

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

of the California Institute of Technology





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 EAS visit <u>http://www.eas.caltech.edu</u>.

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COMMENTS?

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E N G e n i o u s A PUBLICATION FOR ALUMNI AND FRIENDS OF THE DIVISION OF ENGINEERING AND APPLIED SCIENCE



COVER IMAGE Full surface design of the 1 domain of Protein G. Although the protein design problem is *NP*-hard, an exact search algorithm identifies the unique global minimum energy conformation from among 10^{60} initial conformations in about 35 minutes running on 16 IBM SP3 processors. By comparison, an exhaustive search of these conformations would require 10^{30} times the age of the universe. (Current research results from Assistant Professor of Applied and Computational Mathematics <u>Niles A. Pierce</u> in collaboration with Associate Professor of Biology and Chemistry <u>Stephen L. Mayo</u>.)



Welcome to the *first* issue of ENGenious, our semi-annual publication for EAS alumni and friends.

I've had the privilege of serving as the Division Chair for Engineering and Applied Science since June 2000 and in that time I've developed a renewed appreciation of the unique nature of Caltech as a research and educational institution. Caltech is truly a national treasure and an incredibly exciting place to be a part of.

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The Division has a strong history of fundamental research advances and exceptional alumni that have given it a level of visibility and impact far out of proportion to its size. The environment for education and research at Caltech is extraordinary, and the traditions of multi-disciplinary, basic research—aimed at changing the world around us—remain alive and well. Coupled with the enormous economic and intellectual impact of technology, the coming years promise to be an exciting time for the Division.

In this issue of ENGenious we have assembled a variety of articles on current events and research activities, along with campus news and Progress Reports from faculty members. We'd like your input on the publication—let us know what you find exciting, what you would like us to cover more in depth, and what additional features you would like us to include in future issues.

I look forward to keeping in touch.

Sincerely,

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



Interconnect: A Fundamental Constraint André DeHon



ur ability to build machines that automatically process information is intimately tied to the properties of our physical world. Consequently, the fundamental properties and limits of our physical media will often define the nature of the design space in which we build computing devices. This shows up most clearly when we need to interconnect physically distinct computational building blocks.

Computing devices are made up of collections of elements (relays, vacuum tubes, transistors, gates, processors, and so on) which must be linked together if they are to cooperate in order to implement some larger computation or computational structure. The *interconnect* which links these elements has become one of the most important aspects of modern computing devices and has opened a rich engineering design space.

A modern example of a universal programmable computing device is the Field-Programmable Gate Array (FPGA). FPGAs are computing devices that use programmable interconnects to allow the end user to wire up a collection of programmable gates (single-output boolean functions of a few inputs, such as NAND, AND, or OR) in an almost arbitrary pattern. They provide a direct way to programmably implement a logical netlist of boolean gates. In this manner, they allow a user to implement almost any computational function just by programming the gates and interconnect.

In the design of Field-Programmable Gate Arrays and related spatial computing devices, *interconnect has always been the dominant component* consuming the greatest amounts of area, delay, and energy. With interconnection requirements scaling faster than linearly in device gate capacity and fundamental inter-

connection delays in VLSI scaling slower than gate speeds, *this problem is only exacerbated as we go forward*. Further, given the size of silicon systems we can build today—and considering the molecular and biological systems we may be able to build in the near future—all kinds of single-component architectures (e.g., multiprocessor, system-on-a-chip, VLIW, Vector, PIM) will be moving toward greater on-chip parallelism and hence greater use of on-chip, programmable interconnect.

The dominance of interconnect arises naturally from the interaction between the properties of our physical world and the structure of our computational tasks. The limits of two- or three-dimensional space for wiring and finite wire widths, combined with the logical communication structure between computing elements, dictates the distances between elements and the space required for interconnect. Since typical, logical communication structures have interconnection demands that are greater than two-dimensional VLSI substrates naturally support, interconnection requirements grow faster than logic and become the limiting resource dominating device size and speed. Designing efficient computing systems requires that we dually navigate the computational complexity landscape along with the landscape of our physical media to find the optimal balance between resources required to realize our computation.

A key goal of computer architecture is to identify and exploit structures which exist in typical computing problems to minimize the resources required to physically implement them. Many readers will be quite familiar with the way we use the temporal structure in memory references to reduce the cost and latency of physical memory systems using various levels and versions of caching. In a similar manner, as interconnect becomes the dominant consumer of area, delay, and energy in computing systems, we must understand and exploit the structure which exists in communications in order to reduce the size and latency of interconnect.

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Here, we show how area correlates with LUT (gate) utilization for a single design as we increase the interconnect richness (quantified here by the Rent parameter, p). Initially, as we increase richness the area decreases. However, after a point (p=0.7 shown here), increased interconnect richness leads to increased area. What is significant to note in this graph is that the point of minimum area does not correspond to the point at which we reach 100% gate utilization. Rather, we achieve minimum area when the gate utilization is only 85%. We actually get a smaller implementation by allowing ourselves to "waste" some gates in order to use the dominant resource (interconnect) more efficiently. In this case, the 100% gate utilization point requires twice the area of the depopulated, minimum area point.



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ur work has already demonstrated that one key implication of the dominance of interconnect is that, counter to popular intuition, we often want to design our programmable computing structure with a modest amount of interconnect and leave processing elements unused when the interconnection requirements of the task exceed that provided by the substrate. Quite simply, we realize that we have, at least, two distinct commodities that we must balance in our designs: interconnect and computing blocks. Since the balance of these resources is not the same from task to task, or even within a task, it is most efficient to design the substrate to optimize the dominant component, in this case interconnect, at the possible expense of wasting some of the non-dominant resources, in this case computing blocks. Note that this is counter to conventional approaches which seek to provide sufficient interconnection resources such that interconnection limitations can be ignored. The conventional approach is particularly troublesome since interconnect requirements can, potentially, grow as the square of the computing requirements in two-dimensional space. Almost all practical computers in use today rely on this conventional approach.

It is, consequently, imperative that we understand and exploit the structure inherent in our tasks and the structure of our physical media to make any substantial advances in this realm, using the minimum resources necessary for a given application. In this vein, we are working to understand fundamental requirements for both wiring and switching area in limited-dimensional space (e.g., two-dimensional VLSI), including latency–area trade-offs and capacity-routablity trade-offs. We are also working to understand how communication graph topology forces components to be far apart and hence increases communication latency. As we add metal layers to our VLSI processes, but force active components to remain on a single substrate plane, we need to understand how multiple metalization layers change our landscape and how to best exploit this structure.

We are further working to understand how our physical landscape changes as we move to molecularscale building blocks. It is already clear that molecular-scale devices may have a radically different computing-resource cost structure than conventional VLSI. We have seen switches which can be placed in the space of a wire crossing, whereas conventional VLSI switches require 50–100 times the area of a single wire crossing. Wire resistance may become virtually independent of wire length with ballistic electron transport in molecular wires. And, these structures may eventually allow us to build truly three-dimensional circuits with active elements not limited to a single, two-dimensional substrate plane. These differences may help us surpass some of the interconnection limitations in conventional devicesand they will certainly require new architectures to fully exploit the distinct computing-resource cost structure of these physical substrates.

The automated processing of information continues to radically transform the way we do science and engineering, and the way we live our lives. The limits

on our ability to pack computation into small space, with limited energy and maximal speed, sets a fundamental limit on how we can control the world, what level of control we have, and in fact what we can create. Hence, understanding the deep relation between physical computing media and computational tasks remains essential.



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ndré DeHon is Assistant Professor of Computer Science with expertise in physical implementation of computation, including physical substrates (VLSI, molecular, etc.), programmable media (FPGAs, processors), mapping (compilation, CAD), system abstractions

and dynamic management (run-time systems, operating systems, scheduling), and problem capture (programming languages).

