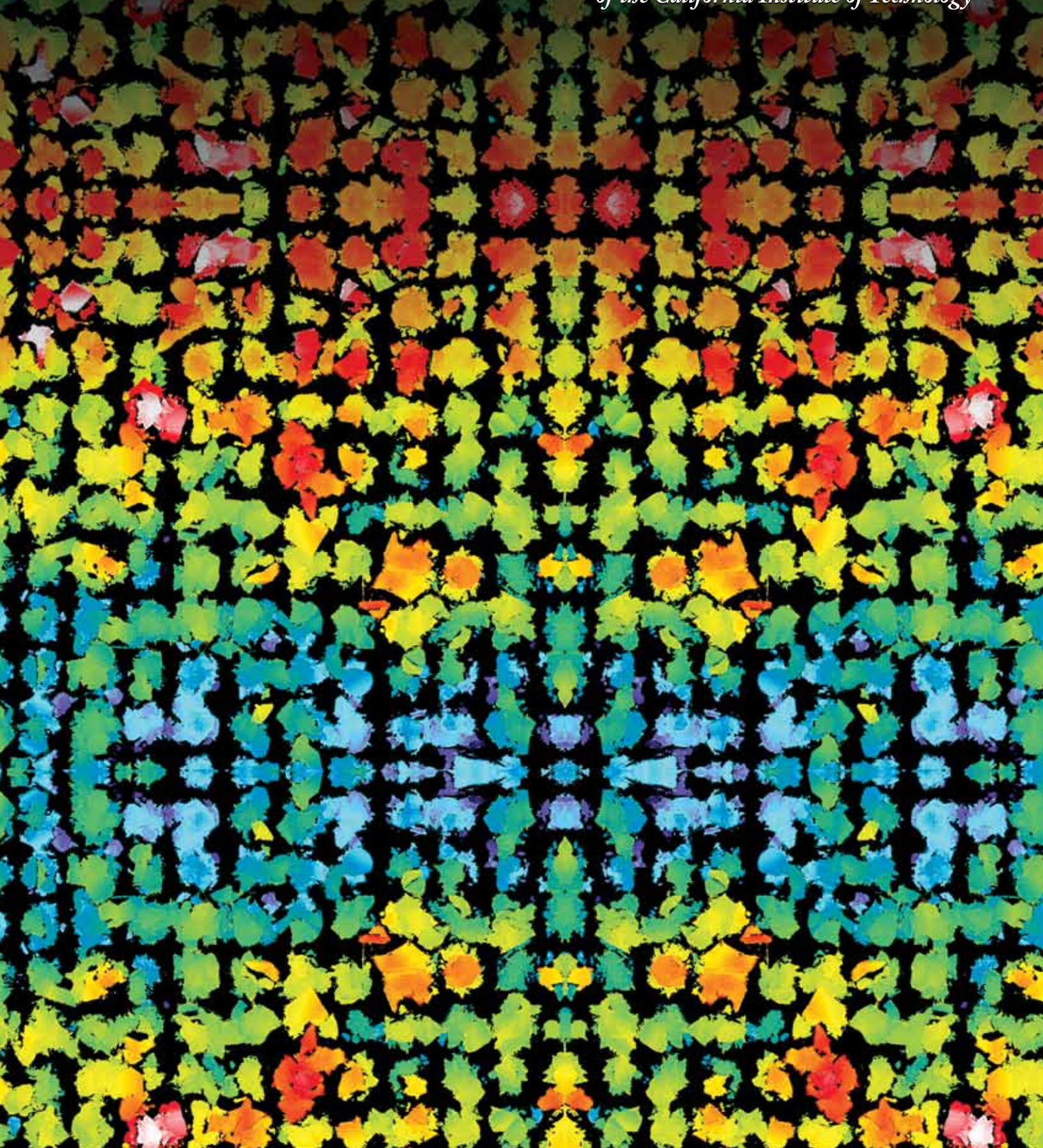


ENGenious

ISSUE 8, 2011

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

of the California Institute of Technology



The Caltech Division of Engineering and Applied Science consists of seven Departments and is home to more than 75 faculty who form an interconnected web of researchers creating the frontiers of modern science and engineering. Their students and postdoctoral colleagues have access to world-renowned educational resources, as well as unparalleled opportunities for both basic and applied research.

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

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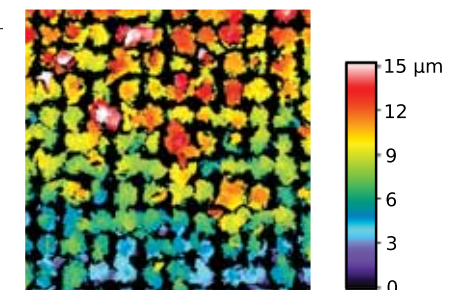
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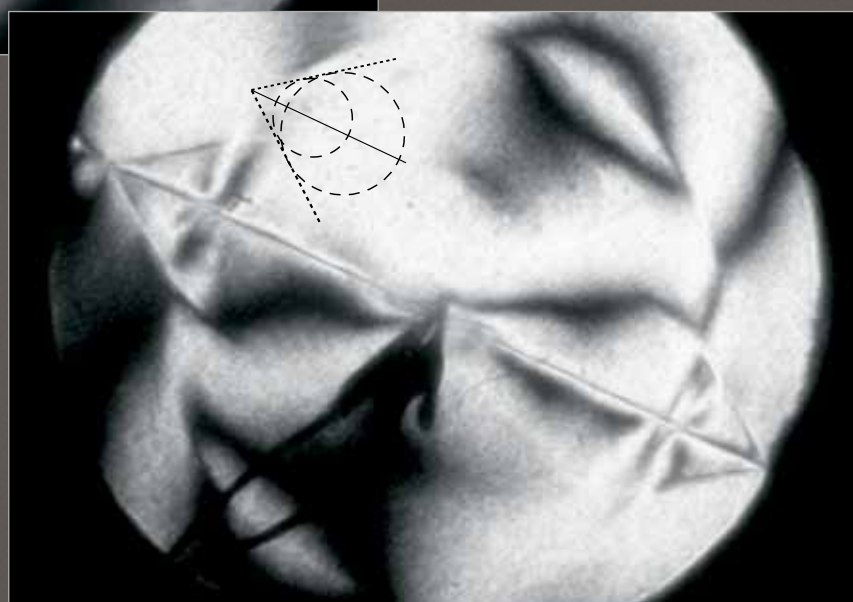
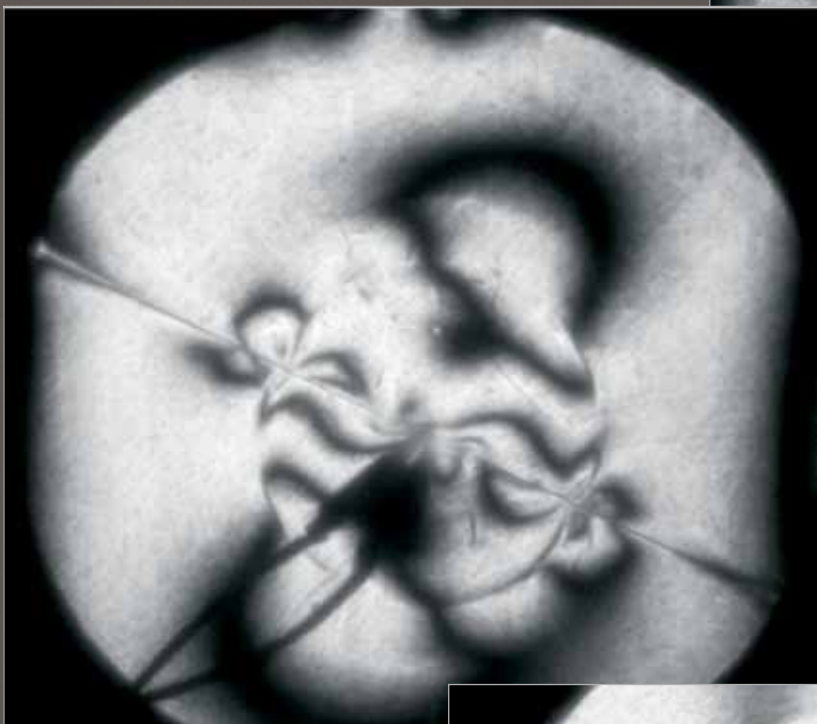
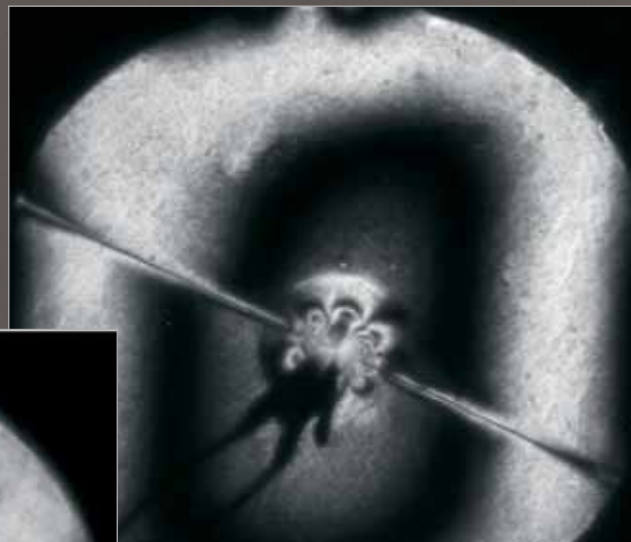
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The Caltech Center for Diversity

Providing a Real Pathway to Membership for Underrepresented Students at Caltech

Cover Image: This research image is a topographical height map of a compound semiconductor material called gallium phosphide (GaP) that is grown on a silicon (Si) microwire array. This semiconductor structure is designed to absorb sunlight and split water to generate solar fuels in a photoelectrochemical cell. Warmer colors represent higher regions of GaP, and cooler colors depict lower regions. The image width is 77 microns, and the rainbow color scale covers 15 microns in height. It was created by graduate student Andrew Leenheer, working with Professor Harry Atwater, as well as postdoctoral scholar Nicholas Strandwitz, working with Professor Nathan Lewis. The image was obtained using a confocal microscope.





Above: Earthquakes generated in the laboratory illustrating the transition from Sub-Rayleigh to supershear rupture speeds. Right: Note the creation of the shear wave mach cones in the solid.

Left: Photo of F-22 Raptor crossing the sound barrier and illustrating the pressure wave mach cone effect in air.

