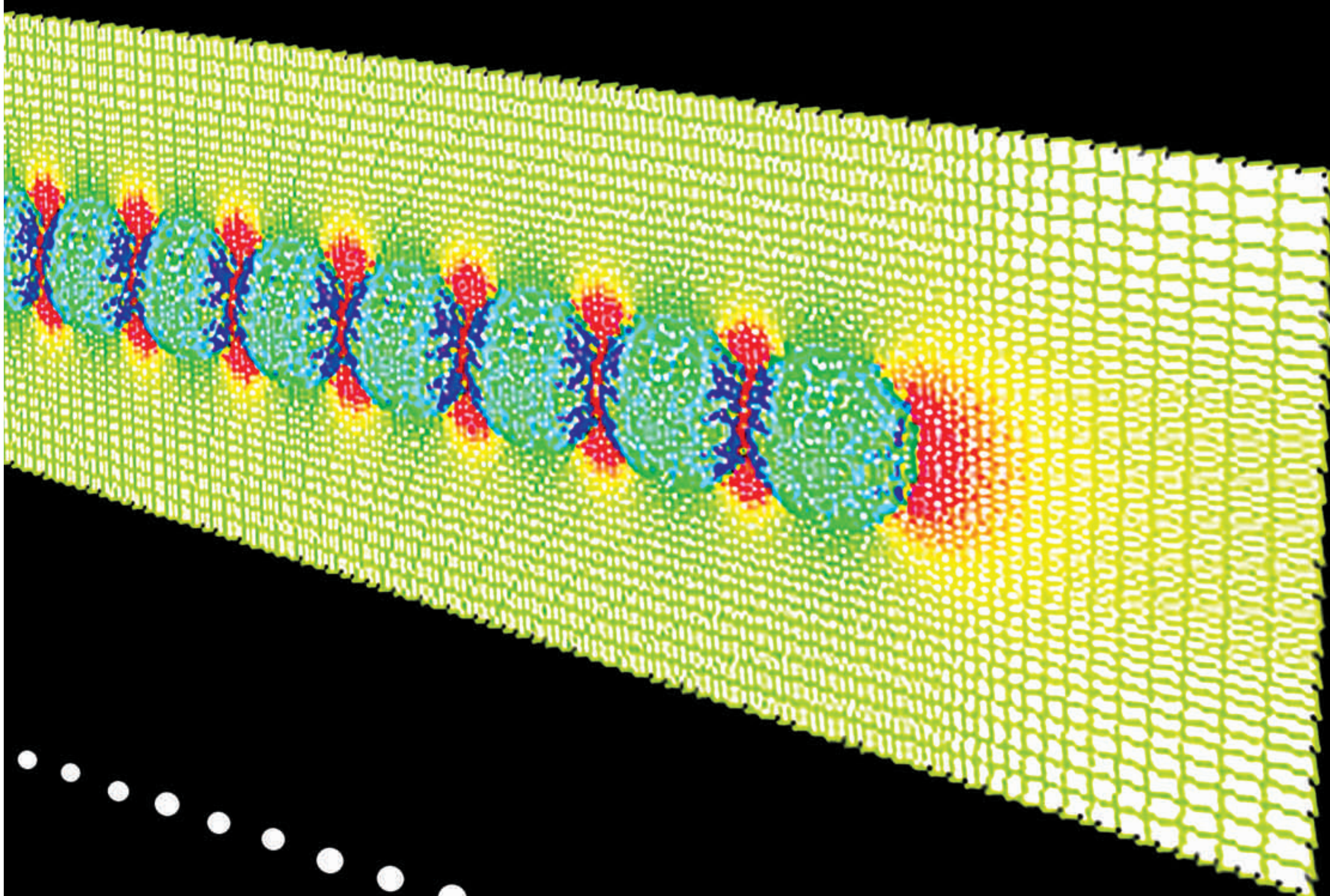
ENGenious

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



NO. 5, FALL 2004

The Division of Engineering and Applied Science consists of thirteen Options working in five broad areas: Mechanics and Aerospace, Information and Communications, Materials and Devices, Environment and Civil, and Biology and Medicine. For more about E&AS visit http://www.eas.caltech.edu.

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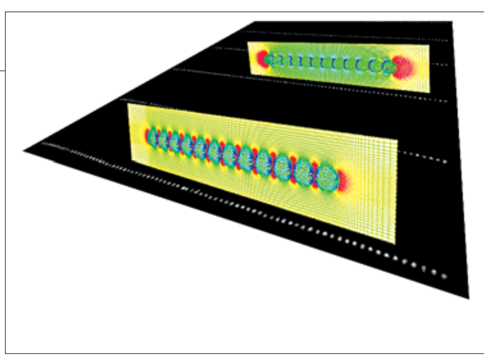
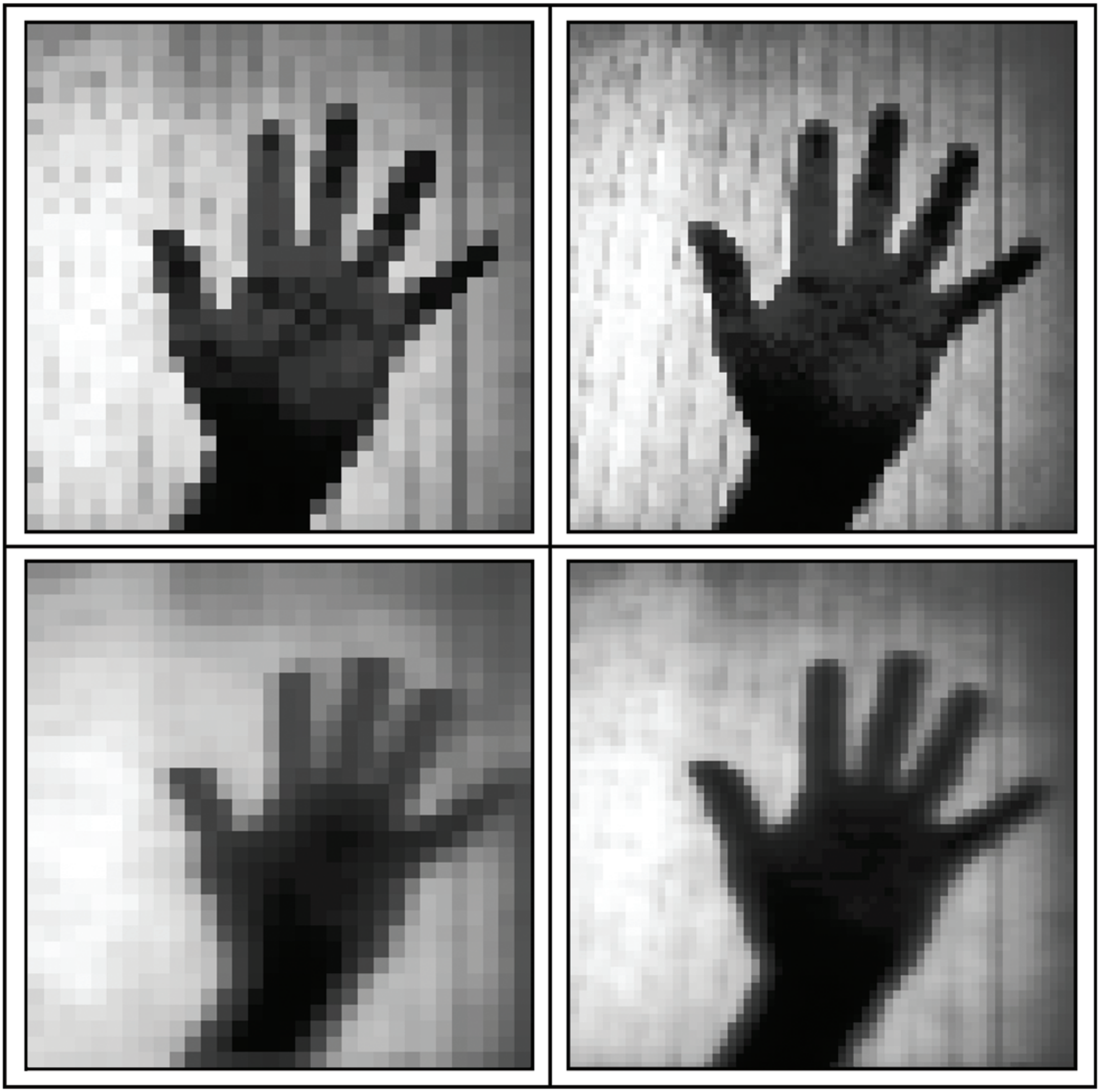


Cover Image: Visualization of two distinct plasmonic modes in an array of twelve 10-nm silver particles. A plasmon can be pictured as a fluid compression wave in the "sea" of free electrons in a metal. The field of plasmonics studies hybrid excitations which share the characteristics of light and of electron oscillations. This unique quality allows the concentration of intense optical fields in regions much smaller than a wavelength, and therefore enables the miniaturization of optical devices to the nanoscale. Key potential applications include any area of photonics in which intense electric fields are crucial, such as nonlinear optics or sensing of very small volumes.

The simulated structures (left) interact strongly with light in two frequency bands. At infrared frequencies the whole array acts like a single antenna (top array), while visible light induces an electron oscillation in each individual particle (bottom array). This is an example of how plasmonic systems allow a great deal of flexibility for engineering a specific spectral response.

These simulations come from the lab of Harry A. Atwater, Howard Hughes Professor and Professor of Applied Physics and Materials Science. Atwater and his group are among the pioneers in photonics and in particular, were the first to experimentally show propagation in a plasmon nanoparticle antenna waveguide.



Upper left: visual perception with a 32 x 32 electrode array retinal implant. Upper right: visual perception with a 64 x 64 electrode array retinal implant. Lower left: visual perception with a 32 x 32 electrode array retinal implant with blur. Lower right: visual perception with a 64 x 64 electrode array retinal implant with blur. Generated with *Artificial Vision Simulator* developed by Dr. Wolfgang Fink, Caltech Visiting Associate in Physics. See page 20 for a Research Note from Professor Yu-Chong Tai and Dr. Fink on retinal implant technology and the possibility of restoring vision to people who have lost photoreceptor function.

In each issue of **ENGenious** *we like to feature one of the academic options, and this time the Electrical Engineering option has stepped forward to share with you a glimpse of recent research activities. I have to say,* this is not your father's EE, *as the phrase goes. The variety of research is astonishing, and embraces phenomena from genomics to computational finance, alongside traditional areas such as communications and signal processing. But even "traditional" areas here are always at the cutting edge, as will be evident.*

There is also a focus on prostheses in this issue. Joel Burdick and Richard Andersen present their work on the world's first cognitive neural prosthesis, which allows the direction of a physical activity (in this case, computer cursor movement) by pure thought alone. Yu-Chong Tai and Wolfgang Fink report on their work in creating a retinal prosthesis, which takes advantage of "smart skin" invented in the Tai lab.

The Institute's capital campaign, "There's only one. Caltech," is in full swing and it gives me great pleasure to announce four tremendous gifts which will transform the research and education in the Division for decades to come.

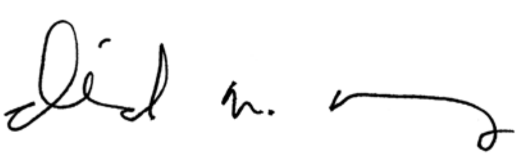
The first two are in support of Caltech's Nanoscience Initiative, which ultimately seeks to develop integrated nanoscale systems that will lead to true nanoscale technology. Caltech scientists and engineers have been working in the trenches of the nano world for more than a decade. Recognizing the maturity of our on-going efforts in the field, the Gordon and Betty Moore Foundation has granted us $25.4 million to reach this next level. Integrated nanoscale systems are only possible through a new collaborative science that transcends what individual laboratories can attempt, and the state-of-the-art infrastructure and equipment that the Moore gift allows us to implement will be unprecedented in the research community. Similarly, Fred Kavli and the Kavli Foundation awarded a $7.5 million grant to Caltech in March to establish the Kavli Nanoscience Institute (KNI). Under the direction of Michael Roukes, Professor of Physics, Applied Physics, and Bioengineering, the KNI will allow us to co-locate many of the disparate groups on campus and create a formal home for the nanoscience community at Caltech.

The Division's research thrust into Information Science and Technology (IST), described in these pages previously, has received a huge endorsement in the form of two outstanding gifts: the first is $25 million from the Annenberg Foundation. The second is $22 million from the Gordon and Betty Moore Foundation. I invite you to turn the page to read more on how these gifts will be used to formally establish the nation's intellectual and academic center for information science.

These gifts are inspiring, and will change the lives of many—from our students and faculty to all the persons who will eventually be touched by the life-enriching and life-saving technologies that will grow from these magnanimous seeds.

As always, we welcome your feedback.

Sincerely,



RICHARD M. MURRAY
Chair, Division of Engineering and Applied Science

Information Science and Technology:
Celebrating the Future

A gathering to welcome 22 new IST postdoctoral scholars took place on Friday, October 15, 2004 in Tournament Park. It was a most pleasant, informal, affair with good food and drink picnic style, providing an opportunity to hang out with the faculty and the ever-so-helpful staff. But the sparkling beverages would have been replaced by champagne if they knew then what we know now: two magnificent gifts have come to IST, one from the Annenberg Foundation and one from the Gordon and Betty Moore Foundation.