Visit André DeHon's research page at

http://www.cs.caltech.edu/~andre

Fuel Cells: Powering Progress in the 21st Century Sossina Haile

uel cells are attractive alternatives to combustion engines for electrical-power generation because of their very high efficiencies and low pollution levels. Like a combustion engine, a fuel cell uses some sort of chemical fuel as its energy source, but like a battery, the chemical energy is directly converted to electrical energy, without a messy and inefficient combustion step. The components in a fuel cell that make this direct electrochemical conversion possible are an ion-conducting electrolyte, a cathode, and an anode, as shown schematically in Figure 1.

In the simplest example, a fuel such as hydrogen is brought into the anode compartment and oxygen is brought into the cathode compartment. There is an overall chemical driving force for the oxygen and the hydrogen to react to produce water. In the fuel cell, however, this simple chemical reaction is prevented by the electrolyte that separates the fuel (H_2) from the oxidant (O_2) . The electrolyte serves as a barrier to gas diffusion, but it will let ions, in this example $O^=$ (oxide ions), migrate across it. In order for the reaction between hydrogen and oxygen to occur, the oxygen atoms must somehow pick up electrons at the cathode and give off electrons at the anode. The reactions are then:

cathode: $\frac{1}{2}O_2 + 2e^- O^=$ anode: $H_2 + O^= H_2O + 2e^-$

overall: 1/2

$$1/2 O_2 + H_2 H_2 O_2$$

Now, in order for the "half-cell" reactions at the anode and cathode to be possible, there must be some external path by which electrons move, and it is precisely this electron motion that provides usable electricity from the fuel cell.







Several different types of fuel cells have been developed over the past few decades, and they are differentiated essentially by the type of electrolyte they employ (see Table 1), which in turn determines the temperature at which the fuel cell operates. For reasons of efficiency, higher temperature operation is preferred, but for portable power applications, lower temperature operation is preferred. High temperatures generally imply that reactions occur quickly and a broad range of hydrocarbon fuels can be directly utilized in the fuel cell, but start-up times can be very long, and there is a limited number of (usually expensive) materials available for fabricating the fuel cell. Thus, the challenge facing Solid Oxide Fuel Cells (SOFCs) is to lower the operating temperature to ~500°C, primarily for reasons of cost. Even lower temperatures are advantageous for applications in which the power demands are not continuous because start-up times are short, but under these conditions chemical reactions are slow and fuel choices are essentially limited to hydrogen and possibly methanol. If the hydrogen is obtained from a hydrocarbon fuel (this can be done by reacting methanol with water to yield hydrogen and carbon dioxide), there is inevitably some residual carbon monoxide in the hydrogen supply. Carbon monoxide, in turn, is extremely detrimental to the catalysts in the fuel-cell anode. It easily adheres to the surfaces of the catalyst particles and renders them inactive, particularly at low temperatures. Thus, there is a large incentive to raise the operating temperature of Proton Exchange Membrane (PEM) fuel cells to ~140°C, at which temperature the catalyst is tolerant to several 100 parts per million of CO.

While there are many technical hurdles still to overcome before fuel cells can become a widespread commercial reality, our work has focused on those obstacles which arise from the limitations of the electrolyte. In considering electrolytes for solid-oxide fuel cells, the high-temperature requirement arises because the oxide ion is big and bulky and requires significant thermal energy to be sufficiently mobile. What we have done is develop proton-conducting oxides as an alternative. About twenty years ago a group in Japan discovered that some metal oxide compounds (ceramics) can incorporate significant concentrations of mobile protons. We have used this idea to explore new compounds and have recently discovered materials with proton conductivities that are 100 times better (at about 400°C) than what was known just two years ago.

The mechanism of proton incorporation and transport in these oxides (most of which have the perovskite crystal structure) is as follows. The normal stoichiometry of the base perovskite is generically AMO₃, where A is a divalent

		Portable		Stationary	
Type 10	PEM 90-110	AFC 100-250	PAFC 150-220	MCFC 500-700	80FC 700-1000
Fuel	H ₂ +H ₂ O	Hg	Hg	HC+CO	HC+CO
Electrolyte ion	Nation HyO*1	KOH DH°T	HgPO4 H ⁺ J	Na2CO5 CO5 ²¹ 1	Y - 2/02 02/1
Oxidant	02	$O_2 \bullet H_2$	02	$O_2 + CO_2$	02

Table 1. Fuel-cell types differentiated by electrolyte temperature of operation.

PEM = Proton Exchange Membrane AFC = Alkali Fuel Cell PAFC = Phosphoric Acid Fuel Cell MCFC = Molten Carbonate Fuel Cell SOFC = Solid Oxide Fuel Cell HC = Hydrocarbon cation and M is a tetravalent cation. In order to generate vacancies on the oxygen sites, a portion of the M^{4+} is replaced with a trivalent cation. The material is then exposed to gaseous H_2O and the formerly vacant oxygen sites become filled with hydroxyl (OH) groups, while the second proton of the incorporated water molecule attaches to some other oxygen in the structure. As a consequence, two hydroxyl groups are created for each water molecule dissolved into the structure. The radius of an oxygen ion in a ceramic material is typically taken to be 1.4 Å. The bond distance between oxygen and a proton in a hydroxyl group is only ~1 Å. It is quite fascinating, then, to

recognize that the proton resides within the electron cloud of the oxygen ion. The protons attain their high mobility from the ease with which they jump from one oxygen ion to the next. Our work in discovering new proton-conducting oxides may make it possible to operate solid-oxide fuel cells



A prototype fuel cell from Haile's group, aka an Oreo cookie.

at temperatures of 400–600°C, a temperature range that retains the fuel flexibility of high-temperature operation but eliminates the material constraints of operation at 1,000°C.

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ur most exciting breakthrough has been in the area of alternative electrolytes for lower temperature operation. State-of-the-art

electrolytes for Proton Exchange Membrane fuel cells use a perfluorinated and sulfonated polymer. In order for the polymer to be conductive to protons, it must be fully hydrated. The electrolyte can almost be considered a composite of the polymer and water, Figure 2. These electrolytes offer the advantage of very high conductivity and are easier to use than corrosive liquid electrolytes such as phosphoric acid and aqueous potassium hydroxide, which, until recently, were the only known electrolytes for low-temperature operation. They also, however, possess several severe drawbacks. Because the ion transport relies on the presence of water, the material can not be utilized above about 90°C. Worse, the dehydration that occurs under accidental thermal excursions cannot be recovered. Another disadvantage is the very high permeability of the membrane to methanol. This permeability implies that if methanol is used as the fuel in a PEM fuel cell, a large portion of the fuel will diffuse across the membrane and react directly with the oxygen, without providing any electrical output. A third

> disadvantage arises from the fact that the mobile ions are not, in fact, protons, as the name implies, but rather hydronium ions, H_3O^+ , $H_5O_2^+$, etc. What this means is that protons essentially hitch a ride on diffusing water molecules to get across the membrane from the anode to the cathode. But as this happens, the membrane becomes

dehydrated at the anode and flooded at the cathode, and careful water management is required for stable fuel-cell operation. These difficulties—required lowtemperature operation, permeability to methanol, and water recirculation issues—are inherent to hydrated



Fig. 2. Polymeric electrolyte system.



Fig. 3. Extreme structural disorder in CsHSO₄.

polymer electrolytes. Accordingly, our approach has been to develop radically different proton conductors based on inorganic (non-polymeric) solids, specifically, solid acids.