For more information, visit rosakis.caltech.edu.



The 75-faculty-strong Engineering and Applied Science (EAS) Division at Caltech may be home to the biggest group of faculty at the Institute, but it is tiny compared to the other famous engineering schools around the world. In order to compete and thrive with such numbers, we have adopted two basic principles. First, by design, we don't cover all areas in engineering and applied science. We dynamically choose only the ones that we consider the most important and we are ready to retire the ones that are not intellectually stimulating. Our faculty does not represent a continuum of research interests and specialties. We are, in the words of my old Caltech mentors, Professors Jim Knowles and Eli Sternberg, a **collection of isolated singularities**. However, in order for these isolated areas of excellence to be effective, the second principle has to be introduced. This principle dictates that the barriers between disciplines, Departments, and even Divisions remain very low so that both faculty and students can cross them, if they wish, without spending unnecessary energy. This is a principle that is also shared throughout the Institute and necessitates the existence of a truly interdisciplinary culture in which turf and labels become secondary to intellectual exchange. Other major engineering schools speak of the value of interdisciplinary research; our difference is that we have practiced it since our founding over 100 years ago. It was simply critical to our survival.¹

In the above analogy, the isolated singularities of excellence represent our chosen disciplinary strengths in research and teaching while our interdisciplinary research groups and centers can be viewed as sparks created between the disciplines. These energetic sparks of interdisciplinary brilliance may or may not be short-lived, but they are triggered by our desire to tackle society's big problems and are facilitated by low barriers to enter new fields. New challenges, such as renewable energy, and new ideas, such

as bioinspired engineering, create new and sometimes unexpected sparks. Long-standing problems, such as terrestrial hazards involving both the fluid and the solid earth, represent longer-lasting sparks. I, for example—a solid mechanic and aerospace and mechanical engineer by training—now spend much of my time in research interacting with geophysicists and seismologists working on shockwave-induced ground motion generated by super-shear earthquakes. The sparks between these particular disciplines have the potential for great societal impact in California and other seismogenic areas around the world. Indeed, engineers do best when they tackle and mitigate humanity's biggest calamities and problems.

This issue of *ENGenious* features a number of our faculty, alumni, and students who are tackling the biggest problems facing and challenging humanity. As you read, I encourage you to think about EAS and Caltech's greatest achievement—the **creation of new schools of thought**. These schools of thought reflect our combined achievements and excellence in both research and education. It starts with the faculty's dedication and commitment to train their students in their singularities of excellence supported by mastery of the fundamentals. Then these students become the next generation of academics, researchers, technologists, and leaders who in turn train their own students and associates, and in the process they influence industry, the economy, and even government policy and societal perceptions. They are the inheritors and carriers of both our educational and our research philosophies.

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

¹One of the fruits of these strategies, sustained over decades, is that Caltech is one of the top universities worldwide. Indeed, Caltech was just rated number-one in the 2011–2012 Times Higher Education world university rankings of the top 200 universities. In addition, it has been ranked first in the subject of engineering and technology.



Charles Elachi accepts the rank of knight in the order of the Legion of Honor from François Delattre, Ambassador of France to the United States.

The Highest Decoration of the French Republic

Charles Elachi (Vice President and Director of the Jet Propulsion Laboratory and Professor of Electrical Engineering and Planetary Science) has been awarded the rank of Chevalier (Knight) and was formally inducted into the French Legion of Honor, known in its native land as the Ordre National de la Légion d'Honneur. Professor Elachi was received into the order, which is the highest decoration of the French Republic, by François Delattre, Ambassador of France to the United States. The appointment is traditionally restricted to natives of France, but it has been bestowed on foreign nationals "who have served France or the ideals it upholds." At the award ceremony at the Athenaeum, Elachi noted that throughout his career, his links to France have continued through unique research opportunities. "Working together over the last three decades, JPL and the French Space Agency have revolutionized the field of oceanography," remarked Elachi, "by developing the capability to observe and monitor ocean currents on a global basis from space."

For more information, visit eas.caltech.edu/news/171.

Left: After a stormy day, CHIP shines brightly at night at West Potomac Park in Washington, D.C., Friday, September 23, 2011.

Right: SCI-Arc/Caltech participants place third in the U.S. Department of Energy Solar Decathlon 2011 affordability contest, with CHIP valued at \$262,495 by jurors.



Solar Decathlon: CHIP Leads the Way in Energy Balance, Engineering, and Affordability

The high-tech house built by a joint team of students from Caltech and the Southern California Institute of Architecture (SCI-Arc), known as Compact Hyper-Insulated Prototype (CHIP), placed sixth at the 2011 U.S. Department of Energy Solar Decathlon. The Solar Decathlon challenges collegiate teams to design, build, and operate solar-powered houses that are cost-effective, energy-efficient, and attractive. The winner of the competition is the team that best blends affordability, consumer appeal, and design excellence with optimal energy production and maximum efficiency. The Caltech/SCI-Arc team tied for first place in the category of energy balance, placed second in the categories of engineering and home entertainment, and ranked third in affordability.

The Caltech/SCI-Arc team was supported by faculty and researchers across Caltech, including Richard Murray, the Thomas E. and Doris Everhart Professor of Control and Dynamical Systems and Bioengineering; Harry Atwater, Howard Hughes Professor and Professor of Applied Physics and Materials Science, and Director of the Resnick Sustainability Institute; and Neil Fromer of the Resnick Institute.

For more information, visit chip2011.com.



Left: Team Explorer takes over a Guggenheim conference room for the week to develop a mission concept.

Right: Prakhar Mehrotra and Jon Mihaly, Caltech Space Challenge organizers, finalizing the orientation presentation.

Team Voyager Wins Caltech Space Challenge

The Caltech Space Challenge was a Keck Institute for Space Studies (KISS) workshop proposed and led by Aerospace graduate students Prakhar Mehrotra and Jon Mihaly. It brought together two teams of students, assembled from participants from around the world, to develop plans for deep-space missions that could carry humans to an asteroid and back. Both Team Explorer and Team Voyager planned missions to an asteroid known as 1999 AO10, which is between 45 and 100 meters in length and is thought to have a relatively slow spin rate. Since little is known about this asteroid, both teams called for robotic precursor missions that could gather information needed to help plan the later human mission. The competing mission descriptions from the teams were so evenly matched that the jurors had to use three different judging methods to finally settle on a winner. In the end, the victory—and shiny new iPads—went to Team Voyager.

For more information, visit kiss.caltech.edu/workshops/space-challenge2011.

LEAD: Launch of Summer Engineering and Computer Science Institute

Building upon Caltech's mission to benefit society through research integrated with education, Computing and Mathematical Sciences lecturers Michael Vanier and Donnie Pinkston partnered with the Caltech Center for Diversity and Apple, to work with 23 diverse and gifted high-school sophomores and juniors. The students came to Caltech as part of the Leadership Education and Development (LEAD) Summer Engineering Institute. The goal was to immerse the students early in their academic development to the innumerable career opportunities in engineering and computer science, empowering them to confidently make better-informed decisions when choosing a university and career. The students' summer projects included a Sudoku solver, a "15-puzzle" sliding-tile game, and a Pong game. The games were a great hit at the final presentations, which were attended by Caltech faculty and staff, parents, and representatives from Apple.

For more information, visit cms.caltech.edu/news/389.



LEAD students Nicole Crawford, Khiana Lowe, and Pablo Lozano

Donnie Pinkston, LEAD CS instructor, and LEAD student Wesley Shipp



Who's New

Three new Engineering and Applied Science faculty members have arrived this fall.

Hyuck Choo

Assistant Professor of Electrical Engineering

Professor Choo's research focuses on micro/nanotechnology-based devices such as nanophotonics, biological and biomedical imaging, and ultrahigh-density magnetic data storage. His research with nanophotonic devices centers around focusing light to create the next generation of magnetic data storage devices. In the area of biomedical imaging, he is developing optical techniques to capture the high-resolution images of biological structures without using toxic dyes or harmful rays. Finally, he engineers optical micromechanical systems that can precisely track and characterize the neuromechanical activities of an individual insect in a swarm. The potential application of this research is in building energy-efficient, nature-optimized, self-coordinating robots.

Choo received his BS (1996) and MEng (1998) in electrical and computer engineering from Cornell University and his PhD in electrical engineering and computer sciences from University of California, Berkeley (2007). He has worked at Kionix, Inc., in Ithaca, New York, and was a Postdoctoral Fellow at the Berkeley Sensor & Actuator Center and the Lawrence Berkeley National Laboratory, where he worked on micro/nanoscale optics and surface-enhanced Raman spectroscopy. Choo is a recipient of the Sevin Rosen Funds Award for Innovation and the Lim Pre-Doctoral Prize.

Visit eas.caltech.edu/people/4982/profile.



Choo



Kochmann

Dennis Kochmann

Assistant Professor of Aerospace

Professor Kochmann's research combines theoretical, computational, and experimental solid mechanics to study the link between microstructure and macroscopic properties of a variety of engineering materials. One of his areas of research is the simulation of microstructures in crystalline solids (such as metals). In contrast to many current phenomenological theories, Professor Kochmann's research aims at physics-based, and hence predictive, multiscale models applicable to polycrystal plasticity and twinning. Another of his research areas is the design of novel composite materials with tunable performance, for instance, materials whose stiffness and damping can be tuned by orders of magnitude, reaching viscoelastic stiffness greater than that of a diamond. He designs these materials using a careful composite architecture and utilizing phases with so-called negative-stiffness mechanisms.

Kochmann received his Dipl.-Ing. in mechanical engineering from Ruhr-University Bochum (2006), his MS in engineering mechanics from the University of Wisconsin-Madison (2006), and his Dr.-Ing. in mechanical engineering from Ruhr-University Bochum (2009). He was a Postdoctoral Associate at the University of Wisconsin-Madison as well as a Postdoctoral Scholar at Caltech. Professor Kochmann has received a Fulbright fellowship and a Feodor-Lynen fellowship from the Alexander von Humboldt Foundation.

Visit eas.caltech.edu/people/4717/profile.

