Computers as an Enabling Technology
for Basic Research in RLE
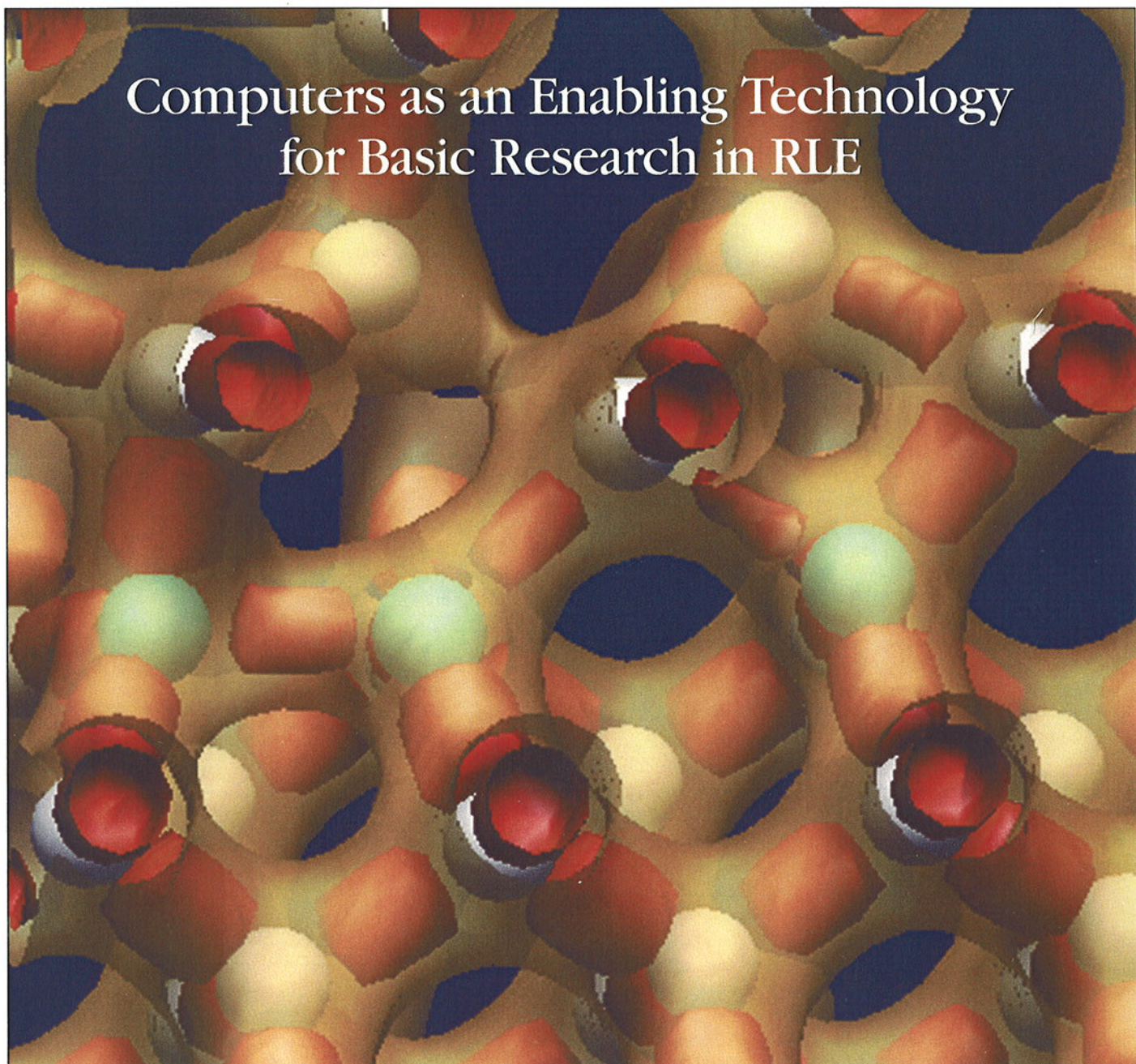
Director's Message