Solid acids are compounds such as CsHSO₄ whose chemistry and properties are intermediate between those of a normal acid (e.g. H_2SO_4) and a normal salt (e.g. Cs₂SO₄). They typically consist of oxyanions, for example, SO₄ or SeO₄, that are linked together via O-H…O hydrogen bonds. Several are known to undergo a structural phase transition at slightly elevated temperatures (50-150°C), at which the proton conductivity jumps by several orders of magnitude. In the high-temperature disordered structure, Figure 3, the XO₄ anion groups undergo rapid reorientation, on a time scale of about 10-11 seconds. The proton typically remains attached to one of the oxygen atoms of the XO₄ group until every so often a neighboring XO₄ group is in the proper orientation for proton transfer to occur, Figure 4. A key feature of the proton transport process is that, unlike polymeric systems, the protons themselves are truly the mobile species, and all the difficulties associated with

the need to hydrate the electrolyte are eliminated. Like proton-conducting oxides, proton-conducting solid acids have been known for about 25 years, first reported independently by Russian and by Japanese groups. They had not been seriously considered for fuel cell (or really any other) application because they suffer from solubility in water. In addition to discovering several new high-conductivity solid acids, we have demonstrated that these materials can, in fact, be used in fuel cells by employing a very simple trick: operation at above 100°C. At these temperatures, any H₂O in the fuel cell is present in the form of harmless steam and does not damage the electrolyte. The challenge then becomes design of a fuel-cell system that ensures that liquid water does not contact the electrolyte during shut-down. Given the myriad advantages offered by anhydrous proton transport, this challenge is one that will surely be addressed. In the meantime, our exploratory synthesis effort continues, and water insoluble analogs are on the horizon.



ossina Haile is Assistant Professor of Materials Science, with expertise in solid electrolytes, fuel cells, inorganic crystal chemistry, and crystallography.



Fig. 4. Proton transport mechanism.

Visit Sossina Haile's research group page at http://addis.caltech.edu/Haile/research.htm

NEW FACULTY

The Division welcomed **three** new faculty members to Caltech over the past few months, strengthening the Division's presence in electrical engineering, applied physics, and mechanical engineering generally, and in areas including wireless communications, optics, biomechanics, and nanofabrication more specifically.

Babak Hassibi Assistant Professor of Electrical Engineering

PROFESSOR HASSIBI'S RESEARCH is in communications, signal processing, and control. He is currently most interested in wireless communications, especially in the use of multipleantenna systems, where he has studied both the informationtheoretic and coding-theoretic aspects of such systems, as well as devised practical high-rate space-time transmission schemes. Other research interests include adaptive signal processing and neural networks; blind channel equalization; statistical signal processing; robust estimation and control, especially connections between robustness and adaptation; and linear algebra, with emphasis on fast algorithms, random matrices, and group representation theory.

Professor Hassibi received a BS from the University of Tehran in 1989, an MS from Stanford University in 1993, and a PhD, also from Stanford University, in 1996. Just prior to joining Caltech, he was a member of the Technical Staff at Bell Laboratories.





Oskar Painter (MS '95, PhD '01) Assistant Professor of Applied Physics

PROFESSOR PAINTER'S RESEARCH interests are in nanofabrication, optoelectronics, quantum electronics, and optics. His current research investigates the new and interesting ways in which light can be guided and trapped by the strong electromagnetic dispersion present in high-contrast periodic materials (photonic crystals). Optical devices formed in such materials are being studied for a variety of applications ranging from next-generation planar lightwave circuits to cavity QED studies of coherent electron-photon processes.

Professor Painter received his Bachelor of Applied Science degree in Electrical Engineering in 1994 from the University of British Columbia, his MS degree from Caltech in 1995, and his PhD in Electrical Engineering from Caltech in 2001. Most recently he helped found and has been working with cQuint Communications, a start-up company focused on bringing a new fiber-optic packaging technology to the telecommunications industry.

<u>Rob Phillips</u> Professor of Mechanical Engineering and Applied Physics



PROFESSOR PHILLIPS'S RESEARCH centers on the development of methods for treating multiple spatial scales simultaneously with special emphasis on linking atomistic and continuum methods. During recent years he has applied such methods to defects in solids culminating in the recent publication of *Crystals, Defects and Microstructures* (Cambridge University Press, 2001). More recently, he has been engaged in bringing similar methods to bear on problems of biological interest with special reference to the emerging field of single-molecule biomechanics. He is delighted to be at Caltech where the type of interdisciplinary research he especially favors spreads across the various divisions.

Professor Phillips received his BA in Physics from the University of Minnesota in 1986, and both his MS in Physics (1986) and PhD in Physics (1989) from Washington University. Prior to joining Caltech, he was on the faculty at Brown University, and recently completed a sabbatical at L'Institut National Polytechnique de Grenoble.

NEW CENTERS

Invention and Outreach:

The Center for the Science and Engineering of Materials

THE CENTER FOR THE SCIENCE AND ENGINEERING OF MATERIALS

(CSEM), under the direction of Professor of Chemical Engineering Julia Kornfield (BS '83, MS '84), celebrated its first anniversary this past September. Established with a \$9.6 million multi-year grant from the National Science Foundation, the Center addresses both research and educational aspects of polymeric, structural, photonic, and ferroelectric materials that will be necessary to solve critical societal needs of the twenty-first century. The Center pioneers a number of exotic and futuristic materials and applications such as liquid metals, responsive gels, and tiny medical sensors.

The Center draws its researchers principally from EAS—but also from the Division of Chemistry and Chemical Engineering. The four major research thrusts are in the areas of biological synthesis and assembly of macromolecular materials; bulk metallic glasses and composites; mesophotonic materials; and ferroelectric thin films. "I have really enjoyed catalyzing connections," notes Professor Kornfield. "It has been wonderful to watch relationships develop between scientists that had little interaction before the Center existed. It's impossible to predict now how these connections will develop, but they will almost certainly lead to unique and unanticipated collaborations as the Center moves forward."

The biosynthesis initiative is led by David Tirrell, McCollum-Corcoran Professor and Professor of Chemistry and Chemical Engineering, and Chair of the Division of Chemistry and Chemical Engineering. Research efforts include the use of artificial proteins to make polymers with exquisite control of properties, and responsive polymers and gels for biomedical and industrial applications, including materials for entrapment of cells in tissue engineering or biosensors.

The team investigating glassy metallic alloys is led by Bill Johnson (PhD '75), the Ruben F. and Donna Mettler Professor of Engineering and Applied Science. This group pursues basic science and new engineering strategies that will lead to custom-designed materials with desirable characteristics such as ultrahigh strength, exceptional elasticity, and ease of fabrication into complex parts.

The effort toward mesophotonics is led by Harry Atwater, Professor of Applied Physics and Materials Science. Mesophotonic devices are optical components and devices sized at or below the wavelength of light. Future applications include engineered optical probes for biology and medicine, and photonic devices that could replace certain electrical devices in telecommunications and computing. Everybody knows that it is impossible to propagate light through structures smaller than the wavelength of light... but CSEM researchers have belied this conventional wisdom, showing propagation of light along waveguides whose lateral dimensions are a few nanometers (a few percent of the wavelength of light). The key is to exploit the tendency for electromagnetic excitations to "hop" between electric dipoles, such as fluorescent dye molecules or metal nanoparticles.

Researchers in the mesophotonics group, led by Professor of Applied Physics Harry Atwater, have demonstrated propagation of light through two types of subwavelength-scale waveguides. The first is a DNA-based waveguide in which a fluorescence excitation hops from an optical donor molecule bound to one end of the DNA backbone to an acceptor molecule at the other end through dye mole-



CSEM Director, Julia Kornfield, and a student at the March outreach program for high-school minority youth. More than 100 students attended.

cules tethered at intervals in between. These fluorescence-resonant-energy-transfer waveguides have so far demonstrated that light can take several hops between molecules bound to DNA, and this

"movement" can be extended to many hops along a longer waveguide.