Austin Minnich

Assistant Professor of Mechanical and Civil Engineering

Professor Minnich researches the physics and engineering of nanoscale heat transport. Nanostructured materials have novel thermal properties with applications in energy such as for thermoelectric materials, which convert heat directly to electricity. Minnich uses experimental techniques, including ultrafast optical experiments, to study transport at the length and time scales of the energy carriers themselves. These experiments measure properties of the energy carriers that are lost at macroscopic scales, allowing for a more complete understanding of nanoscale transport physics. Minnich also uses these results to design novel materials and thermal devices, such as more efficient thermoelectric materials and devices for thermal energy storage.

Minnich received his BS in engineering science from the University of California, Berkeley (2006), and his MS (2008) and PhD (2011) degrees in mechanical engineering from the Massachusetts Institute of Technology. Minnich is the recipient of National Science Foundation and Department of Defense graduate fellowships.

Visit eas.caltech.edu/people/4984/profile.



Minnich

new
faces

It's About Societal Impact

Engineering and Applied Science at Caltech

Societal impact is a glue that binds the seven Departments of the Caltech Division of Engineering and Applied Science (EAS). In the words of the Deputy Chair for Education, Professor Mani Chandy, "Societal impact is a driving force for an engineer and applied scientist. Applying fundamental science to societal problems is a key characteristic of our Division." To better understand how this approach to research and education is created and strengthened, ENGenious met with the leaders of the seven academic Departments.

Greater Impact Through Collaboration

Collaboration is central to the EAS approach of transforming basic sciences into societal impact. At the most macro level, this collaboration occurs through cross-divisional centers focusing on a variety of areas, including natural hazards, quantum entanglement, energy, bioinspired engineering, and information technology. In the next level of collaboration, Departments within EAS join forces. For example, the Departments of Computing and Mathematical Sciences (CMS) and Electrical Engineering (EE) have come together to support the efforts of Information Science and Technology (IST) to benefit science, medicine, and society. In particular, notes Professor Mathieu Desbrun, Director of CMS and IST, "researchers from the core

IST constituents of EE and CMS are together tackling a range of societal problems, from the design of prostheses and cornea implants all the way to green IT."

The CMS Department, Professor Desbrun notes, has brought together researchers from three different disciplines. "Scientifically speaking," he says, "the fact that we are mixing dynamical systems, computer science, and applied mathematics gives us a huge playground to play in. For instance, we have collaborations with NASA for coordination of satellites, and we have projects in biomedicine for treatment of diseases, so the mix has extreme leverage. Research-wise, we have plenty to do for the next few years."

The recent re-engineering of the EAS Division has also had a posi-

tive impact on the Applied Physics and Materials Science Department, explains Professor Oskar Painter (MS, '95), who is Executive Officer. "Some of the restructuring we've done has allowed us to speak in a more coherent, more unified voice to our Division and in turn to the greater Institute and community," he says. "Combining Applied Physics and Materials Science into a Department has broadened us intellectually and has broadened our perspective of research and teaching, which has great benefit for the faculty and students."

Professor Babak Hassibi, Executive Officer for Electrical Engineering and Associate Director of IST, echoes this take on the benefits of collaboration as they relate to teaching and learning. "I see the 21st century as an opportunity for the disciplines that have become highly specialized to begin to talk with one another. A lot of exciting research happens on the boundaries," Hassibi says. "For example, the areas of intercellular signaling, signal processing, and communication have been something that EE researchers have worked on for a long time. They can bring a lot to the table when collaborating with biologists. The EE students are open to this mode of thinking, and every year we have more undergraduates who double-major in areas that would not have been associated in the past, such as EE and biology or EE and

economics. The potential societal impacts of these new ways of thinking are boundless."

The Aerospace Department has a long history of redefining boundaries through collaboration. For example, Professor Guruswami Ravichandran,

"We are looking at lifelong education because it is not just about what happens while they are at Caltech, but what happens after they leave."

Mani Chandy, *Simon Ramo Professor and Professor of Computer Science; Deputy Chair for Education*

who leads the Department, is working with Professor David A. Tirrell in Chemistry and Chemical Engineering to understand how cells interact with extracellular matrix in a 3-D environment. In another project, his group is exploring the mechanics of cell scattering that leads to metastasis,

one of the most dangerous phases of cancer. "We are using a model cell cluster, which is our substrate, and a technique called digital volume correlation, which is a mechanics technique, to measure the displacements that are caused by cells when they are scattering," he explains. From the dis-



Mani Chandy with EAS students



Oskar Painter

“We are the people who live on the border between engineering and fundamental science, and we are the people who are able to transition the new science into technologies that really impact us, so you’re investing in your own future!”

Oskar Painter, *Professor of Applied Physics; Executive Officer for Applied Physics and Materials Science*

placements, we can understand the forces and how the increase in the stiffness of the surroundings leads to cell scattering. Such studies are helping in advancing our understanding of the role of mechanical forces in cellular processes.”

This blossoming marriage of engineering and biology is further described by Niles Pierce, Professor of Applied and Computational Mathematics and Bioengineering, and Executive Officer of the Bioengineering (BE) Department: “The field of bioengineering will revolutionize medicine, renewable energy, global health, and manufacturing over the coming decades. The potential is so vast that it’s a very enjoyable time to dream about what might be achieved. By taking a principles-based approach, we are positioned to play a profound role as biological principles enter the engineering arena.”

From Fundamental Science to Impact

The importance of fundamental science to address the greatest challenges faced by society is described by Tapio Schneider, the Executive Officer of the Environmental Science and Engineering Department: “With a background in physics and math, I was looking for a field in which there are unresolved fundamental science questions whose resolution is important for our day-to-day lives. The climate sciences are such a field; resolving its fundamental questions is clearly relevant for understanding our past and planning our future.” Professor Ravichandran further explains that

“we are not here only to educate engineers and scientists to work on today’s systems, but to create the systems of tomorrow. We believe that in order to achieve that, students need to have very strong fundamentals and truly understand the principles underlying the operations of engines, rockets, fluids, structures, and materials.”

In the area of mechanical and civil engineering, fundamental science is seen as a key to developing technologies that enable and improve society. “I see a range of technologies being developed in our Department that have the potential to improve society,” Professor Kaushik Bhattacharya says. “One of the more important issues is energy. Thus the research of all three of our recent faculty hires has an energy side. We are also working on a variety of biomechanical and biological engineering issues. Finally, we have a huge opportunity and a huge challenge in bringing rather fundamental principles of multiscale models into larger scale engineering—such as on the scale of earthquakes and geotechnical engineering and predicting these behaviors from small scales and fundamental principles.”

Professor Schneider goes on to make a key point about how science can impact societal decisions: “What we can deliver for society at large is solid scientific understanding of how our Earth environment works and how it responds as humans interfere with it. Solid and unbiased science is what we can deliver and should deliver. We are not interested in becoming embroiled in political controversy, and none of us are. Our focus is on gaining clear insights into natural processes and human effects on them, to provide

“I see the 21st century as an opportunity for the disciplines that have become highly specialized to begin to talk with one another. A lot of exciting research happens on the boundaries.”

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

a basis for making decisions, for example, about which policies are effective and efficient to improve air quality.”

To gain this clear knowledge needed to impact the future, Professor Painter appeals to the alumni to “invest dollars, invest time, invest thought. We are the people who live on the border between engineering and fundamental science, and we are the people who are able to transition the new science into technologies that really impact us, so you’re investing in your own future!”

Lifelong Education and Impact

As illustrated by the work of the seven academic Departments of the EAS Division, societal impact starts with an emphasis on education. “We want to ensure that anyone who touches the EAS Division accentuates and enhances his or her skills in lifelong education,” says Professor Chandy. “We are looking at lifelong education because it is not just about what happens while they are at Caltech, but what happens after they leave. Students are only here for four years as undergraduates, maybe



Babak Hassibi

“Scientifically speaking, the fact that we are mixing dynamical systems, computer science, and applied mathematics gives us a huge playground to play in.”

Mathieu Desbrun, *Professor of Computing and Mathematical Sciences; Director of Computing and Mathematical Sciences, and Information Science and Technology*



Mathieu Desbrun

five years for graduates, two years for postdocs. These are short periods of time. They've got a thirty- to forty-year career ahead of them. We need to help ensure that they perform superbly at every stage in their life!" He adds, "The Division's commitment to lifelong learning is evident in the increasing importance of the Center for Technology Management and Education."

Professor Ravichandran describes how this approach to education is implemented in the Aerospace Department: "Our students are

trained in the broad disciplines of fluid mechanics, solid and structural mechanics, and materials and propulsion in aerospace systems and in space engineering, so that they are well prepared to work not only on problems that are of interest today but also the unknown problems of the future. To continue the preeminence of the United States in aerospace," he adds, "I think it's a good idea to invest in the young people who represent the future of this field. We need to have graduates who are well equipped and trained not only to solve problems but also to develop more efficient systems

G. Ravichandran



"We are not here only to educate engineers and scientists to work on today's systems, but to create the systems of tomorrow."

G. Ravichandran, *John E. Goode, Jr., Professor of Aerospace and Professor of Mechanical Engineering; Director, Graduate Aerospace Laboratories*

and spacecraft to explore the unknown. There are many opportunities in space, not only in space exploration, but also in areas such as energy harvesting."

Professor Painter tells his graduate students that it is his job to make sure a PhD degree is more than a graduate school accomplishment for them—it's a mark of a quality scientist. "I think that if you have a dual nature in that you really enjoy tinkering with things like electronics or radios and you also enjoy the mathematics and physics behind such devices, then you should consider Applied Physics and Materials Science. It allows you to live in both worlds. You get to do theoretical work as well as continue to tinker and build new things. You're going to get an education that allows you to be a serious physicist, but also allows you to be an engineer, entrepreneur, and a technologist."

Professor Chandy summarizes the EAS approach to education as a holistic one: "It's not merely about science as an end to itself, but rather success is measured by how the research makes a difference in somebody's life. We tend not to distinguish between theory and application. We don't distinguish between education and research; we expect the best teachers to be excellent researchers and vice versa." Speaking directly to alumni and friends of the Division, he says, "If you care about people individually or you care about society, then you have to be concerned about sustainability, you have to be concerned about disease, you have to be concerned about hazards. If you want to help people in the long term, then



Tapio Schneider

"We at Caltech can take a step back and ask, 'If we want a much better climate model ten years from now, what can we be doing now?' We have the luxury of thinking about approaches that are substantially different."

Tapio Schneider, *Frank J. Gilloon Professor of Environmental Science and Engineering; Director, Ronald and Maxine Linde Center for Global Environmental Science; Executive Officer for Environmental Science and Engineering*

invest in science that impacts society. How do you invest in science? By investing in the lifelong learners—today's students who will impact our society for the next 50 years."