The Annenberg gift of $25 million will be used to construct a new building to serve as the formal home for IST. Now in the design stage, the building—to be called the Walter and Leonore Annenberg Center for Information Science and Technology—is expected to be ready in 2007. It will join the existing Watson and Moore Laboratories forming an "information core" of buildings. Jehoshua Bruck, Director of IST and Gordon and Betty Moore Professor of Computation and Neural Systems and Electrical Engineering, has spearheaded the IST initiative largely because, as he states, "to maintain preeminence in science the U.S. needs new and unified ways of looking at, approaching, and exploiting information in and across the physical, biological, engineering, and social sciences." Upon announcement of the gift, Leonore Annenberg, president and chairman of the Annenberg Foundation, conveyed her excitement. "I am delighted that the Annenberg Foundation will be a part of this visionary enterprise. As a publisher, broadcaster, diplomat, and philanthropist, Walter Annenberg was known for breaking new ground. Support for this important new initiative surely would have pleased him as much as it honors the work of the Foundation."

The Moore gift—another in a string of generous gifts to the Institute—provides $22 million to establish four new interdisciplinary IST research centers. The Center for Biological Circuit Design addresses how living things store, process, and share information, and is developing new ways to design, build, and analyze biological circuits. The Social and Information Sciences Laboratory investigates how social systems, such as markets, political processes, and organizations, efficiently process immense amounts of information and will use this understanding to help to improve society. The Center for the Physics of Information examines the physical possibilities and physical limitations of information and will design the computers and materials for the next generation of information technology. Finally, the Center for the Mathematics of Information will formulate a common understanding and mathematical language of information that unifies researchers from different fields.

Our hats are off to the Annenberg and Moore Foundations!

Stay up-to-date with IST at: http://www.ist.caltech.edu

Let's Do the Numbers

The summer dwindled away and one by one they came from all corners of the Earth: the 2004 entering class. The frosh made a detour to Lake Arrowhead for Frosh Camp, while the graduate students settled in to new office and lab space. There are **207** new undergraduates (**59** of them women), and **213** new graduate students (**58** of them women). Of the **213** graduate students, **42%** (**89** total) join E&AS.

Science and Public Policy

David Baltimore, David Goodstein, Janet Hering, and Ashwin Vasavada.

Caltech and Jet Propulstion Laboratory scientists participated in a forum to discuss the relationship between science and public policy in an October 20th event hosted by the Caltech Social Activism Speaker Series in conjunction with the Union of Concerned Scientists and ScienceInPolicy.org.

The distinguished panelists represented a variety of topics in which government policy and scientific research influence one another. President David Baltimore, Nobel Prize winner in 1975 for his work on virology, addressed the relationship between molecular biology, medical research, and public health. Physicist David Goodstein (Vice Provost, Professor of Physics and Applied Physics, and Frank J. Gilloon Distinguished Teaching and Service Professor) is an expert on energy and energy policy who recently published *Out of Gas*, a comprehensive look at dwindling energy supplies and potential alternatives. In his Watson Lecture of October 14, he predicted that civilization will face its demise within a century unless petroleum-based energy sources are replaced with sustainable alternatives. Janet Hering, Professor of Environmental Science and Engineering, is an environmental scientist who studies the spread of pollutants in aquatic ecosystems with the aim of informing environmental policy in both developed and developing nations. (See her Progress Report on arsenic mobilization in the L.A. Aquaduct, page 8.) JPL planetary scientist Ashwin Vasavada is an expert on climate change and worked as an aide on science policy for U.S. Representative Vernon Ehlers.

Caltech Social Activism Speaker Series: http://sass.caltech.edu

Opposite, top photo: Mackenzie Sikora modeling the new IST t-shirt. Second photo (left to right): postdoctoral scholars Ron Lavi and Dunia López-Pintado, and founding member of SISL (Social and Information Sciences Laboratory) John Ledyard, the Allen and Lenabelle Davis Professor of Economics and Social Sciences. Third photo: IST Managing Director Bob Carroll and CBCD (Center for Biological Circuit Design) Director Paul W. Sternberg, Professor of Biology and Investigator, Howard Hughes Medical Institute. Bottom photo (left to right): IST postdoctoral scholars Razvan Cristescu, Tudor Stoenescu, and Daniel Marco.

designing for the developing world

Teaching at the Intersection of Science, Engineering, and Business

by Kenneth A. Pickar

One of the many delightful things about teaching Caltech students is that you don't have to guess what interests them—rather they tell you. There are two areas I would like to discuss where this has happened to me. One is the subject of entrepreneurship; the other is the subject of building products appropriate for the developing world. The fact that the first subject was started in the late '90s and the second in the past year says something about the zeitgeist of these periods. In the late '90s students wanted to be entrepreneurs—how hard could it be? They still do, but the fainter hearts have gone on to seek other pursuits. Now there is a sense that the world is so seriously divided between haves and have-nots that it is incumbent upon the former to address the issues of the latter. Not a new thought, but one that is gaining increasing resonance.

But let me start a little earlier. My career has been in science: liquid helium physics in school and solid state physics (of the device sort) at Bell Labs, followed by management stints at Bell Northern Research, GE Corporate R&D and AlliedSignal (now Honeywell). At this last enterprise, among my duties, I was the Caltech Campus Representative. I had an opportunity to meet students as potential employees and could follow their early careers after they joined the company. I noticed that although they were, of course, excellent engineers, Caltech graduates did not have the sort of team skills or rudimentary knowledge of how companies actually worked compared with other graduates of elite institutions that we hired. As I knew from long experience in observing employees, these skills were essential. Nothing happens in industry from the sole effort of a single mind working in isolation. I wish it did; it would have made life so much easier! So one of the reasons I came to Caltech is that I thought that it would be a good idea to teach these students some of these skills.

In doing this I followed in a grand Caltech tradition, however inadequately. Robert Millikan purportedly said in 1929 when he hired Horace Gilbert, a newly minted Harvard MBA (horrors!) to teach business to Caltech students, "I understand that a lot of our graduates are going into business. Perhaps we should teach them something about that." Professor Gilbert had a long distinguished career at Caltech and is fondly remembered by all who took his classes.

Let me then tell you a little about what I have been doing with the academic descendents of these students.

I developed two courses. The first was E/ME 103, The Management of Technology. I think Gilbert would have approved because it was based on Harvard Business School and other cases as well as lectures. This allows Caltech students the heady experience of critiquing decisions made by "experts" in large and small companies; decisions which, amazingly, can turn out to be really wrong. One highlight was Caltech graduate and Intel manager, Barry Lieberman (BS '68), presenting to my students the pitch he was planning for Intel upper management. He was to propose an important (i.e., expensive) new piece of lithography equipment. As a tribute to the balanced way that Barry presented the choices, my students were not so sure that it was a good idea! President David Baltimore has been kind enough to guest lecture each year on the challenges and tribulations of the drug delivery process, which has been in the news of late—and not entirely favorably.

I was very fortunate in having as a mentor, when I arrived, Professor John Baldeschwieler [J. Stanley Johnson Professor and Professor of Chemistry, Emeritus]. John, in addition to being a distinguished chemist, has also started a number of companies and is familiar with the entrepreneurial process as a participant. He started the modern era of entrepreneurship education at

Caltech by creating E 102, Entrepreneurial Development. Here each student team writes a business plan to commercialize an original idea. I took over this course as John went emeritus (although, thank goodness, he still advises me). We decided to build on this process and together with Art Center College of Design, our neighbor in Pasadena, USC and UCLA business school graduates, professors Richard Murray and John Ledyard, an NSF grant, and a cast of thousands, we created the Entrepreneurial Fellowship Program, a summer "boot camp" for entrepreneurs. During each program, for a period of six to nine months, recent grads were paid and tutored as they started a company. The Fellows claimed they loved it and there is no doubt we created entrepreneurs, though as yet no successful new companies (which is harder). This program ran for two years, at which point we ran out of money. In entrepreneur-speak, we built a model, but not a sustainable model.

The third course is ME 105, Engineering Design of Products. In addition to the focus on teamwork, this class aims to teach the things that could go wrong in creating a new product. Trivial things like: no one knows how to build it, no one wants to buy it, it kills the user, etc. We investigate how one can anticipate what these "disappointments" could be and design the product in such a way that these problems don't occur. The students actually go through the process of building the product, which is where most of the learning occurs. After all, they need to make mistakes in a safe environment before they do it for real. I am aided in this endeavor by my background over the years of having made every mistake myself.

Last spring, I was approached by students who had just formed a Caltech student club called Engineers for a Sustainable World (ESW). What impressed me about the discussion were their seriousness and their willingness to work hard on the subject—to make it real. They had passion. Thus over the summer, through many meetings, Brendan Kayes, Jon Othmer, Derek Rinderknecht, Eugene Mahmoud, and I built a course. The class time would be coupled with an ESW speaker series devoted to bringing in outside speakers, all practitioners with some successes under their belt.

Our biggest challenge was to find suitable candidate projects for the student teams. It is very important for the teams to have access to someone who represents the customer so that the design is realistic. We turned to Timothy Prestero and Design that Matters (DtM), a Massachusetts-based non-profit group that acts as bridge to bring problems identified by nongovernmental organizations and underserved communities into the classroom for university engineering and business students to tackle in their courses and research. DtM had several years experience in the subject, had helped a number of student teams and—what was very important—had some excellent contacts. The course lectures were tuned to the issues peculiar to this particular subject, but based on the general principles of sound design practice. The teams addressed some basic issues confronting the poorest two billion people on the planet, which most assuredly include clean water, health, and energy.

Each student team is required to build a prototype of their product, or at least the plans for one. They need to include a study of the market for the product, how it will be manufactured and maintained, and address the human factors involved. There is an alphabet of concerns and constraints. Of great importance are the environmental health and safety effects of the materials employed, how the product is made, and how the product is used through to its disposal and possible recycle. These are issues of course which profoundly affect designs for the developed world as well. As the course is just a few weeks old, it's hard to say how effective we will be. But given the initial turn-out and enthusiasm, I am very optimistic.

I could go on about my initial plans for a quiet summer transformed into something quite more interesting thanks to Caltech undergraduates Grant Chang-Chien and Dmitriy Kernasovskiy. They approached me to do a SURF project, and together with Robert Rogan (PhD '04) and UCI graduate student Renee Rottner, we morphed our ideas into an elaborate study of five Caltech start-ups. We investigated what worked and what didn't work for them as they addressed the terribly difficult challenge of commercializing revolutionary technologies. But I will leave that for another time. I'm over on my word limit! ENG

Ken Pickar is Visiting Professor of Mechanical Engineering.

More is available at:

http://www.its.caltech.edu/~kpickar/

http://esw.caltech.edu

http://www.designthatmatters.org

Immobilization of Arsenic in the L.A. Aqueduct System:

How and How Long?

by Janet G. Hering

The hazard posed by arsenic in drinking water has attracted much attention since the recognition in the 1990s of its widespread occurrence in well-water in South Asia, notably Bangladesh. Arsenic occurs less extensively in groundwater in many other countries—including the United States, and in particular, the Southwest.

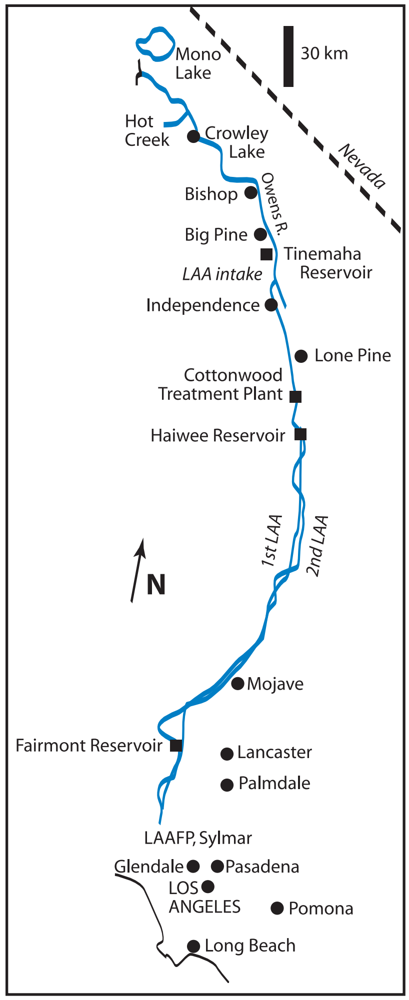
Arsenic occurs naturally in the environment, as a trace constituent of the Earth's crust. It is released into water and air by the weathering of rocks, burning of fossil fuels, smelting of ores, and manufacturing processes. The inorganic forms of arsenic, which are the dominant forms found in surface and ground water (mostly as trivalent arsenite, As^{III}, and pentavalent arsenate, As^{V}), are the most toxic forms. Organic forms of arsenic, which occur naturally in marine fish, are much less toxic and are readily eliminated by the body.