The second nanoscale waveguide structure is called a "plasmon wire," which is a chain of metal nanoparticles along which light 10 - 50nm

hops from one particle to another. Light can even propagate around sharp corners and through nanoscale networks—all of which are impossible in conventional optical waveguides. So much for conventional optical wisdom!



Valerie Villareal is studying the stability of hydrogels (aggregated fluoroalkyl-ended polyethyleneglycol) for applications in capillary electrophoresis. She and her mentors (Professor Julie Kornfield at Catlech and Professor Frank Gomez at CSULA) are hoping to show that drugs (or other components) can be immobilized in the hydrogel and that the hydrogel can also serve as a sieving matrix. Rob Lammertink (a Catlech postdoc, pictured at left) is also working on this project. Kaushik Bhattacharya, Professor of Applied Mechanics and Mechanical Engineering, is leading research to create microactuators based on high-strain ferroelectrics. The team's integrated simulation and experimental approach promises to reveal the microscopic basis of large strain behavior in this class of materials.

Along with the flurry of research activities that the Center enhances, major outreach efforts have been made to bring under-represented minorities to campus for special seminars, tours, and learning activities. The CSEM Undergraduate Research Fellowship Program hosted seven students from California State University, Los Angeles (CSULA) during the past year. These students, working with faculty mentors from both CSULA and Caltech, have been pursuing research in various laboratories.

In March, CSEM hosted a two-day outreach program for highschool minority youth. More than 100 high-school students from science and technology programs throughout the Los Angeles area had a stimulating first-hand exposure to cutting-edge work in materials science, technology, and mathematics. Particularly exciting was a presentation created by CSEM scientist Mario Blanco and Native American artist Rosemarie McKeon exploring the connections between science and Native American life. Blanco and McKeon connected scientific concepts and diagrams to art and cultural concepts, interpreting from multiple perspectives how one might understand the molecular representation of the structure of matter. "The creation of the Center really jump-started campus-wide discussion about outreach efforts that take advantage of Caltech's special strengths and the demographics of the Southern California region," observes Kornfield. "It has allowed this NSF MRSEC [Materials Research Science and Engineering Center] to be part of something bigger. As the Center was growing up, there were numerous outreach efforts on campus that did not connect. The Center was created at a time when the situation was ripe for coordination of more ambitious outreach efforts, which has enabled us to substantially expand upon the programs we had proposed. For example, we had proposed an annual workshop for a dozen high-school students and it grew into a program for a hundred with help and support from other organizations at Caltech."

For more information on CSEM activities, visit their website at http://www.csem.caltech.edu

Caltech Establishes IQI: Institute for Quantum Information by John Preskill

The Divisions of Physics, Mathematics, and Astronomy (PMA) and Engineering and Applied Science have jointly established the Institute for Quantum Information (IQI), supported by a five-year grant from the National Science Foundation. The goal of the IQI is to advance the foundations of quantum information science (QIS), an emerging field that draws on physics, mathematics, computer science, and engineering. Broadly speaking, QIS addresses how the principles of quantum physics can be harnessed to improve the acquisition, transmission, and processing of information.

QIS derives much of its intellectual vitality from three central ideas, all of relatively recent vintage. The first important idea is quantum computation. We have learned that a computer that operates on quantum states instead of classical bits can perform tasks that are beyond the capability of

Aside from its technological implications, QIS is an intellectually stimulating basic research field. Fundamental questions such as *What is the computational power of Nature?*, *Can measurement be reversed?*, and *How much information can we learn?* drive the field and inspire new research directions.

any conceivable classical computer. For example, finding the 200-digit prime factors of a 400-digit composite number would take billions of years on today's supercomputers. But for a quantum computer it would be an easy problem, not much harder than multiplying two numbers together to find their product. The boundary between "hard" and "easy"—between problems that someday will be solved and problems that never can be solved—is essentially different in a quantum world than in a classical world.

The second important idea is quantum cryptography. You can communicate privately with another party over the Internet, but the security of that communication is founded on assumptions about the computational resources that are available to a potential adversary. In contrast, if you were able to communicate by transmitting quantum states (like photon wave packets traveling in an optical fiber) instead of classical bits, you could achieve a higher level of privacy founded on fundamental laws of physics. Quantum "As with any revolutionary scientific insight, the long-term implications [of QIS] cannot be clearly anticipated, but we are confident that they will be profound. We also expect that the emergence of QIS will have an extensive eventual impact on how science is taught at the college and secondary level, and will bring a deeper understanding of quantum physics to a broad segment of the lay public."

—John Preskill, Professor of Theoretical Physics cryptography is based on the principle that it is impossible to collect information about the state of a quantum system without disturbing the state in a detectable way.

The third important idea is quantum error correction, which has greatly boosted our confidence that large-scale quantum computers really can be built and operated someday. The power of a quantum computer derives from its ability to process coherent quantum states, but such states are very easily damaged by uncontrolled interactions with the environment—a process called decoherence. Thus, quantum computers are much more susceptible to error than conventional digital computers. But we have learned that quantum states can be cleverly encoded so that the debilitating effects of decoherence, if not too severe, can be resisted. In principle then, even very intricate quantum systems can be stabilized and accurately controlled.

The scientific mission of the IQI is to elaborate and develop these ideas, and to otherwise illuminate the essential differences between quantum information and classical information. We aim to better understand the capabilities of quantum computers and to bridge the vast gap between the theory and practice of quantum information processing by conceiving new approaches to the physical manipulation of coherent quantum states.

A variety of Caltech groups in both the EAS and PMA Divisions have been engaged in QIS research for several years. The IQI consolidates, expands, and enhances these activities by providing a focal point for QIS research on the Caltech campus. Faculty, research staff, and students from both Divisions interact, promoting the communication and collaboration across disciplinary boundaries that will be essential to the further development of the field.

Central to the IQI's scientific program is a vigorous visitor's program that brings the world leaders of the QIS research community to Caltech for both



Graduate students (left to right) Andrew Landahl, Jim Harrington, and Charlene Ahn discussing the finer points of qubits.

long-term and short-term visits. Almost 40 visitors from the international research community have spent anywhere from several days to several months in residence at IQI since its inception. The IQI also supports post-doctoral scholars drawn from backgrounds spanning the disciplines relating to QIS. The visitors and postdocs affiliated with the IQI occupy space in the Steele and Jorgensen laboratories.

EAS faculty connected with the IQI include John Doyle, Professor of Electrical Engineering; Michelle Effros, Associate Professor of Electrical Engineering; Axel Scherer, Neches Professor of Electrical Engineering, Applied Physics, and Physics; Leonard Schulman, Associate Professor of Computer Science. PMA faculty include Jeff Kimble, Valentine Professor and Professor of Physics; Hideo Mabuchi (PhD '98), Associate Professor of Physics; John Preskill, Professor of Theoretical Physics; Michael Roukes, Professor of Physics; and Kip Thorne (BS '62), Feynman Professor of Theoretical Physics.

In the 21st century, information technology will play an increasingly important role in our daily lives. We also anticipate that thinking about how information can be encoded and processed will facilitate progress in basic science. Though quantum theory is now over 100 years old, we are just beginning to learn some of the profound ways in which quantum information differs from classical information. The IQI aims to lead the quest for a deeper understanding of the role of information in fundamental physics.

More about IQI activities can be found at http://www.iqi.caltech.edu

S N A P S H O T S

'Round About the Institute

The Red Door



What would you call a melange of cool jazz, delicious morsels, a bit of wine, and 200 professors, staffers, their spouses, and other assorted EAS compatriots? Nothing other than the Second Annual EAS Fall Gathering. As it did last year, Dabney Gardens provided an elegant retreat for the EAS campus community to schmooze and chat, get to know new colleagues, catch up with others from across campus, and simply enjoy a delicate fall afternoon.