A Long History of Greatness and Impact

The EAS Division has a rich and long history, with several Departments more than a century old. When planning for the future, many of the leaders reflected on the great researchers and educators that came

before them and how they are standing on their shoulders. "In many ways, I missed the heyday of Applied Physics," Professor Painter says. "Applied Physics at Caltech was started in the late '70s, so it's not that old, but a lot of important things were done prior to my time and I think it's important for me to learn from the alumni about how things were done back then and figure out ways of maintaining that strength." Professor Ravichandran says, "The Aerospace Department is headed in many ways back to its roots. The Department started in

“I see a range of technologies being developed in our Department that have the potential to improve society...we have a huge opportunity and a huge challenge.”

Kaushik Bhattacharya, *Howell N. Tyson, Sr., Professor of Mechanics and Professor of Materials Science; Executive Officer for Mechanical and Civil Engineering*

1928 as part of bringing scientific understanding of phenomena which were of interest to the aeronautics industry. At the time, the aeronautics industry in Southern California and in the United States was in its nascent stage. Today we have similar new opportunities in space: the next stage of space exploration, such as a mission to an asteroid or to Mars. To remain a leader in these areas,” he says, “we need to develop expertise in flight,

materials, propulsion, and systems. To this end, we are also strengthening our connections with the Jet Propulsion Laboratory.”

Almost a year after celebrating the centennial of Electrical Engineering at Caltech, the students are still very energized, Professor Hassibi reports. Speaking on behalf of the EE undergraduate students, he shares a need: “At the moment, all the equip-

ment that undergraduate students can use is attributed to either a particular course or a particular research group. If there’s an undergraduate that has an idea and wants to build something on their own, they’re really on their own. We’ve tried through the student organization to get some money to fund an undergraduate lab, but to do so they will have to accrue the money over several years. If any of the Caltech alums were interested

in funding such a thing, I know the students would greatly appreciate it!”

The roots of the ESE Department are also quite deep and interdisciplinary, Professor Schneider notes. “The modern study of ice sheets, their mechanical properties and stability to perturbations, started here at Caltech in the 1960s, and for many glaciologists, Caltech is the holy grail. Also, Caltech scientists were the first to discover that lead was accumulating in the environment and in humans, and first figured out how smog forms from tailpipe and industrial emissions. This led to the banning of lead additives in gasoline and to the Clean Air Act and the re-engineering of internal combustion engines. We and our children are breathing much cleaner air because of pioneering environmental research at Caltech.”

Taking Risks

The research with the greatest societal impact very often also poses the greatest risk, to both researchers and investors. Professor Schneider explains, “At Caltech, we are in a unique position to deliver a broad, big-picture understanding of environmental systems. Of course there are many people working on similar questions, but many are focused on shorter-term results, such as producing next year’s climate projection. We at Caltech can take a step back and ask, ‘If we want a much better climate model in ten years, what can we be doing now?’” At Caltech, Schneider notes, “we have the luxury of thinking about approaches that are substantially different from the current mainstream, rather than being merely incremental advances over it. These approaches may have a higher risk of failure, but they also have a much higher potential payoff in the longer run. It helps,” he adds, “that we have access to private funds at Caltech, because they help us start radically new projects. Once we can prove the

viability of new approaches, it’s not so difficult to get other funding. But the initial ‘intellectual venture capital’ is crucial, and Caltech is uniquely good at providing it.”

Such seed grants, Professor Bhattacharya says, have transformational power. “When you do research, you often have a new idea, but it’s very new and unconventional. It is at that point that you need a little bit of support. Faculty members will tell you that some of the best work they’ve done is from these seed projects. The first thing you want to know is: Will that work? And if it works, how good will it be? In that situation, you don’t need a very large effort; you need to break the conventional wisdom, and those are the kinds of projects that are the hardest to obtain support for from traditional funding agencies—and those are the kinds of projects that private philanthropy helps us the most with. They also have the highest failure rate because that is the nature of it,” he says, “but the ones that succeed have an incredible impact! You are really enabling things that would not have happened otherwise.”

“We are not after one-off success,” Professor Pierce says. “We are after principles that can underlie a sustained technological revolution over the next three decades. Caltech and EAS are an oasis for research. Tiny and excellent! Because of our small size, we know each other, we talk, we think up ideas together, and we collaborate. Because we are small, we cannot afford to take small risks. We must take big risks. We must identify and tackle the challenges in our fields with the potential for the highest possible impact. It’s an exhilarating experience to think and work in this environment.” ■ ■ ■

Learn more about the faculty at eas.caltech.edu/people, and visit eas.caltech.edu/research_centers to learn more about the research centers.



Niles Pierce

“We are not after one-off success. We are after principles that can underlie a sustained technological revolution over the next three decades.”

Niles Pierce, *Professor of Applied and Computational Mathematics and Bioengineering; Executive Officer for Bioengineering*



Kaushik Bhattacharya

Arati Prabhakar: Leaving the Conventional Trajectory

The most important thing Arati Prabhakar (MS '80, PhD '85) learned at Caltech was that she didn't want to do what was expected of her. After becoming the first woman to earn a PhD in Applied Physics from Caltech, Dr. Prabhakar did anything but follow the traditional route for graduate students at the time.

She first became a Congressional Fellow at the Office of Technology Assessment before serving as a Program Manager and Office Director at the Defense Advanced Research Projects Agency (DARPA) from 1986 to 1993. After serving President Clinton for several years as Director of the National Institute of Standards and Technology, she went to Silicon Valley, where, for the past 14 years, she has been funding and managing world-class engineers and scientists to create new technologies and businesses. In this interview, we find out more about this accomplished trailblazer.

ENGenious: What was your experience as the first woman to receive a PhD in Applied Physics at Caltech?

Prabhakar: I was an Indian immigrant kid who came from a family where my mom started sentences with, "When you get your PhD," and it wasn't a joke. It was sort of an expectation. But, at that time, the students at Caltech were pretty clueless about women. It certainly wasn't thoughtfully hostile, though. On the other hand, it wasn't particularly welcoming. People were just sort of confused. They didn't quite know what to make of it. A couple of women had come through the Department and had decided to change fields. I remember a guy down the hall greeted

me with, "I hope you make it." But he said it with a sense of possibility. The progress that we've made over the last generation or two is pretty interesting. I have kids who are in middle school and starting high school this year. In the environment that they live in, girls talk about being engineers and no one gasps and thinks it's remarkable. It's changed pretty dramatically since my time. The broader involvement you have across society in our profession, the healthier it is for what engineers really care about, which is coming up with solutions that solve problems for our society.

ENGenious: How has your Caltech education influenced you?

Prabhakar: Well, Caltech for me was not a pleasant experience. Other alumni would say, "Oh, those were the best years of my life," and I thought, the best years? I didn't get a lot of jollies out of it. On the other hand, it was a very important experience. Initially, I was on the trajectory to get a PhD with the expectation that I would be an academic, but I rapidly realized that was not what I wanted to do. Today, new PhDs go off and do a huge range of interesting things, but when I graduated in '84, you were expected to go into a tenure-track position at a university, IBM Research, Bell Labs, or some



other serious laboratory. Those were the only choices, and none were what I wanted to do. My advisor, Professor Thomas McGill, was the kind that thought a PhD degree should be an enabler. He didn't see it as a sin to leave research. Out of the blue, Tom said, "Why don't you go be a Congressional Fellow?" Tom was someone who enabled you to do whatever you needed to do. That's such an important person in your graduate career. When you're young and right out of school, it's a great time to just do something without plotting out the whole rest of your life.

Having a very solid technical foundation really helped with judgments I had to make in my career. My first major job after I left Caltech was at DARPA as a Program Manager. I was investing in people that I thought were going to make big leaps forward in technology. I wasn't in the lab doing the work, but I was trying to exercise good judgment about where real breakthroughs might come from. That wouldn't have been possible without the solid technical foundation I received at Caltech.

ENGenious: What have been some of the most satisfying times in your career thus far?

Prabhakar: When I left the conven-

tional trajectory, a whole range of new options opened up to me. After about a year and a half of being a Congressional Fellow, I got the chance to become a Program Manager at DARPA. It was a dream job for me at that time in my life. I walked into the door and someone handed me 10 to 20 million dollars and requested that I find the highest-impact R&D in the area, the one that's really going to make a difference in the world. It was wonderful. I had the privilege of building some programs over time at DARPA that I think have had a lot of impact in the long term. That's one of the most satisfying things. I was at DARPA from '86 to '93, and in that period a lot of our investments were in new semiconductor technologies and, in particular, semiconductor process technology and lithography. In the late '80s, 193-nm photolithography was sort of a pipe dream. No one had the right laser sources. No one had the right optical materials. It was pretty clear that we needed some kind of solution. X-ray lithography didn't really seem like it was a very promising way to go to me, although there was a lot of money getting dumped into that. So, we planted some seeds in the late '80s, and now the chips in your cell phone are made from the tools that use that technology.

ENGenious: What role can government play in new technology development and implementation?

Prabhakar: Well, for energy technology specifically, as in other areas like telecom, there is a critical role for government action. This action includes investments in R&D and setting policies and regulations that define boundaries on the market. However, we're living in a dynamic environment. Geopolitics change. Energy supplies change. New tech-

nologies come online. How do you deal with all of those factors? We need to exercise judgment based on the dynamics of what's happening right now. So, how do you do that? You nurture the ability to adapt and listen to what's going on in the world and implement programs in a way that is going to achieve the right objective. I feel a great privilege in having worked in organizations such as DARPA and National Institute of Standards and Technology [NIST] that can do this. This doesn't happen by accident. It happens by building organizations with people who are able to interact with the outside world—people who are given the autonomy to think and listen and then exercise judgment and who are held accountable for what comes out of that judgment. If you don't have that,

"I walked into the door and someone handed me 10 to 20 million dollars, and requested that I find the highest-impact R&D in the area.... It was wonderful."

you don't get the caliber of judgment that you really need to deal with these complex dynamic issues.

ENGenious: Where does the United States stand in resolving the global energy crisis?

Prabhakar: There is a huge amount of interest in moving to cleaner energy sources and addressing these issues, but you're not going to get that enthusiasm in places where livelihoods and family income depend on coal. We just have to be realistic, and when you peel those layers back, it's about different financial interests and fears. This has to be dealt with. The good news in the United States is that we do have a very strong technology foundation and the innovation engine to come up with new solutions. There are a host of very exciting new ideas that are bubbling and brewing, such

as artificial photosynthesis and ways to store energy at scale.