According to a 1999 study by the National Academy of Sciences, arsenic in drinking water causes bladder, lung and skin cancer, and may cause kidney and liver cancer. The study also found that arsenic damages the central and peripheral nervous systems, as well as heart and blood vessels, and causes serious skin problems. It also may cause birth defects and reproductive problems. Absorption of arsenic through the skin is minimal and thus hand-washing, bathing, and doing laundry with water containing arsenic do not pose a human health risk.

In 2001, the U.S. standard for arsenic in drinking water was changed from 50 to 10 parts per billion (ppb). The new standard will become enforceable in 2006. This change in the drinking water standard was driven by the estimated cancer risk of 1 in 100 associated with drinking two liters of water containing 50 ppb of arsenic each day over the course of a lifetime. That cancer risk is extremely high compared with the 1 in 10,000 risk that is considered acceptable by U.S. Environmental Protection Agency.

Exposure to arsenic in drinking water is usually associated with the use of groundwater for water supply. In Bangaldesh, for example, mobilization of arsenic from aquifer sediments results in the occurrence of arsenic in groundwater at concentrations of hundreds to thousands of parts per billion. Less commonly, arsenic can occur at elevated concentrations in surface waters.

Left to right: Chad Saltikov (former postdoctoral scholar) and current graduate students Davin Malasarn and Kate Campbell.



This is usually associated with the input of arsenic from geothermal sources (i.e., hot springs).

Recently, my research group has been studying the biogeochemical controls on arsenic mobility in the Los Angeles Aqueduct system, which transports water from the eastern Sierra Nevada to the City of Los Angeles for municipal water supply. In this system, we have a unique opportunity to examine arsenic biogeochemistry in the context of a full-scale engineering project that is currently being implemented by the Los Angeles Department of Water and Power (LADWP).

Because of geothermal inputs of arsenic in the Owens Valley, arsenic concentrations in the L.A. Aqueduct water supply are naturally elevated with a historical annual average of 20 ppb. In 1996, an interim arsenic management plan was implemented to lower the concentration of arsenic in the water delivered by the Aqueduct. Since 1996, ferric chloride and a cationic polymer have been introduced into the Aqueduct at the Cottonwood Treatment Plant, an existing facility originally used to control turbidity.

Ferric chloride addition results in the formation of a trivalent iron (Fe^{III}) oxyhydroxide *floc* (a loose aggregation of particulate material) that is transported as suspended load in the Aqueduct and deposited in North Haiwee Reservoir as the flow velocity decreases. Ferric chloride doses are adjusted at the Cottonwood Treatment Plant to remove sufficient arsenic from the dissolved phase so that the arsenic concentrations below the Haiwee Reservoir are less than 10 ppb. While the treated water flowing toward Los Angeles is thus safer for consumption, this practice has resulted in significant accumulation of arsenic and iron in the Haiwee sediments over a period of eight years.

Sediments and *porewaters* (waters present in the interstices of rocks and soils) have been sampled in the inlet channel where the Aqueduct feeds into North Haiwee Reservoir by myself and colleagues Penny Kneebone (PhD ’00), Nicole Jones (undergraduate visitor ’00), and Professor Peggy O’Day (University of California, Merced). Sampling has thus far been limited to locations very near the bank because of restrictions on human contact with the water supply. Thus the samples obtained are not entirely representative of conditions throughout the reservoir.

Sediment cores up to 45 centimeters long were collected from the inlet channel and found to contain elevated concentrations of iron, arsenic, and manganese relative to sediments at a control site. Sediment concentrations of these elements remain elevated throughout the core length sampled (averaging 4% iron, 600 parts per million manganese, and 200 ppm arsenic). Porewater profiles reveal that manganese, iron, and arsenic are mobilized at depth in the sediment with manganese released into the porewaters at a more shallow depth than either iron or arsenic. Arsenic concentrations in porewaters at a depth of about 25 cm in the sediment reached values greater than 1000 ppb.

The depth at which increased porewater concentrations are observed varied in sampling conducted in different seasons but, in general, manganese, iron, and arsenic porewater concentrations were a few ppb or less in the surficial sediments and overlying water. As arsenic and iron were mobilized into the porewaters at depths of 10 cm or more into the sediments, their concentrations in the porewaters were always strongly correlated.

From the water supply perspective, the interim arsenic management plan is fulfilling its objectives. Arsenic concentrations in water delivered to the Los Angeles Aqudcut Filtration Plant in Sylmar are consistently below 10 and often below 5 ppb. Thus, the arsenic deposited to the sediments in association with the Fe^{III} oxyhydroxide floc must be almost entirely retained within the sediment. The low porewater concentrations of arsenic in the surficial sediments, despite elevated concentrations at depth in the sediment, indicate that arsenic diffusing upward through the sediment is sequestered into the solid phase before reaching the sediment-water interface.

Even though elevated concentrations of arsenic are observed at depth in the porewaters of the Haiwee sediments, the arsenic concentration in the sediments is fairly constant with depth. The amount of arsenic that would need to be released from the sediments in order to support the observed porewater concentrations can be estimated by assuming reasonable values for the porosity of the sediment and the density of the Fe^{III} oxyhydroxide floc. These estimates suggest that less than 2.5% of the arsenic and less than 1% of the iron in the sediments is released into the porewaters.

Sediment core.

Given these observations, it is important to try to understand what factors control the rates of release of arsenic and iron. Understanding the biogeochemical controls on arsenic mobilization and sequestration in this system will help us answer questions that pertain directly to the protection of the L.A. Aqueduct water supply. What is the long-term fate of arsenic in the North Haiwee Reservoir sediments? Is continued addition of ferric chloride at Cottonwood necessary to prevent release of arsenic into the overlying water?

Our previous work has shown that release of arsenic to the porewater is associated with the dissolu-

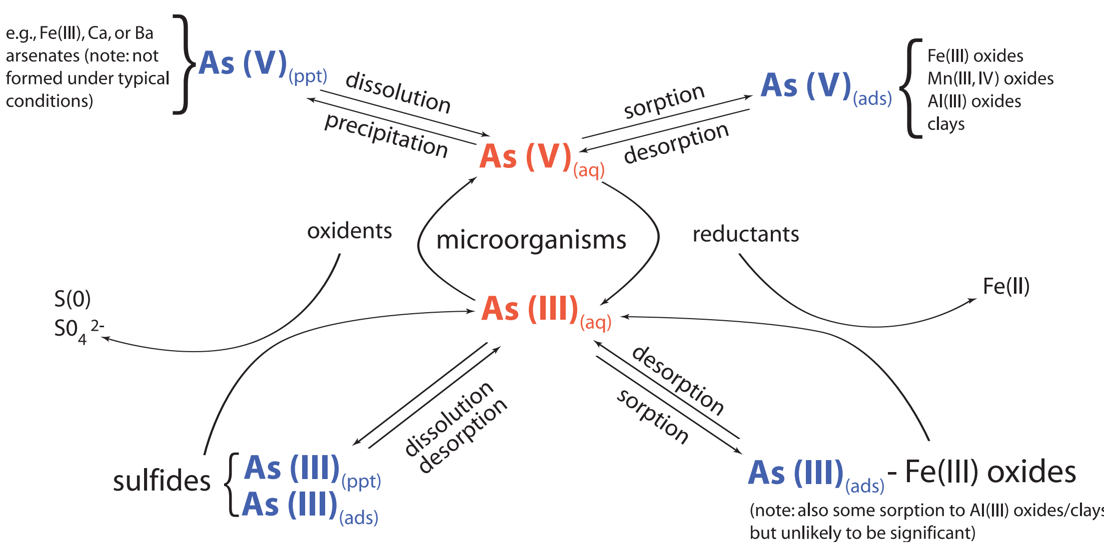


Figure 1. Biogeochemical cycling of arsenic. Partitioning of arsenic between the solid phase (blue) and the dissolved phase (red) changes in response to environmental conditions. As discussed in the text, the dissolution of Fe^{III} oxides under reducing conditions releases arsenic associated with the solid into solution.

tion of the Fe^{III} oxyhydroxide solid, which occurs as the conditions in the sediments become more reducing. This process is illustrated in Figure 1. Yet even as this process occurs, the bulk of the Fe^{III} oxyhydroxide solid remains in the sediment. Why then isn't the arsenic released into solution simply re-incorporated into the residual solid?

Currently, we are examining the hypothesis that the composition of the porewater at depth in the sediment is such that arsenic *adsorption* (accumulation at the solid-water interface) onto the Fe^{III} oxyhydroxide solid is not favorable. In particular, re-adsorption of arsenic could be inhibited by elevated concentrations of Fe^{II}, phosphate, or by dissolved organic matter (DOM) in the porewater. Investigating this hypothesis is complicated by the difficulty of obtaining sufficient volumes (upwards of tens of milliliters) of porewaters for adsorption experiments (or even for complete analytical characterization). Thus, rather than collecting porewater for adsorption experiments, we have adopted an alternative approach in which freshly prepared Fe^{III} oxyhydroxide is introduced into the sediments and exposed to the porewater *in situ*.

For this purpose, my graduate student Kate Campbell modified a gel probe sampler that we had used previously to obtain porewater profiles. In the original gel probe sampler, polyacrylamide (clear) gel slabs held in a plexiglass ladder were introduced into the sediment and allowed to equilibrate with the porewater for a few hours. The gel slabs, which were essentially used to collect about 0.2 milliliters of porewater, were then analyzed in the lab.

For the modified sampler, half of the gel slabs were doped with Fe^{III} oxyhydroxide before being loaded into the sampler. The clear gels will be used (as previously) to obtain porewater profiles of arsenic (and other elements) and the iron-doped gels will provide information on the extent of arsenic adsorption.

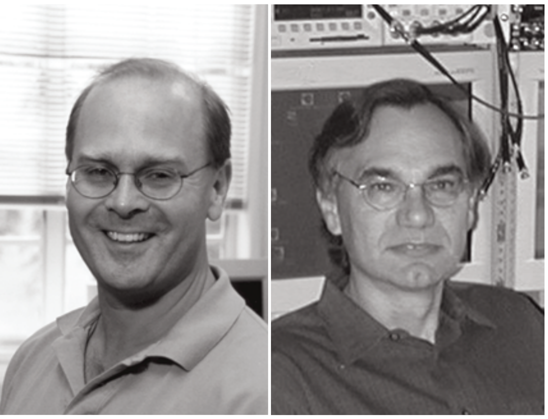
In obtaining porewater profiles using the original gel probe sampler, it can be assumed that the equilibration of the clear gels does not perturb the ambient porewater composition. This assumption is reasonable because the volume of water in the gel slabs is quite small and the concentrations of the porewater constituents are not any higher in the clear gel than in the surrounding porewater. With the iron-doped gels, however, adsorption of porewater constituents onto the Fe^{III} oxyhydroxide may result in significant accumulation of porewater constituents in the iron-doped gels and hence their depletion of these chemical species in the porewater in contact with the sampler. Thus, the accumulation of sorbates in the iron-doped gels and the concentrations of solutes in the clear gels will reflect the ambient porewater composition only if the sorbing constituents are resupplied to the porewater from the sediments on the timescale of equilibration of the (mixed clear and iron-doped) gel probe sampler. Preliminary deployment of the sampler (for several hours) suggested some artifacts associated with kinetic limitations of either arsenic resupply from the sediment or uptake onto the iron-doped gels or both. Subsequent laboratory experiments have indicated that an equilibration time of about 1 day will be required for the field deployment of the sampler.

Los Angeles Aqueduct.

Our study of this system continues. We hope to take advantage of the well-defined characteristics of this system, in which arsenic derives from a fairly constant geothermal source and iron from the LADWP management practices, to explore the coupled biogeochemistry of these elements. E N G

Janet Hering is Professor of Environmental Science and Engineering and the Executive Officer for Keck Laboratories.

For additional information, please see http://www.hering.caltech.edu



By Pure Thought Alone:

The Development of the First Cognitive Neural Prosthesis

by Joel W. Burdick and Richard A. Andersen

Many of us have probably had this fantasy: just by thinking, we direct our computer to turn on and open the document we want to work on. Or another perhaps: mentally commanding the cursor to move on the screen to a specific location. At Caltech, monkeys can already accomplish the latter.

This feat has been achieved through groundbreaking interdisciplinary research and technology that includes advances in neuroscience, engineering, neurosurgery, and neural informatics. Along with many colleagues, Richard Andersen, James G. Boswell Professor of Neuroscience, Joel Burdick, Professor of Mechanical Engineering and Bioengineering, and Yu-Chong Tai, Professor of Electrical Engineering, have developed proof-of-concept neural prostheses and the associated technology that will someday allow use of these devices by humans.

A neural prosthesis is a direct brain interface that enables a primate, via the use of surgically implanted electrode arrays and associated computer algorithms, to control external electromechanical devices by *pure thought alone*. The first beneficiaries of such technology are likely to be patients with spinal cord damage, peripheral nerve disease, or ALS (amyotrophic lateral sclerosis, also known as Lou Gehrig's disease). In the United States alone, there are 2.28 million cases of patients with some form of paralysis.

Although the goal is to develop practical applications, a basic understanding of the brain's neural codes and representations is a cornerstone of this research. Moreover, the brain-machine interfaces (BMIs) that form the core of neural prosthetic technology will afford a new method to study brain mechanisms and will allow, among other things, the testing of new theories of brain function.