Fall Gathering





The Red Door Cafe is the unofficial center of campus. Housed in the Winnett Student Center, it is that local magical place which dispenses liquids and solids, and where, within a few minutes of sipping or munching, everything just seems clearer. The crossroads, if you will, of from here to there.

This intellectual gathering place—a Caltech center *not* funded by the NSF—witnesses more consequential informal and freewheeling conversations between groups of faculty and students than any other on campus, and it has really great chocolate muffins.

Undergraduates are Publishing



Front left to right: Jennifer Li, Marta Kaltreider, Paul Choi, Michael Russo. Middle left to right: Philip Wong, Steve Paik, Jonathan Dama. Back left to right: Robb Rutledge, Lakshminarayan "Ram" Srinivasan, Suhas Nayak. Not pictured: Michelle Giron, Dylan Simon, Robert Christy, Neda Afsarmanesh, Lusine Danakian, Jonathan Foster, Benjamin Lee.

The Caltech Undergraduate Research Journal (CURJ) premiered last April. The shaker and mover behind the project, Editor-in-Chief Lakshminarayan "Ram" Srinivasan, pulled together a team of students from Caltech and Art Center College of Design that produced a publication stunning in both content and design. While the first issue (distributed free) was a complete "sell-out," their website reproduces every issue in both html and pdf formats. Take a look for articles on "Computer Gesture Recognition," "The Aging Enigma," "Evolving Enzymes Faster"—and more—from the first issue.

CURJ will be published twice per year, distributed to campuses across the country, and encourages submissions from undergraduates at all educational institutions. The next issue is slated for Spring 2002.

Visit the CURJ website at http://www.curj.caltech.edu





Keep up to date with the construction at http://pr.caltech.edu/events/broad_site/

Coming Soon

The Broad Center for the Biological Sciences is

named for Caltech Trustee Eli Broad and his wife, Edythe, in recognition of their contributions to Caltech's Biological Science Initiative. The building is designed by architect James Freed, a senior partner in the firm of Pei Cobb Freed & Partners, who also designed the acclaimed U.S. Holocaust Memorial Museum in Washington, D.C. Scheduled to open for research occupancy in June, 2002 (shown here in September, 2001), the Broad Center will house three major new research facilities: a magnetic resonance imaging center, a biomolecular structures laboratory, and a genetic resources laboratory.

Can We Build a Better Voting System?

THE VOTING TECHNOLOGY PROJECT (VTP), a

joint endeavor between Caltech and MIT, was established in December 2000 to prevent a recurrence of the problems that threatened the 2000 U.S. presidential election. While legal battles were still being fought in Florida, Caltech President David Baltimore and MIT President Charles Vest stepped forward to mobilize a team of computer scientists (including Professor Shuki Bruck of Electrical Engineering and Computation and Neural Systems), human factors engineers, mechanical engineers (including Professor Erik Antonsson of Mechanical Engineering), and social scientists (including Professors R. Michael Alvarez and Thomas Palfrey of Humanities and Social Sciences) to respond to the need for strong academic guidance in this intersection of technology with democracy.

After an initial six months of intensive work, the VTP recently issued its first report on the current state of the reliability and uniformity of U.S. voting systems, made concrete proposals to improve the election process before the next national election, and offered guidance in setting the direction of future technological innovation. This report concluded that between 4 and 6 million votes were "lost" in the 2000 election. This staggering find was widely reported by the media. The seriousness of the situation was underlined by Baltimore and Vest in their preface to the report:

"In the last election, Americans learned that at the heart of their democratic process, their 'can-do' spirit has 'make-do' technology as its central element. For many years, we have 'made do' with this deeply flawed system, but we now know how poorly these systems function. Until every effort has been made to ensure that each vote will be counted, we will have legitimate concerns about embarking on another presidential election."

The technological heart of the report describes a new framework by which to design voting systems. This framework is called AMVA—A Modular Voting Architecture—and separates the process of (1) recording a voter's choices on a physical recording device (playfully called a FROG) and (2) casting the vote using the FROG as input. The separation of these two processes is crucial, and is seen as the key to reduce, even eliminate, a number of problems that plague current technology. These problems include security threats posed by complex electronic voting machines, the decline in openness and public control, the need for improved ballot designs, the need for more voter feedback so voters can catch errors, and obstacles to creating independent audit trails, especially on electronic machinery. The actual design and structure of the FROG-which is more than a ballot-may be different from say, state to state, but each FROG would capture information on the voter's choices, the precinct voted in, the official who signs in the voter, and the form of the ballot. It is deposited and becomes part of the audit trail when a voter casts his/her vote. "Building the dream voting machine is not what we were after," explains Shuki Bruck, Gordon and Betty Moore Professor of Computation and Neural Systems and Electrical Engineering, "instead, we focused on redesigning the voting process to facilitate innovation and competition in the creation of high-quality solutions that will help in making every vote count."

Erik Antonsson, Professor of Mechanical Engineering, observes however, that "Contrary to intuition, the patchwork of voting systems in use throughout the country has eliminated systematic fraud, and this should serve as a caution to developers of new systems to maintain this robustness."

"The atrocities of September 11 reinforce the need for a voting system that the electorate trusts, and underscores the importance of the work of this project." —<u>Professor Erik Antonsson</u>





"On a personal level, the Voting Technology Project was a unique opportunity to understand and contribute to an important multidisciplinary project that combines social, political, technological, and business issues." —<u>Professor Shuki Bruck</u>

Visit the VTP website <u>http://www.vote.caltech.edu</u> to learn more about this work or download the complete July, 2001 report.

EFP

Entrepreneurial Fellowship Program: The Art and Science of Business



W

hat if you were a graduating senior, just about to earn your master's or PhD, or were a postdoc here at Caltech and had a great idea for a business? Or, what if you were

one of the above and simply wanted to learn more about the world of business and entrepreneurship? Now switch gears and imagine you were a student at Art Center College of Design, had an idea for a business that required technical expertise, or wanted to learn about the financing, marketing, and management of a successful start-up company. An exciting opportunity debuted this year—the Caltech and Art Center Entrepreneurial Fellowship Program (EFP). With funding from the National Science Foundation's new "Partnerships for Innovation" program and from the private sector, the EFP uniquely brings together CVs, VCs, and portfolios—in short, people who solve problems from different viewpoints—in an intense nine-month educational environment.

The program is led by Caltech's Ken Pickar, J. Stanley Johnson Visiting Professor of Mechanical Engineering, and Art Center's Michael Dobry, Director of the Office of Design Transfer, with Richard Murray (Chair, Division of Engineering and Applied Science) as Principal Investigator, and John Ledyard (Chair, Division of the Humanities and Social Sciences), as co- P.I. The EFP grew out of the needs of students who wanted to make the transition from the academic environment to the world of business. The program addresses the growing demand for Caltech and Art Center people with fluency in the languages of science, engineering, and design who want to learn the language and practice of business, particularly of high-tech business—and to do so without an MBA or repeating the failures of so many underdeveloped start-up companies.

Over the course of the non-degree granting program, the Fellowship recipients (Fellows) are exposed to a rich experiment in education. They refine the design and technology behind their proposed products and services, and perfect their business plans. The Fellows also study traditional business skills, develop their presentation and communication skills, and network with entrepreneurs, venture capitalists, and corporate leaders. The curriculum emphasizes real-world research and experience, evaluated, for instance, by a series of *charettes* (a French term often used in architectural design, denoting concentrated, rigorous short-term projects, administered on the fly, with the express purpose of strengthening decisionmaking skills, developing leadership thinking, and encouraging effective teamwork).