As an engineer, the question in my mind is, What is it really going to take for any one of these to make a real impact on the way we create and use energy? We're still, by far, the global leader in that area, but I don't take that for granted. Unless that is continuously nurtured, it will shrivel up. If the markets don't develop here over time, the technology advantage will wither away. Thus, not only do we have to fund the technology, we have to make sure that there's some place for it to go in a domestic market to thrive over time. The change process that we are on is not going to take us from today's energy system to tomorrow's energy system, and then we're done.

This is going to be a continuing process of transformation. And that's not something our energy system is very good at doing.

ENGenious: What advice would you give to the next generation of Caltech graduate students?

Prabhakar: Realize that there are so many things you can do with the foundation that you get at a place like Caltech. I really am grateful that I had the experience. Both the learning and the Caltech experience, which is very personal. When you live in an academic environment, there's a tendency to think that what you see around you is all there is, but it's not. It's just one small piece of a much bigger world, and it's a world in which you can take that foundation and do a lot of different, interesting, and impactful things. ■ ■ ■

There is a long history of positive accidental results in experimental science. However, when a paralyzed man regains some of his voluntary movements in the accidental result, there is some humanitarian icing on the cake.

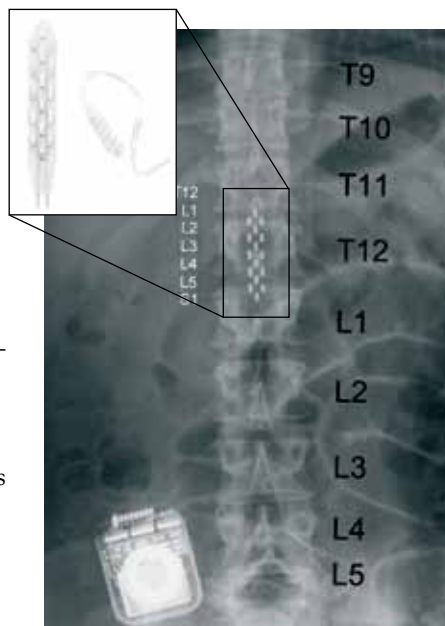
The Next Step: Stimulating Electrode Array Assists Paraplegic Man to Stand and to Move Legs Voluntarily

By Joel W. Burdick, *Professor of Mechanical Engineering and Bioengineering*

Our Caltech team, which includes Yu-Chong Tai, Professor of Electrical Engineering and Mechanical Engineering, in collaboration with Professor Reggie Edgerton at the University of California, Los Angeles, and Professor Susan Harkema at the University of Louisville, has used an epidural stimulating electrode array to assist a 25-year-old paralyzed male athlete to stand, to step on a treadmill with assistance, and, over time, to regain voluntary movements of his limbs. Using a combination of experimentation, computational models of the array and spinal cord, and machine-learning algorithms, we are now trying to optimize the stimulation pattern to achieve the best effects and to improve the design of the electrode array. Further advances in the technology should lead to better control of the stepping and standing processes. More importantly, we hope to better understand and advance our ability to help patients regain voluntary control over their once-paralyzed limbs. We are continuing our experiments to try to duplicate these results on other patients, and our initial results on our second patient are very encouraging.

While my primary research focus has been robotics and mechanical systems, for over a decade I have been investigating and developing adap-

tive electrode arrays that can interface computers to damaged nervous systems. For nearly a decade, my group collaborated with Caltech's Profes-



Implanted electrode array. Inset: Electrical leads implanted in the paraplegic patient.

sor Richard Anderson in the area of neural prostheses, which are direct brain interfaces that allow control of electromechanical devices by thoughts alone through the use of surgically implanted electrode arrays and associated computer algorithms. Eight years ago, my group started working with Dr. V. Reggie Edgerton, Professor of Neuroscience at UCLA, who has worked on spinal-cord injuries

for many years and, in particular, on the use of epidural stimulation as a potential therapy. In epidural stimulation, the stimulating electrode is not directly implanted into the spinal tissue. Such a placement would require opening the dura (a thick sheath surrounding the central nervous system), increasing the possible chances for a life-threatening infection. Instead, epidural stimulating electrodes are placed in the *epidural space* that exists between the interior walls of the vertebra and the dura. We were able to bring some new ideas to Dr. Edgerton's extensive experience in this area. We introduced the idea that an epidural electrode array, in contrast to the small number of wire electrodes used at the time, should significantly improve our ability to more precisely control the stimulation process, leading to better outcomes.

To build these arrays at a small enough scale for experiments in rodent models, we engaged Professor Yu-Chong Tai's group to develop miniature micro-fabricated electrode array systems. While the development of micro-fabricated array technology is still ongoing, our initial animal results with these arrays were impressive enough to convince the National Institutes of Health and the Food and Drug Administration to allow us to implant five humans with epidural stimulating arrays.



Joel Burdick with a robotic device that he developed to train a paralyzed rat's rear legs to recover motor skill while stimulating the animal's nervous system with electrodes implanted along the spine.



Multi-university team working with Rob Summers.

Our first patient, Rob Summers, was a top-tier college athlete who was severely injured when he was hit by an automobile. Rob had been in a wheelchair for nearly three years at the time we implanted a 16-channel electrode array over the lower portion of his spine. Within three weeks after the implantation, the physical therapy team at the University of Louisville had him standing independently with the aide of stimulation. Perhaps more importantly, after about five months of daily stimulation and exercise, Rob started reporting increased control over his bladder and bowel function. In many spinal-cord injuries, not only is the ability to control muscles lost, but the autonomic nervous sys-

tem, which controls bladder, bowel, breathing, blood pressure, etc., is severely damaged. Amazingly, starting at eight months after implantation, Rob regained the ability to voluntarily command movements of his lower limbs. At first, he could wiggle his toes, then he could move his knees, and finally he could flex his hips. These voluntary movements required the stimulating electrode array. Very recently, however, 21 months after the implantation, he made his first voluntary movement without the aid of the stimulator. Over this period, Rob has regained essentially full control of his bladder and bowel, and has significantly improved cardiovascular health, as well as increased sensation below

the level of his spinal injury. We never anticipated these collateral benefits to our human subject!

In early August 2011, we implanted our second human subject. Already, this subject is following the same recovery trajectory we saw in Rob, and in several areas, he is recovering even more quickly. So, it appears that our results can be replicated.

One of my main research objectives is to develop the theory and algorithms that will help us better optimize the stimulating patterns that we apply to the array. At the moment, we find the “optimal” stimulating parameters

by brute-force experiment. As our ability to fabricate and deploy arrays with greater numbers of electrodes increases, it is practically impossible to explore the vast space of possible stimulating parameters by brute force alone. To address this problem, my group is pursuing two approaches. First, we are developing a computational model where the entire bio-electrophysics of the electrode array stimulation process is captured. We are building increasingly accurate geometrical models of the spinal cord using high-field-strength MRI

this problem, we are working with Professor Andreas Krause to develop a machine-learning algorithm to optimize the stimuli. In this process, we apply an electrode stimulation pattern and then watch how the animal or human responds. Based on the response, we use an algorithm that figures out what stimuli should be tried next. It's excellent at starting to build an internal mental model of how the arrays work and then trying to optimize and explore different stimuli over time. Since every person's injury and subsequent response to

the physical therapy. We have also started to build equipment that can be used by our patients in their home environment. We are now considering automation of the type that we have developed for our animal work in order to allow this human therapy to be deployed on a larger scale.


This is a very exciting area of research, and many questions still remain. In no way have we come close to finding a “cure” for spinal-cord injury. But our initial results are promising, giving us the hope

“Rob has regained essentially full control of his bladder and bowel, and has significantly improved cardiovascular health, as well as increased sensation below the level of his spinal injury. We never anticipated these collateral benefits to our human subject!”

images obtained in Caltech's Broad Imaging Center. The electrical properties of the different spinal tissue components are superimposed on the geometries extracted from the MRI model. Next, we build models of the electrode arrays with their resistive and capacitor properties. Then we can simulate how the electric fields penetrate the tissue, and the probabilities that the fields excite or facilitate the operation of different types of neurons. A number of questions can be addressed with the computational model. How do we optimize the electrode stimulation pattern that we apply? Can we use the stimulation to help us optimize the array design itself? Do we want more electrodes or fewer electrodes over time? Should the electrodes be bigger or smaller? Should they be placed toward the side of the cord or more toward the middle? What is the optimal shape(s) of each electrode? All of these questions can be considered with the simulation system.

Because no model can be perfectly accurate, in our second approach to

stimulation is bound to be a little bit different, such an approach is necessary to fine-tune this therapy for each patient. Also, as a patient recovers, the necessary stimuli will change over time. We did not have the learning algorithm ready for patient number one, but we plan to use it for patient number three. Ideally, in the future there will be a smart algorithm monitoring the patient's response on an ongoing basis, perfecting the stimuli to meet his or her evolving needs. Right now, clinicians monitor and adjust the stimuli based on observations and intuition. This is great on a one-patient one-clinic basis, but how do we replicate it to more clinics and patients? Clearly, algorithms embedded into the stimulating infrastructure can help with this scaling problem. Physical training must be carried out in conjunction with the epidural stimulation to achieve a successful outcome. The lumbosacral locomotor circuitry must adapt to the new command signals provided by the stimulating array. In our animal work, we have developed specialized robotic devices to administer and monitor

that this therapy can have a positive impact on a wide range of the spinal-cord injured. Can we accelerate the process and make it work in a variety of patients? That is our next challenge. If we can understand the method better and understand the neurobiology better, we can then try to optimize the technology and its delivery for a wider range of people with different kinds of injuries. There are also tantalizing hints that this approach may also provide some benefit to other debilitating conditions, such as stroke or Parkinson's disease. In the long run, a *biological* approach (stem cells, neural tissue implants, or genetic manipulation of the neural regrowth mechanisms) is clearly the preferred solution. However, such a solution is very likely to benefit from, and perhaps even require, the approach that our Caltech, UCLA, and Louisville team has been developing. 

Joel W. Burdick is Professor of Mechanical Engineering and Bioengineering.

Visit eas.caltech.edu/people/2953/profile.

