The EE Enterprise: Sweeping into Uncharted Terrain

by P. P. Vaidyanathan

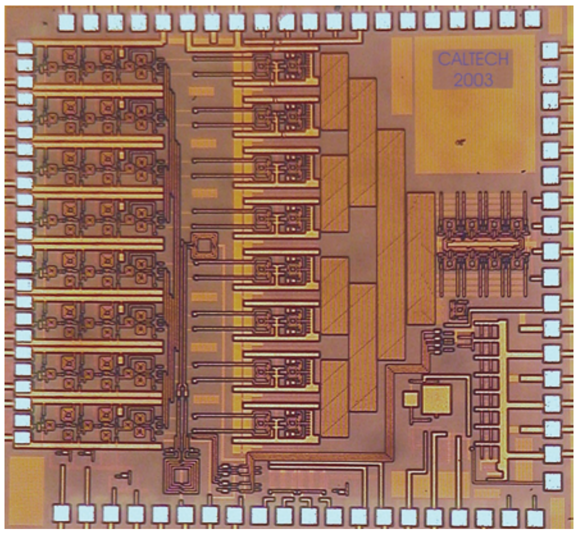
The impact of electrical engineering (EE) on our society cannot be overemphasized. Silicon electronics and computers have invaded and reshaped lifestyles for the last 30 years. Nearly all high-tech devices we routinely use today—cell phones, PCs, flash memory cards, and sensor networks—rely on countless 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.



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.

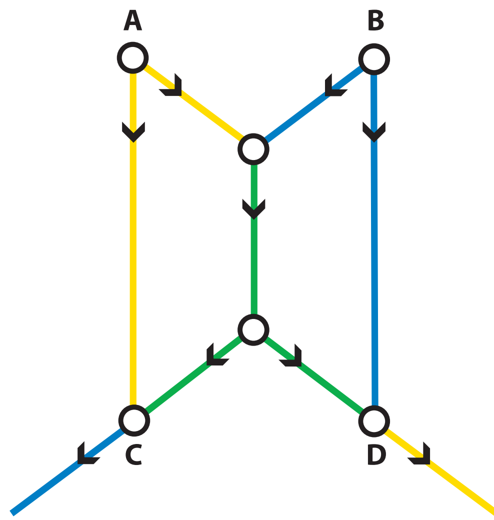
The research of Yaser Abu-Mostafa, Professor of Electrical Engineering and Computer Science, is devoted to the theory, algorithms, and applications of automated learning. Learning can be viewed as an alternative approach to system design. Rather than mathematically modeling the task at hand and implementing 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.

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.



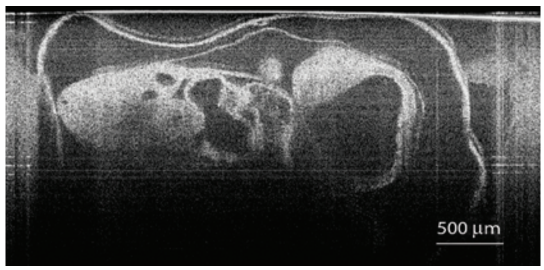
An example of network coding being developed by Professor Michelle Effros: User A wishes to send a binary message to user D (yellow), and B to C (blue). Each link can carry one binary message per use and all links operate in the downward direction. Using routing, transmitting messages from A to D and 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.

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.

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.



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.

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).

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

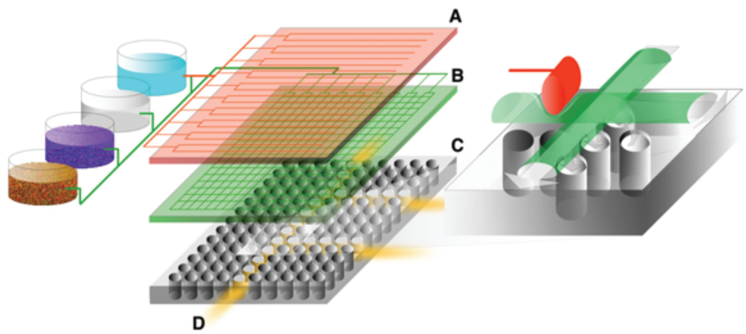
Humans can effortlessly identify, learn and recognize novel objects. The same task is difficult for machines because a machine does not know how many objects there are in an image without knowing about the object beforehand. The algorithms being developed by Professor Pietro Perona and his group replicate 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

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