The curriculum stresses a learning process that is itself entrepreneurial in nature, with methods drawn and blended from traditional MBA curricula, corporate training programs, and non-traditional business disciplines. Many of the methods and much of the content of instruction reflect the realities of a business start-up atmosphere, emphasizing the cultivation of strategic business thinking and risk taking. As prelude to the program's selection process, applicants form interdisciplinary teams of two or three people. Each team creates a business plan for a proposed start-up company that commercializes technologies that the applicants developed or have been exposed to during their studies. Teams are judged on the merits of the business model, use of innovative technology, and the candidates' qualities of enthusiasm, passion, and commitment. Each Fellow receives a stipend and benefits for the length of the program. Caltech's course, Entrepreneurial Development (E 102), open to Art Center students, provides an excellent precursor to the application process.

Of the 75 applicants from Caltech and Art Center, nine Fellows were selected, in four project teams, and they officially began work on July 9, 2001. Their innovations range from a fluids-based means of information display to enhanced synthesis of computer animation. The teams and their projects for the first year are:

- Frederick Romberg (MS '00) (Caltech) and Daniel
 Schenck (Art Center). Bubble Imaging Technologies: developing three-dimensional liquid-motion technology for dynamic displays.
- ► Boris Axelrod, (BS '01) Yasufumi Shiraishi (BS '01), and Serge Sverdlov (BS '01) (Caltech). *Centoid:* development of economic algorithms that will make the collection of small sums of money over the Internet extremely efficient.

Photo, left to right standing: Yasufumi Shiraishi, Serge Sverdlov, Joey Jones, Boris Axelrod, Eagle Jones, Daniel Schenck, Frederick Romberg; seated: Matthew Carroll and Robert Sneddon.

- ► Matthew Carroll (Art Center) and Robert Sneddon (Caltech). *KnowNet:* an Internet communication system for forming "trust networks" for the rapidly growing knowledge management industry.
- ► Eagle Jones (BS '01) (Caltech) and Joey Jones (Art Center). *Synthesized Animation:* development of realtime motion synthesis software to enable easier and faster creation of computer animation and games for the entertainment and Internet industries.

The success of all entrepreneurial endeavors depends on teamwork. The EFP is no exception, and great efforts have gone into bringing on partners as advisors, mentors, and sponsors. These partners have been enlisted as Berlitz instructors, so to speak, to help translate the many dialects of business language; the partners also provide the Fellows with personal and intellectual relationships in the financial, marketing, and legal communities-relationships critical to entrepreneurial success. In addition to their advising and mentoring roles, many partners have brought their companies into the program; Intel, ITU Ventures, National Collegiate Investors and Innovators Alliance, Mohr Davidow, Motorola Ventures, and O'Melveny Consulting are all providing invaluable financial support to the EFP.

The physical and metaphorical point of convergence for the Fellows is the space they share in Moore Laboratory. The participants from Caltech refer to the room as a lab. Art Center folks call it a studio. EFP administrators understand it as an office. The space is, in truth, all the above and more. It's a place where the associated activities of labs, studios, and offices come together in the service of dynamic education.

To learn more about the program as a Fellow or partner, please e-mail Dr. Ken Pickar at pickar@caltech.edu or visit http://www.efp.caltech.edu

CNSE / LEE CENTER

7th Annual Industry Day: Show and Tell

CALTECH'S CENTER FOR NEUROMORPHIC SYSTEMS ENGINEERING

(CNSE), a National Science Foundation Engineering Research Center, directed by Professor Pietro Perona, held its 7th Annual Industry Day May 16–17, 2001 in Beckman Institute Auditorium. For the first time, the conference was held in conjunction with the LEE CENTER FOR ADVANCED NETWORKING, directed by David Rutledge, the Kiyo and Eiko Tomiyasu Professor of Electrical Engineering. The theme of the conference was "Sensor Networks" with faculty from the two centers presenting their research on smart sensors, wireless networks, optical components, communications, collective robotics, and learning in networks, among other topics.

On each day, a panel of representatives from industry—composed mainly CEOs and Chief Technologists—focused on how sensor networks operate in various industries, such as the automotive, defense, aerospace, infrastructure, and medical-care sectors. Invited presenters and the two keynote speakers, Dr. Charles Elachi, the Director of the Jet Propulsion Laboratory, and Dr. Paul Jacobs, Executive Vice President of Qualcomm, explored the opportunities that can be achieved by having a multitude of sensors networked together as well as the challenges of making sense of the data these networks produce.

The audience of over 250 people, representing more than 60 companies as well as Caltech faculty and students, heard the reflections of executives from such companies as Air Fiber, Graviton Systems, IBM, idealab!, Invensys Controls, Qualcomm, Sensoria, TRW Space and Electronics, VivoMetrics, and Wingcast. Speakers from DARPA and the NSF indicated that various government programs are also geared toward tying together various sensors creating what will eventually



Beckman Institute Auditorium audience



Pietro Perona, Professor of Electrical Engineering, and Director of the Center for Neuromorphic Systems Engineering with Yaser S. Abu-Mostafa, Professor of Electrical Engineering and Computer Science.



David Lee (PhD '74), Caltech Trustee and Honorary Chair of the David and Ellen Lee Foundation.

become a sensor web analogous to the computer networks that form the Internet.

In response to this description of the future, a constant refrain from the audience questioned how such a sensor web will deal with problems of privacy and security. Although the panelists did not have specific answers, it was evident that industry and government are aware of the issue and that a mixture of technical and legislative means will be needed to address them. Another challenge that surfaced was how to prevent total, catastrophic failure when sensors are networked and tie everything together from home appliances to telephones, computers, and traffic signals. The danger of a software glitch bringing life back to a "stone age" was mentioned and the answer seems to be a mixture of redundant sensors, developing logical programming environments, and new mathematical tools for assessing complex networks.

Industry members in the audience were also interested in how to make better use of the sensor networks that exist today. In the presence of large streams of data, the question is how to extract the maximum information from this data with potential applications that range from condition-based maintenance to attention-based diagnostics. The audience also benefited from discussions with students from both Centers, as approximately 40 students presented posters.



Caltech President David Baltimore providing opening remarks for the conference.

Visit the CNSE and Lee Center websites for more detail, including downloadable forms of various presentations: <u>http://www.cnse.caltech.edu</u> or <u>http://www.its.caltech.edu/~leectr/</u> (and click through).

A N N I V E R S A R I E S

Computer Science Turns 25: A Child Prodigy is Growing Up

For three intense yet sparkling days last April, the Computer Science Option celebrated its 25th anniversary. The early innovators, including option co-founders Carver Mead (BS '56, MS '57, PhD '60, Moore Professor of Engineering and Applied Science, Emeritus) and Ivan Sutherland (MS '60, formerly Jones Professor of Computer Science, now Vice President of Sun Microsystems), were joined by alumni from three decades, former and current faculty, staff, and administration, friends and spouses and children

for a variety of events. A jampacked alumni gathering on Sunday evening at the Caltech Alumni House—at times rollicking, at times poignant—preceded the more formal events on Monday and Tuesday, April 9 and 10.

Presentations by Caltech alumni, former and current faculty, and distinguished colleagues were offered over a span of two days, and were quite diverse—an historical self-portrait of the option was created by some; we also saw the latest short film from Pixar; heard about the state-of-the-art from



Lunch in the Beckman Institute Courtyard.



Graduate student Min Chen at a poster session.



From left to right: Ben Rosen (BS '54), Phil Neches (BS '73, MS '77, PhD '83), Carver Mead (BS '56, MS '57, PhD '60), Bill Gross (BS '80), Lounette Dyer (MS '87, PhD '91), and Bill Davidow. Other than Mead, all the panelists are Caltech Trustees.