Sossina Haile, Professor of Materials Science and Chemical Engineering, researches ionic conduction in solids, with the twin objectives of understanding the mechanisms that govern ion transport and applying such an understanding to the development of advanced materials for energy technologies. In this article, she discusses her research in the area of solar fuels and her recent work in Africa.

Creating an Energy Roadmap to Maximize Societal Benefit

Energy—it is at the tip of the tongue of almost every politician today, the subject of many a heated dinnertime conversation, and the overriding technological challenge of our era. What should we do to solve the problem? How do we even define the problem? These are questions that scientists and engineers must address with full force if our society is to emerge from its current uncertainty into a sustainable energy future. We must help create the energy roadmap to maximize societal benefit.

Let's accept that our energy problems encompass all aspects of finite supply, geopolitical instability, and environmental damage. The next questions concern the solution: Which energy resource and strategy makes the most sense? Is this a question even worth asking? Should all options remain on the table, or should we start to pare things down? In my view, we have to provide a balanced response. Of course, every energy solution involves trade-off, but we have to make the effort to sort out which are possible big players with potential impact on a large scale and in a time frame that matters. We have limited financial and human resources. We have to be strategic in how we deploy these resources. If we do make the effort,

we can eliminate some ideas from the start, or at least put them on the back burner. Some approaches are unlikely to pan out for reasons such as very high cost or reliance on rare materials.

On the other hand, we cannot focus all the way down to one single solution. We are simply not so prescient to be able to say with full certainty what will work and what won't. Even if we were, Earth is not a "one-size-fits-all" kind of place. Different parts of the world have different energy resource bases. It goes without saying that some places are sunny, others are windy, and others still are bombarded with tidal waves or have vast, powerful rivers. We have to recognize that Earth is varied, and so our energy solutions will also have to be varied to maximize benefit.

solar fuels

That said, let's go back to the idea of picking likely winners. Among the energy resources available to the planet, hands down, the solar resource base is largest. It is an oft-repeated

statistic that the amount of sunlight that hits Earth in one hour is more than all the energy we consume in a year. Therefore, it makes a whole lot of sense to increase the amount of solar energy we use. It won't run out, it is domestically available, and, for the most part, it is environmentally sound. But everyone knows that the sun doesn't shine all the time. So how do we make this resource available whenever it is needed? How do we store the solar energy for immediate, on-demand use? The scientific community has created an answer—"solar fuels." This is an entirely new strategy for solar energy storage that was born in just the past decade.¹ What this appealing phrase means is to use solar energy to convert carbon dioxide and water, which don't inherently have any energy content, into chemical fuels such as hydrogen, methane, synthesis gas (a mixture of hydrogen and carbon monoxide), or whatever compound you prefer, that do have energy content. Essentially, the solar energy is used to "undo" the effects of combustion. Fuel is a fantastic way to store solar energy because we already have an infrastructure that makes use of it, it has an infinite shelf-life (it doesn't self-discharge like batter-



Sossina Haile

ies), and the amount of energy stored per unit volume or per unit mass is extremely high (several times higher than batteries). So converting solar energy into liquid fuels has become a major topic of research.

There are many ways to go about making solar fuels. Our approach involves concentrating the sunlight to create high-temperature heat that can drive the chemical reactions. The big advantage here is that we are able to use the entire solar spectrum—that is, all the wavelengths of sunlight. Most other approaches use some but not all of the wavelengths, which means some of the light gets thrown away. Another

major advantage is that our process works extremely well for making carbon-containing fuels, whereas many others are very much focused on producing hydrogen. Hydrogen will be terrific if and when we have a hydrogen delivery infrastructure. In the meantime, converting solar energy into liquid fuels makes a lot of sense. Of course, there is no silver bullet. Our process requires extremely high temperatures, up to a whopping 1600 degrees Celsius. It can be done, but the engineering required is quite impressive. To get to these temperatures, we work with colleagues who know how to design and construct parabolic mirrors that can concentrate sunlight one thousand times—mean-

ing the sunlight is focused down to an area one thousand times smaller than the original area of solar exposure. At the same time, we are modifying our reaction scheme so that it can work at lower temperatures. Even without improvements, we probably hold the world's record for solar fuel production.

Recently, I've come across a wonderful opportunity to become more directly involved in the societal impacts of technological advances. I have started work with the National Science Foundation (NSF) to advance educational opportunities and technology transfer with Africa, beginning in East Africa. The NSF invited two colleagues and me to establish a materials institute that would initially be a virtual institute. There, we will bring together young American and African scientists—at the graduate student and postdoctoral scholar level—for an extended workshop to provide educational opportunities and to uncover potential areas for collaboration. Our plan is to offer the content in the area of materials for energy in a two-week, short-course format in a relatively intimate setting of 60 students. The NSF has agreed to support a one-year pilot, which is tentatively scheduled for mid-June and will be held in Ethiopia. The topical area is, I believe, timely. The sustainable energy resource base in Africa is enormous, including solar, hydro, and geothermal, yet less than 20 percent of the population has access to electricity. In many cases, making use of these resources requires advanced materials, and our short course will address precisely the development of such materials. My work in Africa is only beginning, but I am hopeful its impact will be far-reaching. ■ ■ ■

Sossina Haile is Professor of Materials Science and Chemical Engineering.

Visit eas.caltech.edu/people/3037/profile.

¹In the period from 2000 to 2010, the number of annual scientific publications with the phrase "solar fuel" in the abstract skyrocketed from 430 to almost 8,000.

David W. Thompson (MS '78) is the Chairman, Chief Executive Officer, President, and co-founder of Orbital Sciences Corporation. ENGenious sat down with him to learn about his time at Caltech and the other experiences that inspired him to start one of the world's leading developers and manufacturers of smaller, more affordable space and launch systems.

From Grasshoppers and Mice to Monkeys and His Sister? What Inspired David W. Thompson to Start a Rocket Company

ENGenious: What inspired you to become an engineer?

Thompson: When I was three years old, my father took me outside in our backyard one fall evening, just after sunset. We looked up in the sky and saw a bright object that had the appearance of a star, except it was moving very rapidly. It was one of the early Russian satellites. Ever since that moment, I've been fascinated by rockets and spacecraft. As I was growing up, it was natural for me to design and build my own amateur rockets. Using them, I would launch objects into the sky, which ranged from homemade electronics to grasshoppers and mice, on experimental flights. The largest of these rockets eventually reached about a mile in altitude and carried a small monkey.¹ Had I stayed in high school one more year, my sister was next up on the passenger list. Fortunately that didn't happen, and instead I was off to MIT for my undergraduate degree in aeronautics and astronautics.

ENGenious: Have you had a similar influence on your own children?

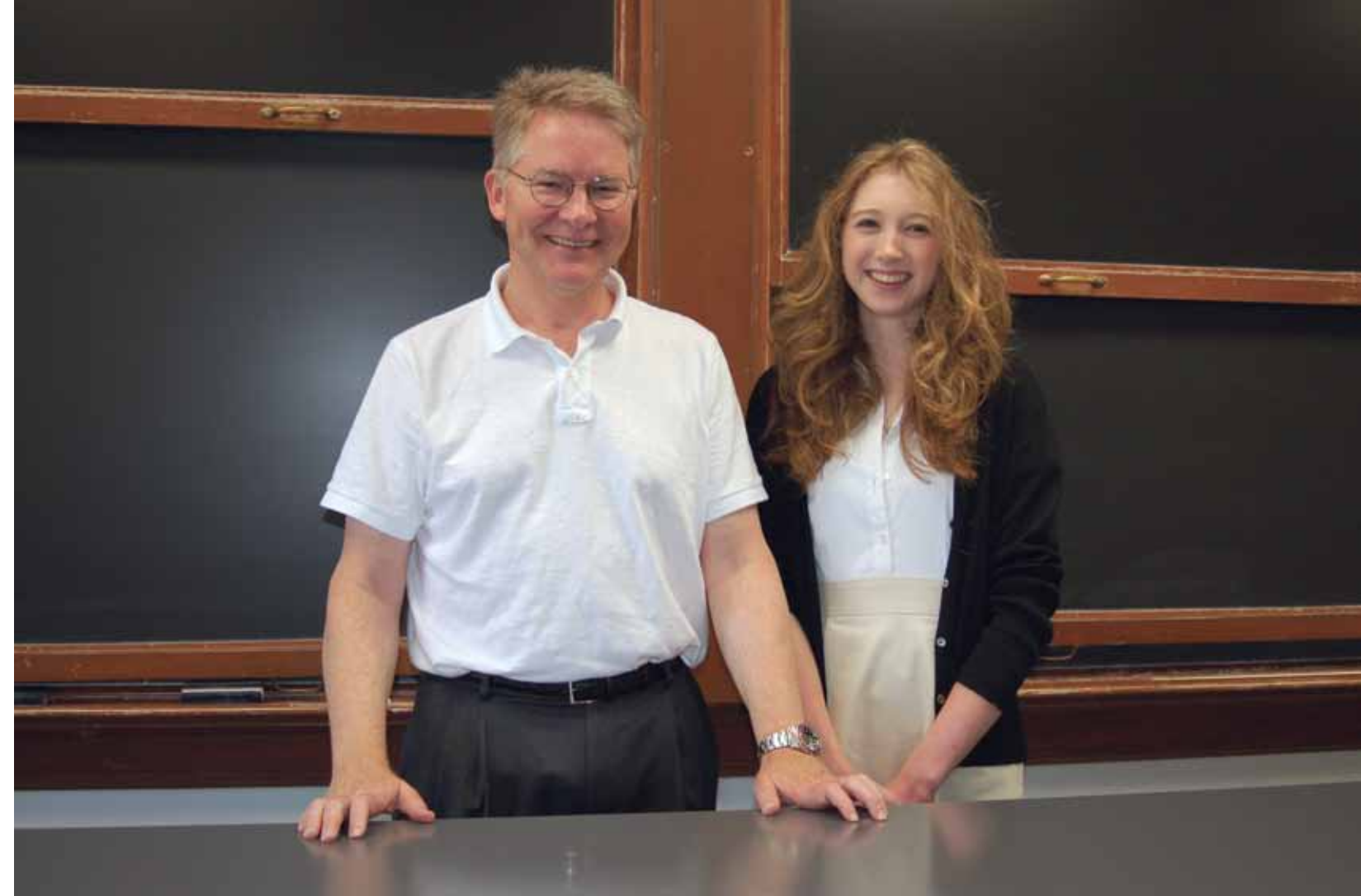
Thompson: Yes, perhaps to an extent. My daughter, Maggie, is more interested in space science than in the engineering focus I had. She has grown up with satellite projects being discussed at home and has traveled with me to rocket launches from a variety of places around the world, from Kazakhstan to French Guiana to Cape Canaveral. Most of all, she was particularly inspired when we attended a meeting some years ago that was honoring the Jet Propulsion Laboratory's contributions to the space program. At that dinner, there were three past directors of JPL as well as Dr. Charles Elachi, the Lab's current leader. She got to meet all of them and was especially taken with Dr. Lew Allen, who headed JPL in the late 1980s. That really sparked her interest in astrophysics, which is the field of study she's decided to pursue

in college. For the past two summers, she's helped Caltech scientists analyze information from an infrared astronomy satellite called WISE, which JPL operates for NASA. From this work, Maggie has more than 20 newly discovered sub-stellar brown dwarfs to her credit so far.