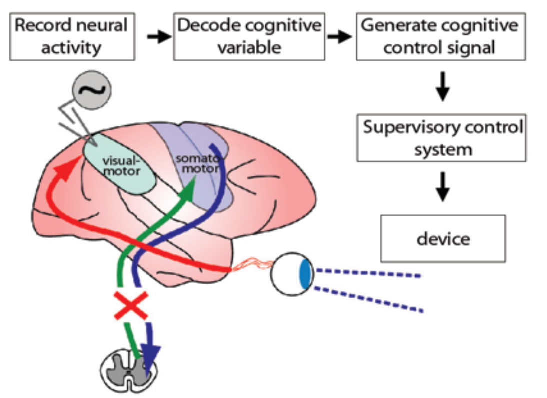


Figure 1. Schematic of the pathway of information flow for the cognitive-based neural prosthetic paradigm. For visually guided movements, signals originating from the retinas pass through visual cortex and the posterior parietal cortex before arriving at motor cortex. Commands to move from motor and premotor areas converge to the spinal cord. In patients paralyzed by spinal cord damage there is a loss of motor signals down to the spinal cord, as well as of somatosensory feedback signals up to the motor and premotor areas. We propose to tap the early planning signals from the posterior parietal cortex. These cognitive signals will be decoded and used to generate control signals for supervisory control systems with hierarchical control of external devices.

A primary issue in neuroprosthetic research is the choice of brain area from which prosthetic command signals are derived. Current studies around the world have focused primarily on deriving neuroprosthetic command signals from the motor cortex (we refer to this approach as *motor-based*). Recordings from multiple neurons are "decoded" to control the trajectories of a robotic limb or a cursor on a computer screen. In addition, progress has been made in using electroencephalogram (EEG)-based signals to derive neuroprosthetic commands.

At Caltech, however, we have pursued a novel approach, which is to use high-level *cognitive* signals for controlling neural prostheses. Read-outs are made of the goals and intentions of the subject, rather than the instructions on how to obtain those goals (see Figure 1). Smart output devices, such as robots, computers, or vehicles, using supervisory control systems, then manage carrying out the physical tasks required to complete the intended goal. The cognitive signals that can be read-out are myriad and can include the expected value of an action and, perhaps in the future, speech, emotional state, and other higher cortical functions. An "expected value signal" is used by the brain to make decisions and can be used by prosthetics to interpret a subject's decisions, preferences, and motivation, all of which would help a paralyzed patient communicate better with the outside world.

Proof-of-Concept: Cognitive-Based Paradigm in Monkey

Cognitive control signals can be derived from many higher cortical areas in the parietal and frontal lobes related to sensory-motor integration. The primary distinction is not the place from which recordings are made, but rather the type of information that is being decoded and the strategy for using these signals to assist patients. In our work with macaque monkeys, we focused on the posterior parietal reach region (PRR), but similar approaches can be used for interpreting cognitive thoughts from other brain areas. It is likely that some areas will be better than others depending on the cognitive signals to be decoded and the parts of the brain that are damaged.

The PRR has many features of a movement area, being active primarily when a subject is preparing and executing an arm movement.

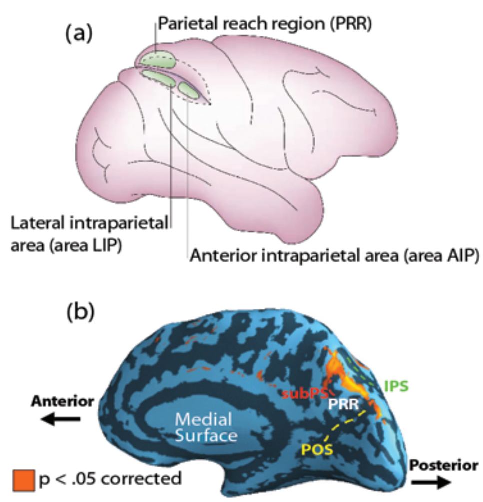


Figure 2. (a) Schematic of the locations of areas within the posterior parietal cortex specialized for reaching (PRR), eye movements (LIP), and grasping (AIP) in monkey. (b) fMRI localization of the human analog of PRR. [Drawings have been adapted from (a) Stuphorn, V., E. Bauswein, K-P. Hoffmann, *Neurons in the primate superior colliculus coding for arm movements in gaze-related coordinates.* Journal of Neurophysiology, 83: 1283-1299, 2000. (b) Andersen, R.A. and C.A. Buneo, *Sensory-motor integration in posterior parietal cortex*, in *The Parietal Lobes - Advances in Neurology* (Vol 93), D.D. Spencer, Editor. 2003, Lippincott, Williams and Wilkins: Philadelphia, PA. p. 159-177.]

However, the region is in direct neural connection with the visual system, and vision is perhaps its primary sensory input. Moreover, this area codes the targets for reach in visual coordinates relative to the current direction of gaze (also called retinal or eye-centered coordinates). It is coding the *desired goal of a movement*, rather than the intrinsic limb variables required to reach to the target. In contrast, motor cortical areas in the frontal lobe tend to code movements in intrinsic, limb-centered coordinates. Moreover, the PRR can hold the plan for a movement in short-term memory through persistent activity of its neurons. This intention-related activity provides a useful neural correlate of the intentions of the subject for subsequent decoding. The human homologue of PRR has recently been identified through fMRI experiments (see Figure 2).

There may be advantages to using the visual-motor system for neural-prosthetic applications. Paralysis resulting from spinal cord lesions or other disease processes will compromise sensory feedback, resulting in a major loss of the subject's capability for error correction. Vision, however, is generally not compromised with paralysis and therefore can still provide accurate feedback. Paralysis also results in degeneration and reorganization in the motor cortex. In the case of spinal cord lesion degeneration results from direct damage of cortico-spinal motor neurons and from the loss of somatosensory input, the main sensory input to the motor cortex. Visual-motor areas within the posterior parietal cortex are relatively more removed anatomically, with few cortico-spinal projecting neurons and with vision being a major source of sensory input. Thus it is possible that these areas may undergo less degeneration with paralysis, and therefore provide a stable source of command signals. Moreover, the posterior parietal cortex appears to be essential for visually guided, on-line correction of movement trajectories.

We have developed proof-of-concept neuroprosthetic systems in the Andersen laboratory. The work involves three monkeys that are each trained to operate a computer cursor by merely "thinking about it." The experimental set-up consists of neurophysiological recording chambers which simulate the function of a neural prosthesis (see Figure 3). Signals from electrodes placed in the PRR are amplified, filtered, and digitized. These sampled neural signals are then processed to extract the intended reach direction, as well as the current cognitive state of the monkey. The decoded reach direction and cognitive state the form the basis for a command signal sent to a computer interface or electromechanical device.

In particular, we have the monkey think about positioning a cursor at a particular goal location on a computer screen, and then we decode his thoughts. He thinks about reaching there, but doesn't actually reach, and if he thinks about it accurately, he's rewarded. Combined with the goal task, the monkey is also told what reward to expect for correctly performing the task. Examples of variation in the reward are the type of juice, the size of the reward, and how often it can be given. We are able to predict what each monkey expects to get if he thinks about the task in the correct way. The monkey's expectation of the value of the reward (his cognitive state) provides a signal that can be employed in the control of the neural prosthetic device (in this case, ultimately the cursor).

This type of signal processing may have great value in the operation of prosthetic devices because once the patient's goals are accurately decoded, the devices' computational system can perform the lower-level calculations needed to run the devices. Since the brain signals are high-level and abstract, they are versatile and can be used to operate a number of devices. These signals could also be rapidly adjusted by changing parameters of the task to expedite the learning that patients must do in order to use an external device. The result suggests that a large variety of cognitive signals could be interpreted, which could lead, for instance, to voice devices that operate by patients merely thinking about the words they want to speak.

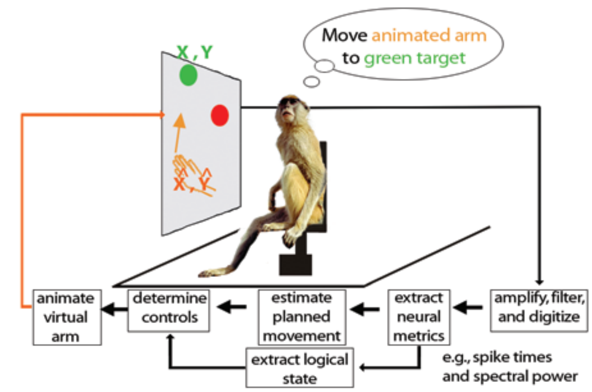


Figure 3. Schematic showing experimental set-up and components of algorithms developed for cognitive neural prosthesis.

The ability of the monkeys to position the cursor on the computer screen with their intentions improved considerably over a period of one to two months. This is consistent with a number of studies of cortical plasticity and suggests that patients will be able to optimize the performance of neural prostheses with training.

The local field potential (LFP) is the aggregate extracellular signal that is recorded by an electrode from the activity of neurons within its listening sphere. It has recently been found that the local field potentials recorded in the posterior parietal cortex of monkeys contain a good deal of information regarding the primates' intentions. This information is complimentary to that obtained from action potentials. The LFP gamma band (approximately 25-90 Hz) temporal structure in the PRR is tuned for reach direction like the action potential activity of individual neurons. Moreover, the decoding of behavioral state from PRR activity was better when using LFPs as compared to spikes. Thus the LFPs provide the most reliable indication of changes in cognitive state.

From a practical point of view, these oscillations are extremely useful for neural prosthetic applications. A major challenge for cortical prostheses is to acquire meaningful data from a large number of channels over a long period of time. This is particularly challenging if single spikes are used since typically only a fraction of the probes in an implanted electrode array will show the presence of spikes, and these spikes are difficult to hold over very long periods of time (see below). However, since local fields come from a less spatially restricted listening sphere, they are easier to record and are more stable over time. In our experience, most electrodes in an array can record LFP signals for at least two years, making this one of the most robust signal gathering methods. Thus it would be of great advantage to be able to use the LFP signals for decoding when and where monkeys intend to make movements.

We now turn to some of the engineering issues that are relevant to the development of future cognitive neural prostheses.

Moveable Electrodes for Autonomous Neuron Isolation and Tracking

The front end of a neural prosthesis consists of an array of chronically implanted electrodes. A key challenge is the yield (number of useful signals) and longevity of these electrode arrays. The reported values of yield and longevity vary widely across different animals, cortical areas, and array designs. While some arrays have provided useful signals for several years, the quality of single-cell activation in most channels of fixed-geometry implanted electrode arrays noticeably degrades after a few weeks or months. Factors contributing to this deleterious loss of signal include reactive *gliosis* (bio-incompatibility of the electrode's surface material). Another difficulty arises from the arrays' fixed electrode geometries, which cannot be adjusted once they are implanted. Consequently, the array's useful signal yield may be low if the electrodes' active recording sites lie in electrically inactive tissue, are distant from cell bodies (which generally produce the largest extracellular signals), or sample cells with non-optimal receptive fields for the task at hand. Even if the initial placement is satisfactory, fixed-geometry electrode arrays can drift in the brain matrix due to tissue movement caused by respiratory or circulatory pressure variations and mechanical shocks. This drift can lead to the separation of the electrode from the vicinity of active cells, thereby lowering signal yield.

Ideally, it would be advantageous to be able to readjust the electrodes continuously after they are implanted to overcome these effects. Such continual adjustment would significantly improve the quality and yield of signals harvested by an electrode array. Electrodes that could break through scar tissue after its build up would also be useful. Manual adjustment of electrodes, which is the standard practice today, is tedious and impractical for paralyzed patients. Electrodes that could continuously and autonomously position themselves so as to optimize the neural signal would provide a great advantage.

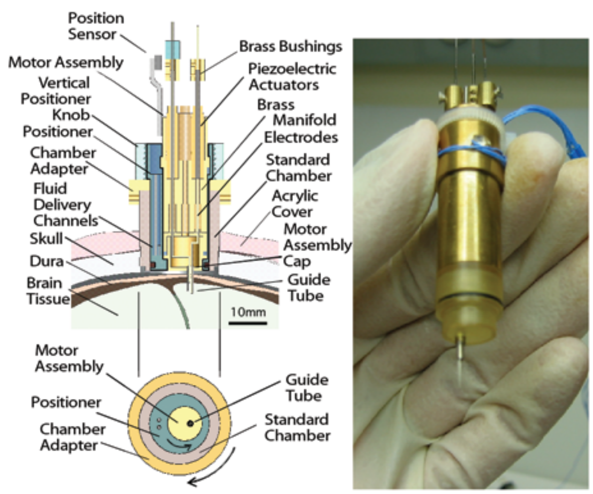


Figure 4. Schematic view (left) of the motorized MEMS-based movable electrode array system (right).

To solve these problems, the Burdick lab has developed a new class of computer-controlled multi-electrode systems that continually and autonomously adjust electrode positions under closed-loop feedback control so as to optimize and maintain the quality of the recorded extracellular signal. These electrodes can maintain high signal quality without requiring human monitoring and intervention. They also allow specific populations of neurons to be selected, thereby simplifying decoding and control algorithms that are based on decoding neuronal populations.