Caltech ex-pats at Hewlett-Packard, Microsoft, Myricom, and Sun Microsystems; and learned of possible futures from the newest Caltech faculty. Presentations brilliantly encapsulated the field from vacuum tubes to VLSI to computer graphics, to massively parallel computing and networks, all the way to DNA, quantum computing and substrates beyond silicon. (A full description of the talks is available in a recent of *Engineering & Science*, Volume LXIV, Number 1, 2001.)

Interwoven among the technical talks were social gettogethers, poster sessions, and lab tours, a panel discussion on "Entrepreneurship and Computer Science," moderated by Caltech Trustee and Board Chairman Ben Rosen (BS '54), as well as a banquet, with the inimitable Carver Mead providing the keynote address.



Jean Chandy, Carver Mead, Barbara Smith, and Alain Martin with Martin Rem.

We hope you were there; if not, check out the website for more details and a photo gallery of highlights at http://www.eas.caltech.edu/cs25/



From left to right: Option co-rounder Ivan Sumeriana (MS '60), former Chair of Engineering and Applied Science Bob Cannon, President of Pixar Animation Studios Ed Catmull, and former faculty member, now Assistant Director of Research at Microsoft, Jim Kajiya.



From left to right: Two generations of CNS visionaries—David Van Essen, Christopher Koch, John Hopfield, and Carver Mead.

Computation and Neural Systems: A Birthday Bash to Celebrate the First 15 Years

In 1986, a unique confluence of ideas, people, and recent scientific and technological developments came together at Caltech, giving rise to a new interdisciplinary graduate program: Computation and Neural Systems (CNS). The CNS program concentrates on the fascinating problems at the interface between cellular biology, neurobiology, electrical engineering, computer science, and physics. Its unifying theme is the relationship between the physical structure of a computational system (physical or biological hardware), the dynamics of its operation, and the problems that it can solve. CNS students and faculty have carried out groundbreaking work in a range of fields, including computer science, electrical and neuromorphic engineering, neural networks, robotics, biophysics, neurophysiology, and artificial life.

Over the weekend of September 30th, Carver Mead (BS '56, MS '57, PhD '60, Moore Professor of Engineering and Applied Science, Emeritus), John Hopfield (Dickinson Professor of Chemistry and Biology, Emeritus), and David Van Essen (BS '67, Edison Professor of Neurobiology at Washington University in St. Louis)—the visionaries who created and shaped CNS into what would become the first program of its kind, spawning intellectual tentacles that now reach worldwide—brought their unique world views back to campus, re-inspiring two generations of students and colleagues to continue with the revolutionary work incubated at Caltech just 15 years ago. Along with dozens of alumni who were in town for the two-day birthday bash, current students, faculty, and friends (over 130 in all) shared meals, shared stories, and "talked shop."

"This turned out to be a wonderful opportunity to bring everybody back to campus and to hear about achievements over the past 15 years," observed Christof Koch, Troendle Professor of Cognitive and Behavioral Biology and Professor of Computation and Neural Systems. Professor Koch was responsible for organizing the event and noted that he was pleased so many people made the trek back to campus to meet with old friends and share ideas.

Many alumni gave talks on topics ranging from the very technical—"Neuromimetic Vision Algorithms"—to the very topical—"Five Jobs in Five Years: A View from the Trenches in Silicon Valley."













Among those giving presentations were Alex Backer (MS '98, currently working on his PhD); Vance Bjorn (MS '95, now with Digital Persona, a company which he co-founded); Tobi Delbruck (PhD '93, currently at the Institute of Neuroinformatics in Zurich); Dawei Dong (PhD '91, currently teaching and doing research at the Center for Complex Systems and Brain Sciences in Boca Raton, Florida); Laurent Itti (PhD '00, now assistant professor of Computer Science at the University of Southern California); Sanjoy Mahajan (PhD '98, currently doing post-doctoral work in physics at the University of Cambridge); David McKay (PhD '92, currently a Reader in the Department of Physics at Cambridge University); Bill Softky (PhD '93, emeritus of five Silicon Valley companies in five years); and Jiajun Dale Wen (PhD '00, currently with Oracle Corporation).

Erik Winfree (PhD '98), Assistant Professor of Computer Science at Caltech, gave a talk entitled "From Neurons to Molecules: Computing the Natural Way." Also speaking were visiting professor Heinz Schuster (Chair for Theoretical Physics at the University of Kiel and regular visiting faculty member at Caltech every second year) and Dr. Chris Adami (Faculty Associate in Computation and Neural Systems at Caltech and Research Scientist at JPL).

On hand as well was Professor Thanos Siapas, who will shortly be moving from MIT to Caltech to take an assistant professorship. He will be a member of both the Division of Engineering and Applied Science and the Division of Biology. His presentation was titled "The Organization of Network Interactions Across Cortico-Hippocampal Circuits and Their Role in Memory Formation," and his expertise involves recording and analyzing the neural activity of hundreds of individual neurons in parts of the mammalian brain thought to be involved in memory and spatial orientation.



A photo gallery containing images from the CNS birthday bash is available on-line at http://www.anniversary.cns.caltech.edu

I D E A F L O W

Ann Dowling Makes a Caltech-Cambridge Connection

THE GORDON AND BETTY MOORE DISTINGUISHED SCHOLAR PROGRAM,

begun in 2000, brings to campus technologists, scholars, and artists of great distinction, or in the case of younger people, of great promise, for visits lasting two to nine months. This year, the Division of Engineering and Applied Science is pleased to host Professor Ann Dowling as a Moore Distinguished Scholar.

Professor Dowling comes to Caltech from the University of Cambridge, where she is Professor of Mechanical Engineering, Director of the University Gas Turbine Partnership, Head of the Division of Aeronautics, Fluids, Energy, and Turbomachinery, and a Fellow of Sidney Sussex College.



Dowling has traveled to Caltech with a small entourage of research associates—Aimee Morgans, a graduate student, Simon Stow, a post-doctoral associate, and Dr. Tom Hynes, an engineer and recent scientific collaborator, who also happens to be her husband.

Her colleagues at Caltech are principally Richard Murray, Professor of Mechanical Engineering (also her host); Fred Culick, the Richard L. and Dorothy M. Hayman Professor of Mechanical Engineering and Professor of Jet Propulsion; and Tim Colonius, Associate Professor of Mechanical Engineering. "Extracting the physics from flow modeling and simulation, a theoretical endeavor," is one of the main areas she will be concentrating on while at Caltech; she also hopes to spend a good deal of time in the library (a luxury not possible when facing myriad day-to-day tasks back at Cambridge). On her agenda as well is the task of developing ideas and strategy for future areas of research in her lab.

Professor Dowling's research interests are in the areas of acoustics and vibration, unsteady fluid mechanics, and flow instability. Current applications of this research include the modeling and control of instabilities in gas turbine combustors, road-tire interaction noise, helicopter noise, sound/vortex interaction, and the vibration of towed underwater structures. She is a consultant to both the aerospace and underwater industries. Professor Dowling has been a faculty member of the Department of Engineering at Cambridge since 1979. She has published extensively in scientific journals and is the co-author of two books. She is currently Vice President of the Royal Academy of Engineering and a Council member of the Engineering and Physical Sciences Research Council, which funds academic research in the U.K.





THE NEXT TIME you are in Southern California, stirring your gin and tonic laden with beautiful cubes of H_2O , you might want to thank George W. Housner (MS '34, PhD '41), Carl F Braun Professor of Engineering, Emeritus. Some of the water in those ice cubes probably comes from the Feather River, which exits the Sierras north of Sacramento. The water runs into the Oroville Dam, eventually makes its way south down the American River to the California Aqueduct, and finally to the spigots of Los Angeles, passing through about 20 dams and a handful of pumping stations on the way—as well as crossing the San Andreas fault no fewer than three times.