ENGenious: How has Caltech influenced you?

Thompson: As a Caltech graduate student, I was particularly intrigued by a case-study course taught by GALCIT faculty and visiting lecturers that chronicled the development of different aircraft and satellites. I was very interested in a satellite made by Hughes Aircraft Company called the HS-376, which for many years had the distinction of being the best-selling communications satellite in the world. In the course, I learned about not only the technological aspects of designing it, but also the

¹Did these animals come back to Earth safely? Yes—most of them, anyway...



David Thompson with his daughter Maggie

marketing and the financial challenges of building it into a successful business. As I pursued an MS in Aeronautics, an idea started to take shape—it originally struck me one afternoon when I was studying in the Kármán Laboratory at Caltech—that it should be possible to create a commercial rocket company. After graduating and spending a couple of years working at NASA as an engineer, I decided I didn't know enough about business to do this right away. Instead, I went to business school, where I got together with a couple of fellow students and carried out a research project for NASA looking at new opportunities in space commerce. After completing our MBAs, we continued to refine the commercial rocket idea. I ended up going to Hughes Aircraft, which was heavily populated

with Caltech graduates. For a year, I worked at Hughes during the day and further developed the concept for the company at nights and on weekends. My former schoolmates and I developed a more refined business plan that finally led us to incorporate Orbital in the spring of 1982. So the original, somewhat vague idea I had at Caltech as a graduate student in 1977 led, five years later, to the founding of Orbital.

ENGenious: What is a typical day for you like?

Thompson: My family and I live in northern Virginia, close to where Orbital is headquartered, so I have something unusual in the Washington, D.C., area—a short commute to work. There is a certain degree of

predictability in my schedule on a monthly cycle, but not so much on a daily basis. One day may be quite different from another. For instance, Orbital may have a customer visiting the company who wants to see how one of the satellites we're building for him is coming along. Or, if it happens to be a particular week in each month, we'll have a couple of reviews of the business results from our operating divisions. Perhaps I then would have a lunch meeting with a new group of employees to ask for some of their ideas and impressions while they're still pretty new to Orbital. Afterward, I might spend some time updating a presentation that will be used with investors to keep them apprised of the company's progress. Later, there might be a rocket program that has some problems that need to be

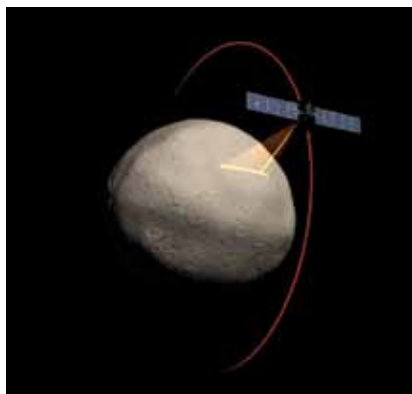


Artist's rendering of the Cygnus spacecraft, designed to transport supplies unmaned to the International Space Station.

investigated, or I might have a meeting at NASA headquarters or at the Pentagon. And before I know it, it's time to go home for dinner.

ENGenious: As a CEO, do you still use your technical background to make decisions?

Thompson: Yes, I do. Let me give you a recent example involving our communications satellites. We're always trying to improve their basic economic figure of merit, which is essentially the capacity of the satellite to generate revenue divided by the cost to build and launch the machine. It costs roughly \$100,000 per kilogram



Artist's rendering of the Dawn spacecraft gathering spectral data from Vesta.

to manufacture and deliver a satellite into orbit, so anything we can do to reduce its mass is extremely important. To this end, we have been looking at changing our propulsion system to use much higher performance electric thrusters, as opposed to chemical rocket engines, for in-orbit maneuvering functions. We've used similar technology on several deep-space missions for JPL, including the Dawn asteroid probe that is now in orbit about a large main-belt asteroid called Vesta. Next year, Dawn will restart its electric propulsion system to transfer to Ceres, the largest asteroid in the solar system. The spacecraft was launched about four years ago and has already traveled a couple of billion kilometers, but without its electric thrusters it would have been too heavy to reach one asteroid, to say nothing of a second. With that experience, we're now looking at whether ion propulsion or a related technology is sufficiently mature to be applied to commercial satellites. Decisions at this level—assessing whether the value to customers of using a new technology outweighs the risk of that technology—are the types of things I get involved in. But when it comes down to the engineering details, there are people at Orbital much smarter

than I am to do that work.




ENGenious: Why is Ceres interesting?

Thompson: It's a huge proto-planet with a surface area about seven times that of California. It's believed to be the only asteroid massive enough to have been pulled into a completely spherical shape over billions of years. And it's also thought to contain quite a bit of fresh water in the form of ice, with some scientists speculating that there may be more fresh water on Ceres than there is on Earth. If proven to be correct, this would make Ceres a popular destination for future deep-space missions, because not only is water vital to life, but its constituents, hydrogen and oxygen, are the best chemical rocket propellants that we know of. Just think: 500 years from now, Ceres could be the equivalent of a Middle Eastern oil field today. I'm afraid we'll have to leave that to future GALCIT entrepreneurs to capitalize on.

ENGenious: What advice would you give to aerospace students who are thinking of going to industry?



Hubble Telescope image of Ceres

Thompson: Well, the aerospace business has changed quite a bit in the 35 years since I first came to Caltech. The fundamentals of fluid mechanics, structural materials, propulsion systems, and so on remain important. But other technical areas have assumed greater prominence, such as systems engineering, communications and information systems, electronics, and software. The content of a new aircraft or satellite is now much more weighted toward some of these new disciplines. Therefore, one part of my advice to students would be to pursue a broad curriculum that provides a solid grounding in the traditional disciplines, but also covers aerospace systems engineering, electronics, communications systems, and software. A second suggestion is for students to get some early exposure to the practices of aerospace program management to give them a frame of reference for their subsequent careers. Many Caltech students are destined for positions beyond that of an individual technical contributor. They will become program managers, vice presidents of engineering, and heads of companies. In fact, we have a good number of Caltech graduates at Orbital in those positions today. The new GALCIT that has emerged in recent years, with closer connections to JPL in the space-systems engineering areas, is doing just that. It has always been strong in the fundamental aerospace sciences, but it's now emphasizing engineering and program management practices as well. The future for students at GALCIT is really bright. I can't wait to see what comes out of the current generation of Caltech students!   



Artist's rendering of the Taurus II rocket at the Wallops Flight Facility in Virginia.

David W. Thompson is the Chairman, Chief Executive Officer, President, and co-founder of Orbital Sciences Corp.

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Gerard Holzmann is a Faculty Associate at Caltech in the Department of Computing and Mathematical Sciences and is the Lead Scientist of the Laboratory for Reliable Software (LaRS) at the Jet Propulsion Laboratory (JPL). He was recently part of a small team of NASA and JPL engineers commissioned by the U.S. Department of Transportation to study the possibility of software triggers for unintended acceleration in Toyota vehicles.



Gerard Holzmann

Ruling Out Bad Behavior:

Designing Software to Make Extremely Dangerous Consequences Not Just “Unlikely” but “Impossible”

ENGenious: What inspired you to become an engineer?

Holzmann: You can view engineering as the art of combining components in such a way that the whole becomes greater than the sum of its parts. This is an effort to strive for perfection: the illusion that we can build things that work perfectly all the time and that accomplish things that we as humans cannot. The most interesting part for me is that no matter how hard we try, the perfection that we aim for almost always remains elusive.

Engineering is interesting because it perpetually confronts us with the frailty of our understanding of how things work. A computer program, for instance, can be “perfect” in the sense that it will make a machine do precisely what we tell it to do, in precisely the order in which we tell it to do it. But almost inevitably things still go wrong, not because the computer misunderstands our instructions, but because we as programmers don’t always appreciate the complexity of what we are trying to do, which

means that we often get the instructions wrong in subtle ways.

ENGenious: Can you give an example?

Holzmann: A few years ago, NASA lost contact with the Mars Global Surveyor (MGS). The spacecraft had been orbiting Mars since September 1997. It all started with a regular maintenance action involving a minor update to some parameters to increase their precision. But the update for one of these parameters was off by one word in the memory. This meant that this key parameter (and the one next to it in the computer’s memory) was corrupted and ended up having the wrong value. It went unnoticed at the time. Six months later, though, the solar panels’ positions had to be adjusted from winter to summer, but because of the first corrupt parameter the solar panels rotated too far. This automatically put the spacecraft in “safe mode.” Safe mode is programmed to have two priorities. The first is to be power positive—that means to make sure

that the batteries are always charged. The second priority is to maintain a communication link with Earth. Clearly, not doing so can lead to a loss of the mission. Since the solar panels were considered stuck, the only remaining way to point the panels at the sun to charge the batteries was to rotate the entire spacecraft, which was done automatically. As the spacecraft was charging the batteries, the fault protection system noticed that they were heating up. Typically, this means that they’re overcharging. So

Mars Global Surveyor (MGS)



the fault protection system decided that the batteries must be full and stopped charging. But the batteries were actually getting hot because the rotation that the spacecraft underwent in order to point the solar panels at the sun exposed the batteries to the sun as well. The fault protection system did not know this. To act on the second priority, the spacecraft had to point its antennas at Earth, but the Earth-pointing parameter was next to the soft-stop parameter for the solar arrays, and had also been corrupted in the earlier update. So the spacecraft was unable to find Earth as it tried to send out its calls for help. Next, the fault protection system noticed that the batteries had cooled off and were almost depleted—so it went back to its first priority. This cycle repeated a number of times until the batteries were fully depleted and the spacecraft became uncommandable. The curious thing is that the fault protection system was doing precisely what it was programmed to do, but there was this circumstance that nobody had thought of until it happened. How do you predict these things? Well, that is

very difficult, but it is precisely what makes this fascinating. You think you’ve covered all the possibilities, but you probably didn’t even scratch the surface.