We have developed algorithms that can autonomously isolate and then maintain the signal from a single neuron. These algorithms use a variant of stochastic optimization to find the best probe position using only the recorded electrical signal. The algorithm has been used successfully on a number of occasions to automatically isolate and maintain extracellular signal activity in monkey PRR, as well as rat barrel cortex. To demonstrate the future potential for this approach, we have also built a custom micro-drive containing four electrodes that are independently actuated by miniature piezoelectric motors. This device (Figure 4) can fit inside the standard recording chamber that is used in the Andersen recording laboratory.

However, the eventual goal is to use micro-electro-mechanical systems (MEMS) technology to produce a movable electrode array implant. To this end we are collaborating with Yu-Chong Tai and his group. One promising method is to use electrolysis techniques to move and lock the probes in place. This movement is accomplished by passing electrical current within small bellows chambers filled with fluid. The gas released by electrolysis increases pressure within the bellows and moves the electrode. The electrodes can be moved in the opposite direction by introducing a catalyst and reversing the current flow. Advantages of this electrolysis technique include relatively low driving voltage, low heat dissipation, the ability to lock electrodes in place without the need for continuous power dissipation, the ability to generate very high forces, and the ability to provide hundreds of microns of electrode displacement.

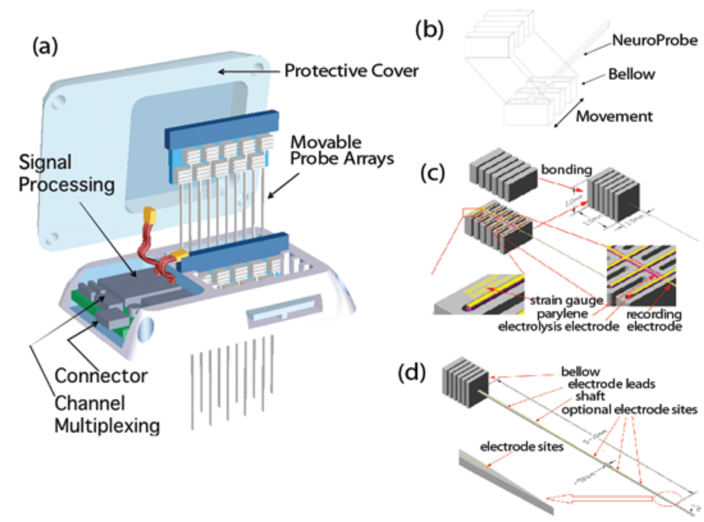


Figure 5. (a) Schematic diagram of linear arrays of electrolysis actuators. (b) Bellows for moving the electrode. (c) Details of the bellows construction. (d) Silicon electrode shaft and metal electrode contact attached to the bellows.

Microfluidic delivery systems could also be added to the implant (see Figure 5). These microfluidic systems would also work via electrolysis, and could potentially deliver anti-inflammatory agents to manage the effects of the electrodes' presence, or to deliver therapeutic agents. The MEMS movable probes and microfluidic channels can be constructed as linear probe arrays. These arrays would consist of the electrodes/needles, micro-electrolysis systems, and control electronics. The individual chips with linear arrays would be stacked within a chamber, allowing the most flexibility in the overall geometry of the implanted array of electrodes and microfluidic channels. The depth of the individual chips can be adjusted coarsely using a motorized chip adjuster following surgery. After coarse adjustment, electrolysis actuators would provide the fine-tuning of the electrodes' positions automatically and continuously. The integration of pre-processing electronics (e.g., pre-amplifiers, filters, and multiplexers) into a multi-electrode array front-end would improve recording performance by improving signal-to-noise ratio and buffering the signal of high-impedance electrodes. Such a pre-processing chip has recently been developed.

Thought into Action: Control Systems Based on Intelligent Devices and Supervisory Control

Also required for a cognitive-based prosthetic system are intelligent devices and hierarchical, supervisory control algorithms. Any system that translates thoughts into action will employ a computer interface, and often some electromechanical devices. Such systems must match the information that is decoded from the brain to the informational requirements of the computer interface and the commanded devices. On the brain side, the cognitive approach focuses on decoding high-level information at the abstract or symbolic level. The informational requirements on the electromechanical device side can vary widely with the type of device and intended task. For graphical computer interfaces, the problem of control system design reduces to matching the cognitive states of the brain to the symbolic states of the task. For instance, iconic menus on computer monitors can be used for communication with a wide range of devices from household utilities to computers for exploring the Internet.

Physical electromechanical devices require more detailed instructions. Supervisory control systems can convert symbolic level commands into detailed motor device commands, which are then carried out and monitored by the supervisory controller. There is much to be gained by pursuing this approach, as it has additional advantages for both the patient and the system engineer. To interface the brain to different electromechanical devices, often only the lowest level of the control hierarchy needs to be re-engineered for the specific mechanical device. Similarly, the hierarchical nature of supervisory control should allow patients to learn much more quickly how to command a new device.

Since a patient's workspace will be limited, knowledge of that workspace, combined with the decoded desires of the subject, may be sufficient to successfully complete tasks using intelligent devices. For example, given the Cartesian coordinates of an intended object for grasping, a robotic motion planner can determine the detailed joint trajectories that will transport a prosthetic hand to the desired location. Sensors embedded in the mechanical arm ensure that it follows the commanded trajectories, thereby replacing the function of *proprioceptive* feedback (internal feedback within muscles, joints, and tendons) that is often lost in paralysis. Other sensors can allow the artificial arm and gripper to avoid obstacles and control the interaction forces with its surroundings, including grasping forces, thereby replacing *somatosensory* feedback (external feedback based on touch). Only the intent to grasp or ungrasp an object is needed to supervise these actions. Hence, low-level physical details and interactions need not be specifically commanded from decoded brain signals. However, if available, motor signals can augment low level plans and controls.

Work continues on all fronts, and we have recently identified the human homologue of the macaque parietal reach region. However, it is still unknown if neural activity in human PRR can be decoded in the same way as that in the macaque PRR. To address this question we are working with human participants (epilepsy patients) who have chronically implanted electrodes placed on the surface of cortex and within deep brain regions. Recordings taken from these participants while they execute delayed reaches allow us to acquire high signal-to-noise intracranial EEG (iEEG) activity from cortical areas during motor planning. Analysis of this neural activity is aimed at determining which properties of the signal can be used to decode and predict planned movement. The positive results to date of our unique approach to the development of cognitive neural prostheses have inspired us to continue, with the possibility of transitioning the technology to humans within several years. ENG

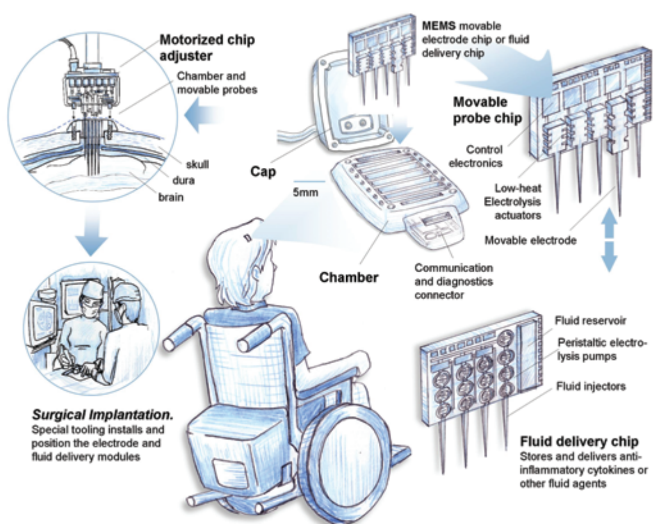


Figure 6. This conceptual diagram illustrates a future neuroprosthetic system that combines arrays of movable electrodes and micro-fluidic delivery systems.

Joel Burdick is Professor of Mechanical Engineering and Bioengineering and Richard Andersen is the James G. Boswell Professor of Neuroscience.

Learn more about Joel Burdick's research at:
http://www.me.caltech.edu/faculty/burdick.html

More on Richard Andersen's research at:
http://vis.caltech.edu/

Donald Cohen: Marvelous Mathematics, Myriad Manifestations

by Thomas Hou

Donald S. Cohen, Charles Lee Powell Professor of Applied Mathematics, took emeritus status in July 2003, thereby closing one chapter of his colorful and productive career at Caltech and opening another. Throughout his 38-year career at Caltech, Don has contributed substantially to the research and teaching of applied mathematics at Caltech. He has also served on a number of influential committees and held a variety of administrative positions. Many of his former students have fond memories of Don as both an outstanding teacher and a friend.

Don Cohen was born in Providence, Rhode Island in 1934. He first studied physics at Brown, but then found that his real interest was in applied mathematics. After graduating from Brown in 1956, he went to Cornell to study probability and statistics. Subsequently, he went to the Courant Institute to study for his PhD degree in applied mathematics (which he obtained in 1962). At the time, the Courant Institute was the center of applied mathematics and home to a tremendous amount of exciting research. At the Courant Institute, Don studied with Joe Keller, one of the most influential applied mathematicians.

Caltech decided to establish an applied mathematics program in 1965 under the leadership of Gerald Whitham. Don was one of the earliest faculty members recruited to this new program. In fact, when Don was offered a faculty position at Caltech in 1965, the applied mathematics option had not been officially established. Don's initial appointment was with the mathematics option. He rose quickly through the ranks, earning promotions to associate professor in 1967 and to full professor in 1971. In 1998, he was appointed the Charles Lee Powell Professor of Applied Mathematics.

Don's research in applied mathematics has covered a wide range of topics. Some of his earliest work was in an area that is now called the theory of reaction-diffusion equations. Together with students and colleagues, Don developed and used multiscaling perturbation techniques to make some of the first contributions to bifurcation in reaction-diffusion theory. This work had its major applied thrust in the emerging theory of multiple solutions in chemical reactors. All of this work is still being referenced in several fields.

"All we have to do is write that mess as something easy... plus all the other junk."

Don's research on nonlinear differential equations, pattern formation, stability, and bifurcations has had enormous influence in the areas of mathematical biology and chemical engineering. Along with several colleagues, he helped formulate basic models that led to the development of more quantitative studies of population dynamics in biological systems. Don applied similar techniques to analyze the stability of chemical reaction systems. Continually keeping pace with modern applications, Don's later works focused on mathematical models in the materials science of polymer films. Some of these studies focused on questions of how the properties of polymers could be tailored to control time-release of drugs in the next generation of pharmaceuticals.

"Nothing's happening at infinity. Infinity is Kansas City, maybe."

Don will be remembered by many generations of Caltech students who had him for the AMa 95 or AMa 101 applied mathematics course sequences. He was a very popular teacher and was often the source of colorful and very memorable quotes [see inset quotes]; some were collected by students in an article appearing in *The California Tech*. He had a special ability to make the analysis of even complicated problems seem easy. His playful style in solving problems always entertained, engaged, and challenged students. Don's outstanding teaching skills have been well recognized by Caltech students. He received awards for undergraduate teaching excellence in 1979, 1987, 1998, and was awarded the Richard P. Feynman Teaching Prize for Excellence in Teaching in 2000.

Don has been a popular advisor and mentor at Caltech not only because of his scientific expertise, but also because he is so personable. He is quick to put his students at ease, and often engages them in good-natured verbal sparring. Don

“The answer is no, but it usually turns out in applications you can get away with it for a while.”

“Stopping at this point in the problem is worse than stopping at the beginning.”

is also a seemingly endless source of funny stories about his earlier days at Caltech and at the Courant Institute. More often than not, these stories also manage to convey some lesson about life beyond the classroom, and his students have found them to be so valuable that they have adopted them for use with their own advisees. Don shared his vision for problem solving with nineteen graduate students, many of whom have gone on to become professors of mathematics at other top universities.

Don’s athletic prowess is well known among his students. Don was always willing to play tennis with any of them who were foolish enough to think they could beat him. Other activities, such as trips to the beach, or hiking, or river rafting expeditions, were also common occurrences when one worked with Don. Of course, work has always come first, guided by Don’s skillful advising. He somehow always seems to know the right thing to do or say when a student is stuck on a problem. Don also knows when not to say anything, forcing a student to figure things out on his or her own.

In addition to his contributions to research and teaching, Don has served on a number of influential committees and held several important administrative posts. He was the Executive Officer for Applied Mathematics from 1988 to 1993. He served as the Chairman of the Faculty from 1983 to 1985, and chaired the Faculty Advisory Committee to the Trustees to select Caltech’s fifth president from 1986 to 1987. He also served on the Academic Freedom and Tenure committee many times (both as member and as chairman). In addition, he served on various national committees of the Society for Industrial and Applied Mathematics, the American Mathematical Society, and the American Association for the Advancement of Science. From 1993 to 1995, he served as the Director of the Center for Nonlinear Studies at Los Alamos National Laboratory.