Back in the late '50s, when Housner first saw the plans for this complex system of dams, pumping stations, and waterways, he wrote a letter to Harry O. Banks, director of water resources for the state, and pointed out that they were "facing big earthquake problems." Banks was not impressed, but thankfully, Alfred Golze (chief engineer and later deputy director in direct charge of design and construction) was, and he accepted and implemented the engineering recommendations of Housner and his colleagues. This was the first time that modern earthquake engineering techniques were applied to

dams and pumping stations—it set a precedent for civil engineering projects throughout the world, and is still regarded as a model of earthquake safety today.

Housner, the founder of the modern science of earthquake engineering, was honored on his 90th birthday last December by friends and colleagues with a wonderful fête at Caltech. His friends and longtime colleagues (including professors John Hall, Ronald Scott, Paul Jennings, Thomas Heaton, Clarence Allen, and William Iwan), spoke in turn and gave a glimpse of the multifaceted Housner—his interest in things literary; his great contributions to the field of earthquake engineering and the resulting practical changes this work elicited, particularly the modification of building codes in Los Angeles and elsewhere; his character and collegiality—in short, an overview of how Housner has wrought great changes in the world around him, as well as brought much more than dynamic stability to his society of engineers, scientists, and friends.

Termite Gut Microbes: An Environmental Force to Be Reckoned With

A Glimpse of the Work of Jared R. Leadbetter

THE CURRENT FOCUS OF PROFESSOR JARED LEAD-BETTER'S RESEARCH is the

mutually beneficial symbiosis formed between termites and their diverse gut microbes. Termites are important globally, being dominant fixtures of many tropical and subtropical ecosystems. Far from being merely the pests we rightfully assogenerated during the fermentation of wood polysaccharides in many environments, but its fate in the termite is remarkable. Termite gut microbes typically convert the bulk of cellulose-derived H_2 into acetate (neutralized vinegar), which is thereafter used by the termite as a key carbon nutrient. This contrasts with other environs that might oth-



ciate with domicile destruction, they play important roles in the turnover of plant material into carbon dioxide and in the process of N₂-fixation. As it turns out, termitegut microbes play critical, irreplaceable roles in both of these important activities. Many of these microbes are found unique to the termite gut, a tiny environment unto itself about 1 to 10 microliters in volume. As many as 2,000 species of termites occur worldwide, each with their own unique microbiota: these insects play host to a remarkable biodiversity.

Leadbetter has sought to better understand the details of the microbial involvement in these gut functions. Specifically, he has focused his research on the cellular nature of a very unusual competition for hydrogen gas that occurs in the gut. This fight occurs between two distinct groups of microbes: methane-generating *Archaea*, and acetate-producing *Bacteria*. H₂ is an important free intermediate erwise seem similar at first blush, including the rumen of the cow. There, the majority of the hydrogen gas is converted into methane, a potent greenhouse gas with zero nutritional value to the animal. The gut tracts of animals in general are a major contributor to global methane, but termite emissions are responsible for only a few percent of

the total budget. However, if their unusual acetate-generating bacteria were absent, these insects' methane emissions could increase ten-fold, perhaps becoming the most significant biological source of this potent greenhouse gas. Thus, termites and their microbes are important to global atmospheric chemistry as much for what they have evolved *not* to emit, as for what they actually do.

One surprising finding of Leadbetter's research is that several of the microbes catalyzing the conversion of hydrogen gas into acetate are so-called spirochetes. These helical- or wavy-shaped bacteria are notorious for their undesirable roles in the causation of disease in animals. Diverse spirochetes are the agents of diseases such as syphilis and Lyme's arthritis. However, Leadbetter's research has revealed that in the termite, they play useful roles. This notion was recently extended by the finding that several gut spirochetes are

involved with the fixation of N_2 gas into biologically useful forms—an important contribution to the protein-poor, wood diet of their hosts. The view of spirochetes as being beneficial to both their own immediate environment, and to ours, is novel. Leadbetter's research seeks to continue to illuminate the unique features of these microbes, the underlying bases for their interactions within the guts of termites, and their impact on the external environment.



California dampwood termites (Zootermopsis angusticollis) feeding on pine bark.



High magnification image of gut fluid and spirochetes, several of which are H₂-consumers.



Low magnification images of gut fluid and cellulose-decomposing, H₂-producing protozoa.

For further information visit

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

Applied and Computational Mathematics Executive Officer: Professor Thomas Yizhao Hou

The Applied Mathematics Option was established in the mid-1960s. It consisted of a small group of outstanding applied mathematicians whose expertise and research spanned a variety of areas, with a strong emphasis in fluid mechanics and related fields.

The composition and research direction of the option has changed significantly during the last eight years, starting with the hire of Professor Thomas Hou in 1993 and Professor Oscar Bruno in 1995, and gathering further momentum with the hires of Professor Niles Pierce in 1999 and Professor Emmanuel Candes in 2000. Together with Donald Cohen, the Charles Lee Powell Professor of Applied Mathematics, Professor Daniel Meiron (Associate Provost for Information & Information Technology), and Professor Peter Schröder, this mix of faculty provides new strengths in computational electromagnetics, computational molecular biology, multi-resolution analysis and image processing, statistical estimation, mathematical modeling and simulation of materials science, asymptotic and perturbation theory, computational fluid mechanics, and numerical analysis.

Implicit in the faculty's current research endeavors lies a healthy and concerted shift in emphasis with a significant focus: the study of scientific and engineering systems whose behavior is determined by phenomena at multiple scales. Further emphasis in this area will enable Caltech to take a leadership role in the field of multiscale analysis and simulation in a manner that has not yet been identifiably achieved by any mathematics department worldwide. The option has recently renamed itself Applied and Computational Mathematics to reflect this new scope.

Thomas Yizhao Hou, Professor of Applied and Computational Mathematics, is one of the leading experts in analysis and simulation of multiscale and free-boundary problems. In his eighteen-year research career, his interests have centered on developing and analyzing effective numerical methods for vortex dynamics, interfacial flows, and multiscale problems. In recent years, he and his coworkers have developed an effective multiscale numerical method which combines multiscale modeling and simulation in a systematic and integrated fashion. This method can be used to study pollution transport and secondary oil recovery in multiscale heterogeneous porous media. More recently, Hou and Gang Hu (PhD '01) have resolved a long-outstanding open problem: singularity formation induced by the three-dimensional Kelvin-Helmholtz instability. The understanding of the Kelvin-Helmholtz instability is important in many fluid dynamics applications. Contrary to conventional wisdom, they found that when viewed in appropriate physical variables and coordinates, the three-dimensional problem is essentially the same as the corresponding two-dimensional problem. This was very surprising and was considered a major breakthrough in the field. Dr. Gang Hu, who received the Carey distinguished dissertation award in ACM



for the year, has switched gears and is now working for Lehman Brothers on Wall Street; but he has recently reported back to Hou that his modeling and simulation training at Caltech have proved very useful in the real world.

Professor Hou was born in Canton, China, and studied at the South China Institute. Upon obtaining his PhD from UCLA in 1987, he joined the Courant Institute as a post-doctoral scholar, and then became a faculty member in 1989. He moved to the applied math option at Caltech in 1993 and became executive officer in 2000. Hou was awarded the Wilkinson Prize in Numerical Analysis and Scientific Computing in 2001, the Francois N. Frenkiel Award from the American Physical Society in 1998, and the Feng Kang Prize in Scientific Computing in 1997. He is an invited plenary speaker for the 2003 International Congress of Applied and Industrial Mathematics: was an invited speaker of the International Congress of Mathematicians in Berlin in 1998; and was a Sloan Foundation Research Fellow from 1990 to 1992.

For more information on Applied and Computational Mathematics visit http://www.acm.caltech.edu





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