ENGenious: How is JPL’s Laboratory for Reliable Software making flight software more reliable?

Holzmann: We started the Laboratory for Reliable Software when I joined JPL in 2003. It has the daunting task of trying to achieve long-term improvements in the reliability of the software we use to fly interplanetary space missions. So far, we’ve introduced the use of state-of-the-art static source code analyzers as part of the software development process at JPL. These analyzers can intercept a lot of common software defects that otherwise slip through. We’ve also

developed a new Institutional Coding Standard for all flight code developed at JPL, we initiated a new and more thorough code review process, and we’ve started a formal “certification” course for our flight software developers. We’ve made good progress in the last few years, but we don’t take anything for granted.

ENGenious: Tell us about being asked by the U.S. Department of Transportation and NASA to study the possibility of software triggers for unintended acceleration events in Toyota vehicles.

Holzmann: I was very fortunate to be part of the team of software experts that could work on this problem. I was asked to apply some of the techniques I developed for these types of problems in my years as a computing

science researcher at Bell Labs. We were given unlimited access to the source code that drives Toyotas and to the technical experts who could explain its working in detail. I learned more about the software controls in cars than I could have imagined. We immersed ourselves in this problem

“...to make sure that unacceptable events are actually rendered ‘impossible’—and not just ‘unlikely’...we first have to recognize that no single part of a complex system is ever perfect, and that includes the software.”

for about five months in 2010, working full-time at Toyota facilities in Los Angeles, and I believe we were able to complete a really thorough analysis of the code. The puzzle was the usual one: Can we find out how something that is not supposed to be happening might happen anyway? We were able to rule out a number of potential causes for unintended acceleration, although much of our analysis has not been released publicly. The complexity of an analysis like this immediately leads back to my original fascination with software complexity: it should be possible to design software in such a way that we can rule out bad behavior conclusively. My colleagues and I are today even more determined than ever to develop such a method for use in safety critical systems.

ENGenious: What are the main research challenges in reliable systems design?

Holzmann: The main challenge in reliable systems design is to make sure that unacceptable events are actually rendered “impossible”—and not just “unlikely.” To do this, we first have to recognize that no single part of a complex system is ever perfect, and that includes the software. The key is to build reliable systems from potentially unreliable parts. Nothing is foolproof. So we often try to




find a compromise between cost and benefit, but extremely dangerous consequences should be firmly placed outside such a cost-benefit analysis. Many have not yet fully embraced this approach, partly because it is tempting to interpret events with a very small probability of occurrence as virtually impossible. We only have to look at how nuclear power plants sometimes fail to see that extremely low-probability events are still very much possible.

ENGenious: Are engineering students trained well to design reliable systems? What, if anything, should change?

Holzmann: I think there are two possible answers to this. In most areas of engineering, the answer is yes. Civil engineers, for instance, can design a building or bridge to successfully withstand an earthquake of a certain magnitude. In software engineering, though, the answer is often negative. The prevailing belief is that the hardware has known failure modes, but that software can be perfect. The fault protection software onboard a spacecraft is designed to recover the spacecraft when a hardware problem strikes, but it is often powerless when a software problem occurs. The fault protection software itself, furthermore, can also be faulty or subtly incomplete. We should design

safety critical applications in medical devices, cars, power plants, and spacecraft with knowledge of the failure modes, including software failure modes. This is something that we are not very good at today.

ENGenious: One way of improving the reliability of systems is to have them tested extensively. Should members of the community participate in testing? Can systems such as OnStar help?

Holzmann: Direct measurement of the true performance of a system in practice is invaluable. It is how we learn the hidden flaws and what gives us the opportunity to adapt our designs to improve them. In a sense, all spacecraft that are currently active across the solar system have the equivalent of an “OnStar” button. Every time a spacecraft presses that button, so to speak, we learn something new about how the spacecraft we built yesterday works today and how it could be designed even better tomorrow.   

Gerard Holzmann is a Faculty Associate at Caltech in the Department of Computing and Mathematical Sciences and the Lead Scientist of LaRS at the Jet Propulsion Laboratory.

Visit lars-lab.jpl.nasa.gov.

ENGenious sat down with Eva Graham, the Director of the Caltech Center for Diversity (CCD), to learn more about the center and how it has been serving the Caltech community since its creation in 2008.

The Caltech Center for Diversity

Providing a Real Pathway to Membership for Underrepresented Students at Caltech

ENGenious: How was the CCD created?

Graham: It has been three years since the Office of Minority Student Education at Caltech was combined with the Women’s Center to form the Caltech Center for Diversity. In this area, Caltech was following a trend already established at several other educational institutes. It has not only been more cost-effective, but it also has given us the opportunity to reach communities that we may have missed before, because now we have overlap in expertise and programming areas. With the overlap, we are able to reach a woman who is African-American and Lesbian, Gay, Bisexual, Transgender, Questioning and Allies (LGBTQA). We are also down the hall from International Student Programs, which provides us with the opportunity to work with international students.

ENGenious: What has stayed the same?

Graham: We have maintained our programs for women and minority students. Their foci are the same. With women, we still focus on helping them access resources and become part of the community. Long before the CCD was created, the Women’s Center was doing a great job helping women understand their roles in science and engineering. I’m happy to say that now women are seeing themselves as part of an even larger community. There are larger numbers of women on campus, and we’re hearing less and less about inappropriate behavior toward women. Certain programs are as popular as ever, such as self defense, assertiveness, and programs related to being women in a laboratory environment (because they might still be the only woman in a lab). With minority students, the focus has always been on outreach, recruitment, and retention. We also focus on community building, because the numbers of minority students remain low.

ENGenious: What has changed?



Eva Graham

Graham: For the LGBTQA community, we’ve focused on providing a safe space for coming out and gathering. We continued a working group made up of students and staff. The students are representatives of PRISM, which is Caltech’s campus social group for lesbian, gay, bisexual, and transgender students with support from staff, faculty, and their straight allies. In addition, we have created a Safe Zone program on campus led by one of the CCD Assistant Directors, Linda Webb. The program is designed to help build community, increase awareness, and support a safe space for the LGBTQA community. Student members of the program have designed their own logo, which is displayed in the offices on campus that are safe spaces for LGBTQA students who are struggling or have questions. In addition, we hold monthly community lunches. By

student request, we don't have presenters. Everyone just comes out for the food and loud music, and to get to know each other. These programs assist in building community for LGBTQA students and allies on campus.

ENGenious: What are some of the challenges experienced by the students who seek your services?

Graham: All Caltech students are highly capable when they get here, no matter what hue, part of the country, or racial or ethnic background they come from. They're capable! The challenge is coming to a community that's so different from what they know and from what they've been used to. It's like they're in shock. We have to be very cautious and not too quick to label them with syndromes. We're not dealing with a homogenous group of students. Our students are from all over and they come with lots to offer. The only way to gain the benefit of having them here is to help them be the best they can be. Part of this is to have zero tolerance for intolerance of difference. Intolerance of difference truly undermines our educational mission, and it makes it impossible to make sure that everybody is getting the most out of their Caltech experience. No one person has the right to limit another person's development or to limit her access to resources.

ENGenious: How are the alumni involved with CCD?

Graham: We have been working on creating more interactions between current students and alumni. Recently, one of the CCD Assistant Directors, Portia Harris, arranged an LGBTQA mixer for the alumni and current students. The alumni were so grateful and commented on the great change they are seeing on campus. One alumna from the 1960s recalled how LGBTQA students used to hide. Today, students can meet and interact with successful alumni from various backgrounds and professions and see that it gets better, that they can have success in their own lives. For some students, the alumni are the students' only access to life after Caltech.

ENGenious: What are concrete ways that the campus and our approach to diversity are different since the CCD was created?

Graham: One of our main accomplishments is that now there is more awareness on campus. We have staff and faculty calling our offices and asking questions because they are now aware of the different student populations they'll be working with. The awareness has given people an opportunity to say, "I don't understand," or, "How can I help?" And that's what you want. You don't want there to be a lot of fear associated with saying you don't know the

answer to something. And in those moments, we're here to field those questions.

Let's imagine that you're a faculty member and you think you have a student who is struggling with an undetected disability because you witnessed inappropriate behavior in the classroom or the laboratory. You can go directly to the dean of students, or you can come visit us at CCD. Our resources are completely confidential, so we'll keep your questions and identity confidential. We take the information and work with the appropriate parties to figure out the best way to work with the student and the faculty. We may get the dean of students involved, or, depending on the situation, it might be our Americans with Disabilities Act representative, Dean Barbara Green, who takes the lead. We also draw on other resources as needed, such as the Counseling Center, to make sure that the student and faculty are supported. Our goal is to help everyone in our community be the best they can be. The prime example of this at Caltech is Stephen Hawking; once you make the accommodations, the sky is the limit for what you can accomplish. It really is about helping a person access his or her full capability.

Another aspect of our work is to promote diversity and to really champion it. We know that differences in perspectives and approaches help students. The University of Illinois conducted a two-year diversity study beginning in 2004 and found that its faculty of color and international faculty were more likely to try different techniques when teaching difficult subject matter than their majority colleagues. We are promoting innovation, and we're promoting a climate where everybody feels valued. If we're ascribing to pluralism across the board, then we need to value each member of this community. Part of that is accepting boundaries that other people have for you and for themselves, and making sure that you've got some standards for yourself. **EN**

Eva Graham is Director of the Caltech Center for Diversity.

Visit diversitycenter.caltech.edu.



Lobby



Lounge



The Jorgensen Laboratory, formerly the home of computer science in EAS, is being renovated to serve as the new home for two of Caltech's key energy and sustainability research efforts: the Resnick Institute and the Joint Center for Artificial Photosynthesis. Large concrete overhangs have been removed to introduce more natural light and ventilation. Ninety percent of the materials from the interior demolition of the building are being reused or recycled. The goal for this laboratory-intensive building is LEED Gold Certification. The architects, John Friedman and Alice Kimm, have incorporated many energy-efficient design features to embody the innovative research that will be conducted within.



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