Don remains active in his research. His main focus is the mathematical modeling of biological systems. Currently, he divides his time between Pasadena and Santa Fe. Recently, he became a grandfather. Visiting his daughter in Washington, D.C. and spending time with his grandchild gives him great satisfaction. We are very pleased that Don still spends most of his time at Caltech. Both ACM and Caltech cannot afford to lose his valuable expertise and advice. ENG

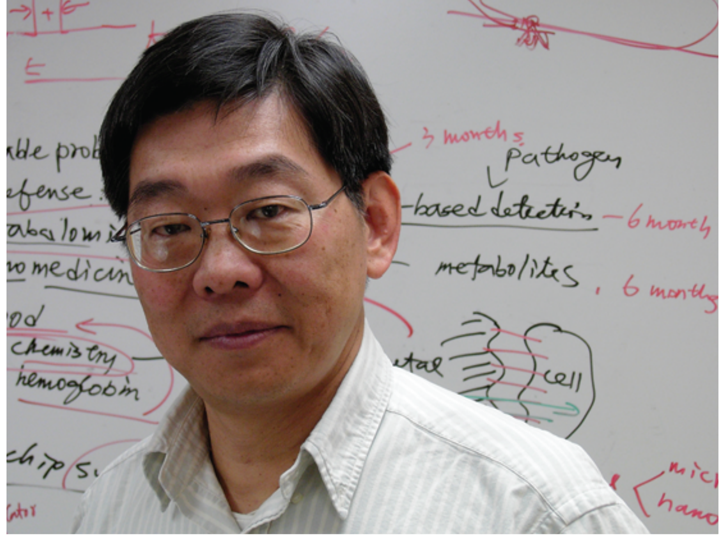
The author, Thomas Hou, is Charles Lee Powell Professor of Applied and Computational Mathematics and Executive Officer of the Applied and Computational Mathematics Option.

R E S E A R C H   N O T E

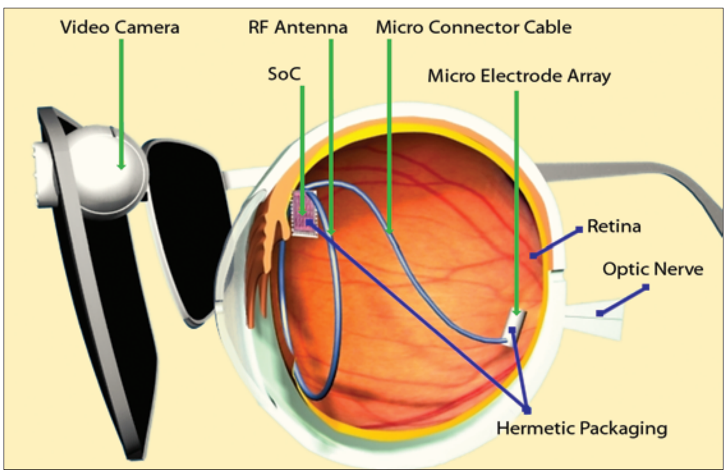
Retinal Implant Research:

The Possiblility of Artificial Vision

by Yu-Chong Tai and Wolfgang Fink



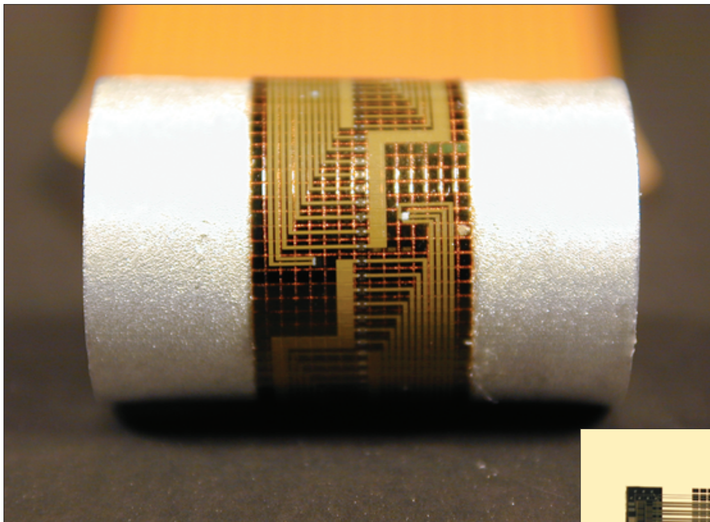
Blindness is the second most-feared disease next to cancer. Each year there are about 100,000 people newly diagnosed with blindness due to Retinitis Pigmentosa (RP, an inherited condition in which all photoreceptors are eventually lost) and Age-related Macular Degeneration (AMD). Both diseases primarily affect only the photoreceptors of the retina. Unfortunately there still is no medical cure for either RP or AMD. However, over the past ten years there has been investigation into the possibility of creating a retinal prosthesis that mimics the biological function of the photoreceptors in stimulating downstream neurons in the retina. It has been demonstrated that such a prosthesis, called an epi-retinal multi-electrode array, can allow patients to "see" again through electrical stimulation from a 4 x 4 electrode array placed directly on the surface of the macula (the precision vision region of the retina). This technology is similar to the cochlear implant which uses a small number of electrodes to mimic lost function in the auditory system. A 4 x 4, or 16-pixel array, however, cannot produce the useful ambulatory vision needed for a blind patient to use their visual system in an autonomous manner. Thus, this epi-retinal implant technology has to improve dramatically. A healthy retina has over 100 million photoreceptors. A retinal implant that enables ambulatory vision would need thousands, if not tens of thousands, of stimulating electrodes.



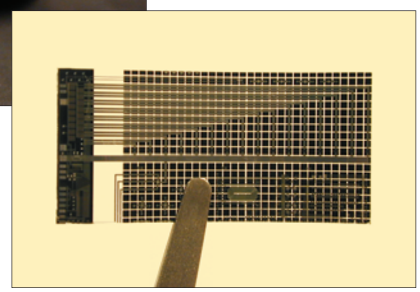
An intraocular epi-retinal prosthesis will use an external camera and external microelectronic systems to capture and process image data and transmit the information to an implanted microelectronic system, all in real time. The external system is being developed by Dr. Wolfgang Fink at Caltech in close collaboration with Dr. Wentai Liu's lab at University of California, Santa Cruz and Dr. Mark Humayun's lab at USC. The implanted system would decode the data and stimulate the retina with a pattern of electrical impulses to produce visual perception. (Image courtesy Humayun et al.)

My lab at Caltech has developed a flexible "smart skin" technology that may just be the answer. The flexible smart skin is made by MEMS technology and is only tens of microns thick. The flexibility of the skin is important because the device can be folded and inserted surgically into the eye through a small, quick-to-heal incision. Furthermore, the skin can conform to the curved surface of the retina to provide intimate contact to the target neurons. Moreover, the skin is integrated with silicon integrated circuits and numerous sensors such that the extension of this technology can provide as many channels as needed for the retinal implant.

As a result of the natural extension of this smart skin technology to the retinal prosthesis, a close col-



Actual smart skin sample demonstrating its flexibility at wrapping around a curved surface.



An IC-integrated flexible parylene smart skin.

laboration between my lab and Dr. Mark Humayun's lab at the Keck School of Medicine of the University of Southern California (Doheny Eye Institute) has been formed (part of the NSF-funded USC/Caltech/UCSC Biomimetic MicroElectronic Systems Engineering Research Center). The long-term goal for my lab is to produce a totally integrated retinal prosthesis that contains a power-delivery secondary coil, a power-and-signal management system-on-a-chip (SoC), and a flexible high-density retinal electrode array. Although this project is just in its initial stages, there have already been two major advancements. The first is the completion of a biocompatibility experiment in which unmodified parylene, the major component of the proposed retinal prosthesis, was placed in the intraocular space of an eye for six months. Our experiments showed that parylene did not cause an immune or foreign-body response for the duration of this implantation. The second is that we have successfully produced flexible gold/parylene 16 x 16 electrode arrays that are currently undergoing soak tests in saline solution.

Dr. Mark Humayun and his team at USC recently reached an important milestone on the clinical side, with the implantation of an active stimulating epi-retinal device in a blind human. The patient had reported vision loss for 50 years from RP and had documented no light perception in the eye before implantation of the device. When a 16-electrode device (4 x 4 matrix) was activated one week after implantation, the patient saw spots at all 16 electrodes. Further testing demonstrated spatial discrimination between two electrodes that allowed the ability to discern gross movement of objects in the field of the patient's camera.

These results are major advancements towards producing a clinically viable, intermediate-density retinal implant in the near future. ENG

Yu-Chong Tai is Professor of Electrical Engineering. Wolfgang Fink is Visiting Associate in Physics.

Visit Yu-Chong Tai's Micromachining Lab at:
http://touch.caltech.edu/

Learn more about Wolfgang Fink's Research at:
http://www.wfbabcom5.com/wf3.htm

The EE Enterprise: Sweeping into Uncharted Terrain

by P. P. Vaidyanathan

The impact of electrical engineering (EE) on our society cannot be overemphasized. Silicon electronics and computers have invaded and reshaped lifestyles for the last 30 years. Nearly all high-tech devices we routinely use today—cell phones, PCs, flash memory cards, and sensor networks—rely on countless EE advances and ingredients. Information technology, birthed and nurtured in EE departments, drives an increasing portion of the world's economy, and leaves very few of the world's population untouched.

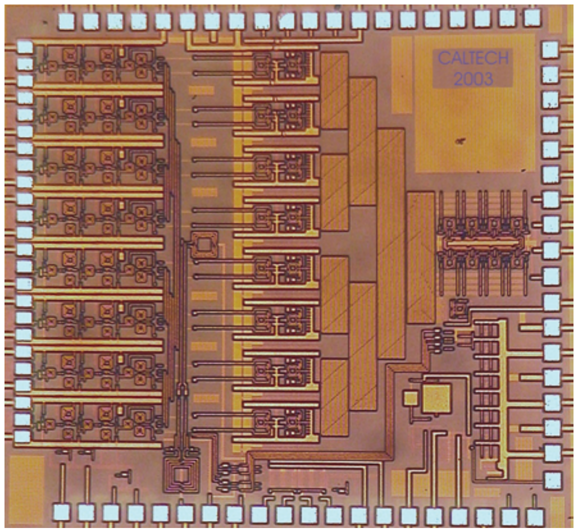
Just a few decades ago, EE departments in the U.S. were small enclaves, with a limited number of courses and research activities in areas such as electrical circuits, power electronics, active and passive filters, and electromagnetics. These expanded into different specializations, resulting in many significant changes in EE curricula and research directions. Over time, many of the mathematically intense topics such as information theory, feedback controls, signal processing, and communication theory became part of the EE program in most schools. The field has evolved rapidly and today typical areas of interest include electronics, telecommunications, signal and image processing, adaptive/learning systems, magnetics, nanotechnology, and photonics. Training in areas such as biological circuits and genomics are becoming increasingly important. EE has become one of the most multidisciplinary areas of technical studies, covering a broad range of applications such as coding, communications, signal processing, electrical circuits, microwave devices, and nano-fabrication techniques. EE at Caltech is no exception—and in many ways we are at the vanguard, as the research here sweeps across highly varied terrain.

A number of us have become increasingly interested in biology. Jehoshua Bruck, Gordon and Betty Moore Professor of Computation and Neural Systems and Electrical Engineering, and his group are developing new abstractions for biological circuits that in turn provide new ideas for a paradigm shift in logical circuit design. This includes analysis and synthesis methods for combinatorial circuits with feedback. Bruck also has significant interest in the study of the structure and function of the *C. Elegans* nematode, with a focus on examining extra- to intra-cellular information flow and processing (how cells receive, amplify, and integrate signals from a variety of stimuli). Bruck has been instrumental in establishing the Information Science and Technology initiative at Caltech (more on this below), for which he is the founding director. Visit the Bruck Group at http://www.paradise.caltech.edu.

Pietro Perona, Professor of Electrical Engineering, is Director of Caltech's Center for Neuromorphic Systems Engineering (CNSE), a National Science Foundation Engineering Research Center. A substantial number of EE faculty are involved in the CNSE, including Yaser Abu-Mostafa, Ali Hajimiri, Demetri Psaltis, and Yu-Chong Tai. Faculty members from other options on campus join them in developing artificial sensory systems and more generally, intelligent and autonomous machines. The CNSE is celebrating its 10th year this November. Visit the CNSE at http://www.cnse.caltech.edu.

Perona's work centers on computational vision. He is interested both in human vision and machine vision applications. He is currently mostly involved in understanding how a visual system may learn, represent and recognize objects, scenes and human actions and activities. He is also joining Team Caltech this year, and is teaching a class on vision systems for autonomous vehicles. Many of the students taking his class are designing the vehicle to be entered in the DARPA Grand Challenge.* Visit the Perona Group at http://www.vision.caltech.edu.

The research of Yaser Abu-Mostafa, Professor of Electrical Engineering and Computer Science, is devoted to the theory, algorithms, and applications of automated learning. Learning can be viewed as an alternative approach to system design. Rather than mathematically modeling the task at hand and implementing the model as a system (a computer program or a piece of hardware), he starts with a generic model that has a number of "untuned" internal parameters. Depending on how the parameters are tuned, the model can implement vastly different tasks. The role of learning is to take examples of the task, such as inputs together with their target outputs, and use this information to tune the parameters of the learning model to mimic the desired task. This approach is essential when the task at hand does not lend itself to exact mathematical modeling, as is the case in many practical applications. His group has pioneered the use of hints in learning and has developed special expertise in learning from very noisy data, which led to activities in computational finance. Visit the Abu-Mostafa Group at http://www.work.caltech.edu.



Ali Hajimiri's novel antenna array transceiver system on a single, silicon chip can function in a multiplicity of ways because it integrates high-frequency analog and high-speed signal processing at a low cost. Most silicon chips have a single circuit or signal path; Hajimiri's innovation lies in multiple, parallel circuits on a chip that operate in harmony, thus dramatically increasing speed and improving performance. The chip runs at 24 GHz (24 billion cycles in one second) which makes it possible to transfer data wirelessly at speeds as high as 1 Gb/s (1 billion bits per second). The chip can, for example, serve as a wireless, high-frequency communications link, providing a low-cost replacement for the optical fibers that are currently used for ultra-fast communications. It can function as "radar on a chip" and be used ubiquitously on cars to provide smart cruise control. With both a transmitter and receiver (more accurately, a phased-array transceiver), the chips work much like a conventional array of antennas. Unlike conventional radar, which involves the mechanical movement of hardware, this chip uses an electrical beam that can steer the signal in a given direction in space without any mechanical movement.

Yu-Chong Tai's micro-electro-mechanical systems (MEMS) Lab continues to create exciting frontiers with new materials, technology, and applications. The "smart skin" technology developed in Tai's lab has transitioned into a high-visibility project for retinal implants for blind people [see Research Note, page 20]. Tai, Professor of Electrical Engineering, is also working with professors Joel Burdick and Richard Andersen on cognitive neural prostheses, in particular, on movable electrode array implants [see page 12 for a Progress Report on this topic]. Among many other projects, he also continues to work on nanoscale technologies to enable "lab-on-a-chip" devices. Visit the Tai group at http://touch.caltech.edu.

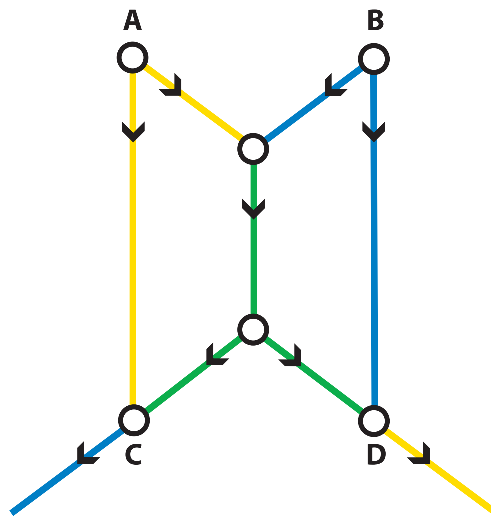
Recently, Changhuei Yang, Assistant Professor of Electrical Engineering and Bioengineering, has joined us with emphasis on the new discipline of biophotonics, that is, the imaging and extraction of information from biological targets through the use of light. One of Yang's recent foci is in creating imaging systems that probe the small (nanometer scale) and slow (nanometer/second) dynamics of living cells. Yang also works on molecular contrast optical coherence tomography (MCOCT), capable of high-resolution bio-

*The Grand Challenge is a desert race (Los Angeles to Las Vegas) for autonomous, off-road vehicles; it will take place on October 8, 2005. More detail may be found at http://team.caltech.edu.

logical imaging. Recent results include a novel MCOCT implementation that is capable of profiling the distribution of a specific protein within a target sample. The extension of MCOCT to protein molecular imaging is significant, as it opens the possibility of MCOCT imaging of genetic expression of molecular probes in the same manner that fluorescent proteins are employed in fluorescence-based molecular imaging. Visit the Yang Group at http://www.biophot.caltech.edu.

My own interest in biological themes comes from my interest in the application of signal processing, digital filtering, and computer science concepts in the identification of coding and noncoding genes. With the enormous amount of genomic and proteomic data that is available to us in the public domain, it is becoming increasingly important to be able to process this information in ways that are useful. My group is also continuing work in many aspects of digital signal processing theory including filters, filter banks, wavelets, and image processing. In recent years I have been interested in the application of digital filter banks in communications, especially blind identification and equalization of wireless channels. Visit the Vaidyanathan Group at http://gladstone.systems.caltech.edu/dsp/.

In the area of optics, Caltech has one of the world's leading research groups. Through the efforts of Demetri Psaltis, Thomas G. Myers Professor of Electrical Engineering, and his colleagues, a new multi-university DARPA center in optofluidics has been recently established at Caltech. Optofluidics refers to a class of adaptive optical circuits that integrate optical and fluidic devices. The introduction of liquids in the optical structure enables flexible fine-tuning and even reconfiguration of circuits such that they may perform tasks optimally in a changing environment. Their approach is based on a nanostructured optical substrate integrated with a microfluidic structure that performs functions such as reconfiguration of functionality, adaptation of properties, distribution of chemicals to be analyzed, and temperature stabilization. Visit the Optofluidics website at http://www.optofluidics.caltech.edu, and the Psaltis Group at http://optics.caltech.edu.



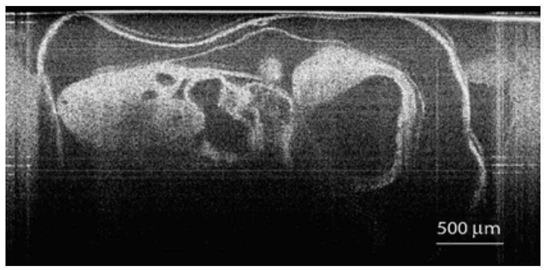
An example of network coding being developed by Professor Michelle Effros: User A wishes to send a binary message to user D (yellow), and B to C (blue). Each link can carry one binary message per use and all links operate in the downward direction. Using routing, transmitting messages from A to D and B to C requires two channel uses since both messages must traverse the central bottleneck link. Network coding allows both messages to be sent simultaneously using a single channel as follows. A sends the same message to both C and D; B sends the same message to both D and C. The message sent along the bottleneck is a mixture of the message from A and the message from B (e.g., the binary sum of the corresponding bits). When C decodes the data that came via the bottleneck, (A and B mixed, green), he uses the data that came directly from A to determine how to decode the mixed data and extract the message from B. When this concept is applied to a large-scale, multi-node system, even failure at isolated nodes will not impede the flow of information.

Axel Scherer, Bernard A. Neches Professor of Electrical Engineering, Applied Physics, and Physics, has been engaged in a multiplicity of nanofabrication activities such that today, we can produce structures with lateral sizes as small as 6 nm by combining electron beam lithography and dry etching. Scherer's research laboratory is built around producing such nanostructures and applying them to new optoelectronic, magneto-optic, and high-speed electronic devices. The aim of his research group is to develop functional devices which use their reduced geometries to obtain higher speed, greater efficiencies, and which can be integrated into systems in large numbers. Successful integration of such devices in large numbers requires detailed understanding and optimization of both the individual processing steps as well as the device performance. Visit the Scherer Group at http://nanofab.caltech.edu.

Amnon Yariv, the Martin and Eileen Summerfield Professor of Applied Physics and Professor of Electrical Engineering, and his group are working principally in three areas lately: optical resonators, integrated optics based on polymeric fabrication, and microstructured optical fibers and devices. In contrast to conventional optical fiber in which waveguiding is due to total internal reflection, light is traversely confined in microstructured fibers by Bragg reflection. Therefore, light may be guided in air or a vacuum inside these fibers, potentially reducing the effects of material dispersion and nonlinearities. Yariv's research into high-resolution and high-performance optical components by molding replication in polymeric materials resulted recently in the demonstration of 3-D optical circuitry. A new research thrust in the group involves designing new phase-coherent optical communication modulation and demodulation devices to take advantage of the hitherto neglected optical phase and thereby extend to the optical domain techniques such as CDMA, FM, phase coding, and heterodyne detection—all of which are mainstays of wireless and microwave systems.

There is considerable integrated activity in wireless communication and networking research at Caltech. The Lee Center for Advanced Networking, directed by David Rutledge, the Kiyo and Eiko Tomiyasu Professor of Electrical Engineering, includes a number of faculty members interested in various aspects of networking. Small, portable satellite communications systems are enabling high-speed world-wide communications. A key challenge remains, however, and that is to obtain sufficient transmitter power at high frequencies from transistor circuits with inexpensive power amplifiers. The groups of Ali Hajimiri, Associate Professor of Electrical Engineering, and David Rutledge have made breakthroughs in producing power amplifiers for cellular telephones, wireless LANs, and satellite communications.

Hajimiri's High-Speed Integrated Circuits (CHIC) group focuses on applications of silicon-based integrated circuits to various applications in communications, sensing, and computing. The CHIC group has been the birthplace of important developments such as world's first fully integrated CMOS power amplifier. Recently they have built a novel antenna array system on a silicon chip that functions as the world's first "radar on a chip." This chip, a phased array system, runs at 24 GHz which makes it possible to transfer data wirelessly at speeds available only to the backbone of the Internet using optical fiber. Hajimiri was named one of the 100 Top Young Innovators by *Technology Review* (2004).



This is a cross-sectional scan of a mouse embryo for the study of heart development. It is obtained with a Swept-Source Fourier-Domain Optical Coherence Tomography (SSFDOCT) system, which has a signal-to-noise ratio of 120 dB and resolution down to a few microns. The obvious advantages of OCT is that it performs high-resolution and non-invasive cross-sectional scans (down to 4 mm below the sample surface in the case of this system) without doing any damage to the object that is being imaged, making OCT an ideal tool for biomedical imaging. These techniques are being developed by Professor Changhuei Yang.

In addition to directing the Lee Center, Rutledge is the Associate Director of Information Science and Technology (IST), and as such has been active alongside Bruck in creating the nation's first educational and research initiative devoted to bringing the study of information, whether it be manifest in biological or man-made systems, into direct focus. Through IST, we have begun to educate the information generalists of the future. These are young scientists and engineers who will combine a deep knowledge of information science with a breadth of experience across multiple disciplines, from biology to physics to economics. [ENGenious covered the birth of IST in our Winter 2003 issue; there is an update in this issue's Snapshots section, page 4.] Visit IST at http://www.ist.caltech.edu.

In his own research group, Professor Rutledge is building circuits and antennas for a range of applications at frequencies from one MHz all the way up to the THz range. Radio and microwave circuits are the core of the wireless communications revolution and play a central role in radars, remote sensing, and satellite broadcasting. His research is in quasi-optical powercombining, micro-electro-mechanical systems (MEMS) for RF and microwave circuits, and Class-E amplifiers for communications transmitters. For further details see http://www.ee2.caltech.edu/People/Faculty/rutledge.html.

Steven Low, Associate Professor of Computer Science and Electrical Engineering, has developed FAST TCP, a protocol that can transfer data at multi-Gbps

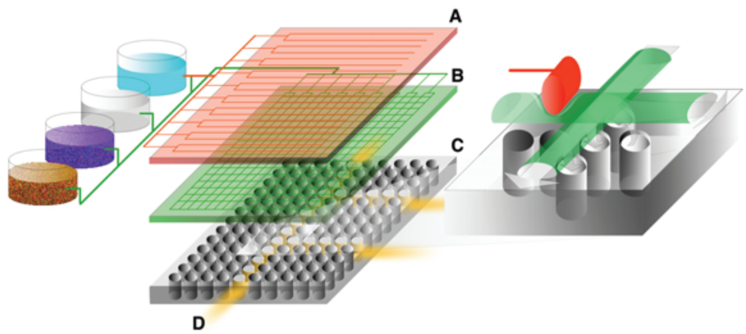
Humans can effortlessly identify, learn and recognize novel objects. The same task is difficult for machines because a machine does not know how many objects there are in an image without knowing about the object beforehand. The algorithms being developed by Professor Pietro Perona and his group replicate strategies used by the human visual system by using a two-stage process consisting of (1) bottom-up attention and (2) object recognition. The *attention algorithm* calculates the saliency of every pixel of the input image and uses this information to predict the location, size, and shape of likely objects. The *object recognition algorithm* extracts features from the regions predicted to contain objects and tries to recognize them. In the case that it does not recognize an object, it assumes that it is new and learns it. In (a), the two outlined objects are, among others, learned. Even if it has only seen the same object once, it is able to identify it in subsequent images (b) and (c). This approach allows the unsupervised learning of multiple objects from a single image. [Figure adapted from U. Rutishauser, D. Walther, C. Koch, P. Perona, *Is bottom-up attention useful for object recognition?* CVPR 2004, IEEE Press.]

(billion bits per second) rates globally, efficiently, and robustly. His group has been involved in setting many of the recent data transfer speed records, and holds the current record. In September of this year, the team transferred 859 gigabytes of data in less than 17 minutes at a rate of 6.63 gigabits per second between Caltech and the CERN facility in Geneva, a distance of more than 15,766 kilometers. The speed is equivalent to transferring a full-length DVD movie in just four seconds. Low is also actively developing theory, algorithms, and prototypes for control and optimization of networks and protocols.

In the area of communications, Robert McEliece, Babak Hassibi, Michelle Effros, and myself have strong groups which work on state-of-the-art research problems in digital communications and signal processing.

Robert McEliece, Allen E. Puckett Professor and Professor of Electrical Engineering, has an active group on information and coding theory. His general goals are to develop theoretical performance analyses of existing and proposed storage/transmission systems, and to design new higher performance systems. McEliece recently won the 2004 Shannon Award of the IEEE, which is the highest honor in the field and recognizes consistent and profound contributions to the field of information theory. Visit the McEliece group at www.mceliece.caltech.edu.

Michelle Effros, Associate Professor of Electrical Engineering, works on data compression and information theory. Recently, her group has been studying data compression and transmission techniques for network environments. Data compression is the science of information representation. The goal of data compression for network systems is to represent information in a manner that facilitates efficient and reliable transmission and storage. In a sensor network, measurements are taken by a variety of independent sensors operating in a shared environment. Network compression algorithms allow us to remove redundancy between measurements taken by distinct sensors, even when these sensors are required to act autonomously. Effros' group has pioneered new fast algorithms for network compression system design and implementation. They have also created theory and algorithms in the new field of network coding. Network coding is an alternative to routing that can increase the capacity of shared network environments. Effros was named one of the world's 100 Top Young Innovators by



An optofluidic system composed of: (A) microfluidic valve network, (B) microfluidic channels, (C) photonic bandgap structure, and (D) optical beams. The new field of optofluidics is being pioneered by Professor Demetri Psaltis and his colleagues.

Technology Review in 2002. Visit the Effros Group at www.ee2.caltech.edu/People/Faculty/effros.html.

Babak Hassibi, Associate Professor of Electrical Engineering, joined us in 2003, and is currently most interested in wireless communications, especially in the use of multiple-antenna systems, where he has studied both the information-theoretic and coding-theoretic aspects of such systems, as well as devised practical high-rate space-time transmission schemes. His group also works in the area of wireless networks, where they have studied how various performance measures such as capacity, power-efficiency, fairness, etc., scale in different wireless networks. Visit the Hassibi Group at www.systems.caltech.edu/EE/Faculty/babak/grouphomepage.html

Finally, the research of John Doyle, John G Braun Professor of Control and Dynamical Systems, Electrical Engineering, and Bioengineering, covers a vast number of phenomena, all linked by belonging to complex systems that exhibit both robustness and fragility, or "highly optimized tolerance." This past summer, his 50th birthday was marked by a symposium that brought together leaders in the areas of communications, computational complexity, biophysics, biological systems, medicine, quantum physics, statistical physics, engineering, and mathematics for interactive exchange of ideas on the design, analysis, and control of complex systems. Visit the Symposium website at www.cds.caltech.edu/doyle-fest.

This was but a brief overview of the current activity in EE, but it is apparent that the breadth of research here has certainly redefined what it means to be an electrical engineer. The past few decades have seen a radical application of EE themes throughout the study of nature and the development of technology, and we look forward to continuing this contribution to the expansion of EE in the next several decades. ENG

P. P. Vaidyanathan is Professor of Electrical Engineering and Executive Officer for Electrical Engineering.

Who's New

Welcome to Our New Faculty

Mathieu Desbrun: Associate Professor of Computer Science

Professor Desbrun's interests revolve around the study of discrete differential geometry, including processing, animation, and simulation of meshed geometry, as well as theoretical work on foundations of computation on discrete manifolds.

Before moving to Caltech, he was an Assistant Professor in Computer Science at the University of Southern California (USC) where he received an NSF CAREER Award in 2001 and the ACM SIGGRAPH Significant New Researcher Award in 2003.

Desbrun received his Engineering Degree (equivalent of MEng) in Computer Science with distinction from the National Engineering School of Computer Science and Applied Mathematics in Grenoble (1991–1994), his Graduate Degree (equivalent of MSc) in Computer Graphics and Vision at the University of Grenoble, France (1993–1994), and his PhD in Computer Science at the National Polytechnic Institute of Grenoble, France (1995–1998).

Houman Owhadi: Assistant Professor of Applied and Computational Mathematics and Control and Dynamical Systems

Professor Owhadi's interests are in applied mathematics, particularly probability theory, partial differential equations, homogenization, turbulence theory, game theory with large number of agents, stochastic analysis, large deviations, heat kernels, non-equilibrium statistical mechanics, and transport and diffusion in random media. One of Owhadi's particular areas of interest is the multiscale analysis of partial differential equations and stochastic differential equations, more precisely the mathematical description and analysis of systems involving a very large number of scales without any separation between these scales.

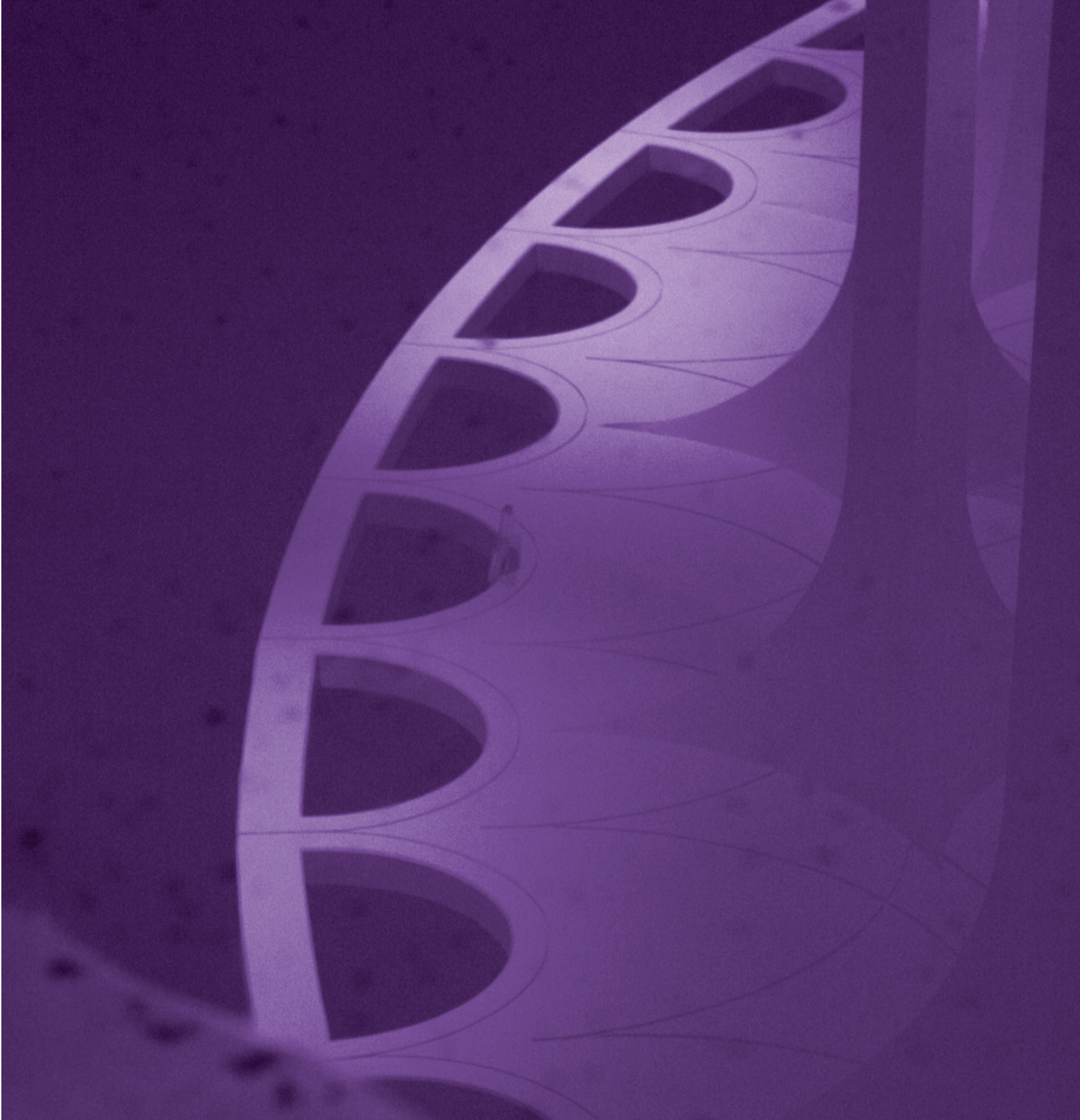
Owhadi received Master's degrees from École Polytechnique (Paris), the University of Jussieu (Paris), and the École Nationale des Ponts et Chaussées. He received a PhD in Mathematics from the Swiss Federal Institute of Technology (2000). Most recently Owhadi was a senior civil servant at the Corps des Ponts et Chaussés, an Aly Kaufman Fellow at Technion, and a CNRS Research Fellow at the University of Provence.

Moore Distinguished Scholar

Sandra M. Troian: Professor of Chemical Engineering, Princeton University

Professor Troian's research interests are in high-resolution lithography by microscale contact printing; microfluidic delivery systems using micropatterned thermocapillary flow; boundary conditions for liquid on solid flows; rivulet instabilities in driven spreading films; onset and evolution of digitated structures in spreading surfactant films; and slip behavior and foam stabilization in polymer-surfactant films.

Troian is a Professor of Chemical Engineering at Princeton University, and is also an affiliated faculty member in the Departments of Physics, Mechanical and Aerospace Engineering, and Applied and Computational Mathematics. Sandra Troian received her Bachelor's degree in Physics from Harvard University in 1980, a Master's in Physics at Cornell University in 1984, and her PhD in Physics from Cornell University in 1987.



In memorium. Arnold Orville Beckman (1900–2004).

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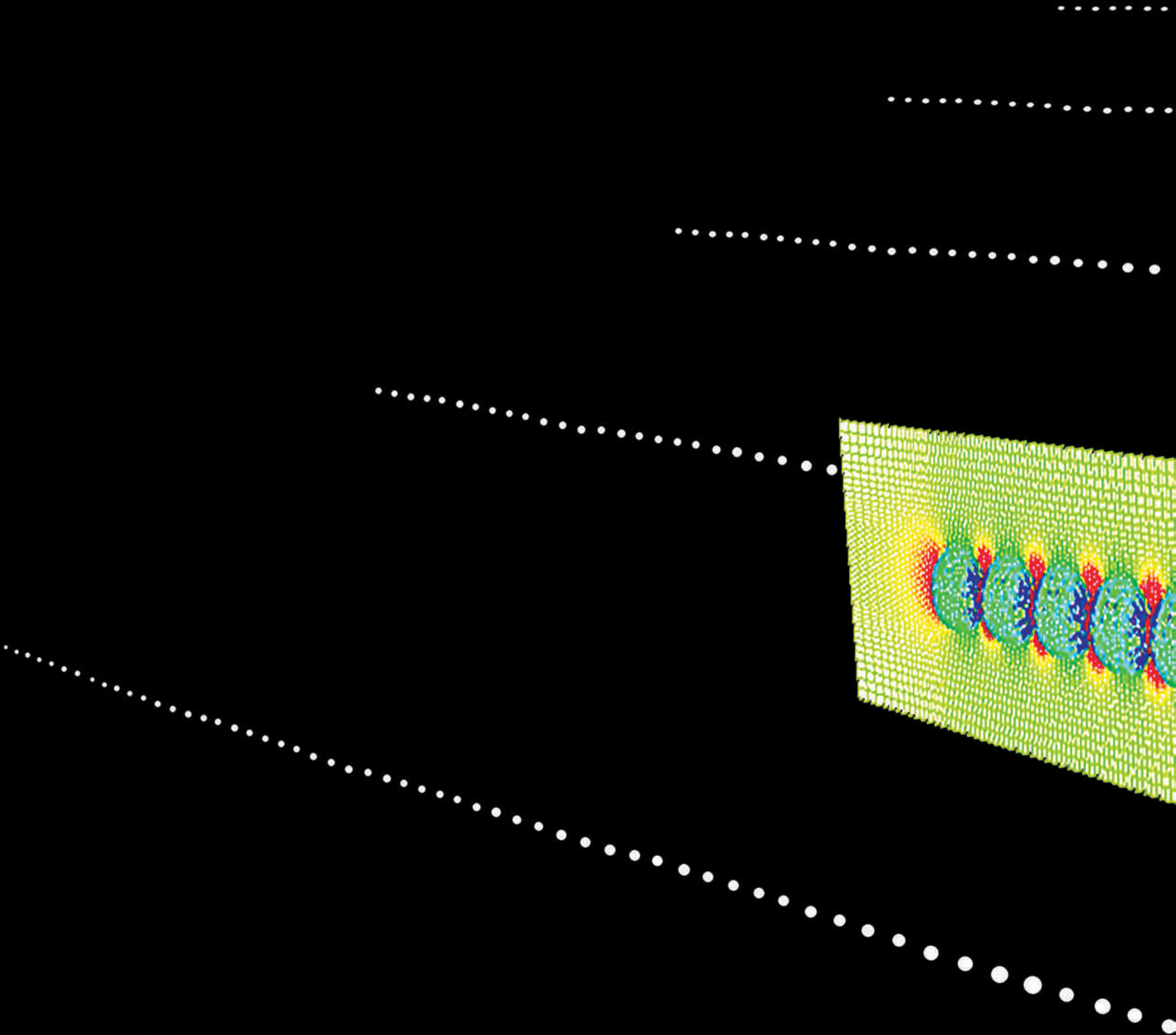

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