We all realize that computers form an increasingly large part of the set of tools we use to do our work. In this issue of *currents,* we illustrate not only the incredibly broad scope of this impact on RLE's research, but also the way in which the nature of certain research topics leads to new computational resources, both hardware and software. In this way, computing has become a vital part of our research enterprise, and we are creative exploiters of it at all levels, from the smallest low-power circuits to the largest highly parallel multiprocessor machines. Not only do we find computing central to the modeling, simulation, and visualization of inanimate physical systems, we also increasingly find it at the heart of our work on biological systems, includ-
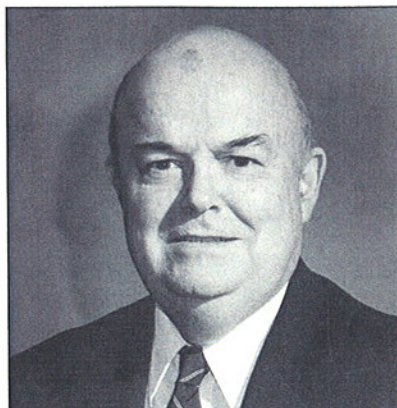
Jonathan Allen, Director,
Research Laboratory of Electronics

ing human-computer interactions. In addition, while experimentally derived data often drives modeling and simulation, innovative "comput-

er experiments" also suggest new areas of exploration for physical effects predicted by fundamental theory.

Given these rapidly evolving techniques, it is not surprising that the constant interplay of research and teaching in RLE has led to new environments for learning. These new learning environments facilitate direct interaction between students and the simulated behavior of entities under study, be they electronic circuits or biological cells, so that students can build their own internal models in a highly personal way. From all these examples, we see that computing is an integral part of our research enterprise, providing an important component in how we seek to understand and learn the nature of our world.

Throughout history, scientists have searched for the fundamental laws that govern our universe. In their search, four different scientific methods have been used to carry out research in the quest for answers. The first is called *observational science,* where a situation or phenomenon is studied and then carefully documented. Observational methods are used in many natural sciences, for example, in animal behavior studies, astronomy, and the geological sciences. In the second method, *experimental science,* experiments are carried out to provide insight into basic scientific principles. Here, it is important to use control groups for comparison and to keep as many factors as constant as

possible to isolate cause and effect. Examples of experimental methods include tests to determine the appropriate chemical concentrations for new medicines or the comparative testing of airplane design in a wind tunnel. The third method involves *theoretical science,* where a theory or law is hypothesized and then proven by additional research or mathematics. The complex equations that describe certain properties or phenomena in the physical sciences, such as the familiar $e=mc^2$ formula of Einstein's theory of relativity, are examples of theoretical science.

Until recently, these three methods were the only ones typically used for most scientific investigations. The fourth

Front cover illustration: *The core of a dislocation in crystalline silicon as seen from the perspective of its electrons. Calculated by physics graduate student Gabor Csanyi with the special density-functional language DFT++ developed in Professor Tomás A. Arias' group, the image contains reddish-gold regions corresponding to atomic bonds and spheres that represent the cores of the silicon atoms. Greenish atoms are at the center of the dislocation. The surprising result of this image is seen in the white atom located slightly above and to the right of center. This atom, which has two greenish atom neighbors, has a very subtle structure rarely found in crystalline silicon. With five neighbors and five bonds, it is known as a "floating bond" and previously had only been theorized to exist in amorphous silicon. Calculations for this research ran on the experimental Xolas shared memory processor at MIT's Laboratory for Computer Science, which took several weeks to produce the results shown above.*

and newest method is the rapidly expanding field of *computational science*. As computers have become increasingly powerful, scientists have exploited their capabilities more frequently to study complex problems in a variety of disciplines. Previously, scientific hypotheses had been tested through experimentation, but since many scientific questions are incredibly massive, they cannot be broken down into testable components.

Computational science offers a potential solution to these difficult questions and enables the execution of complex calculations needed to solve them.
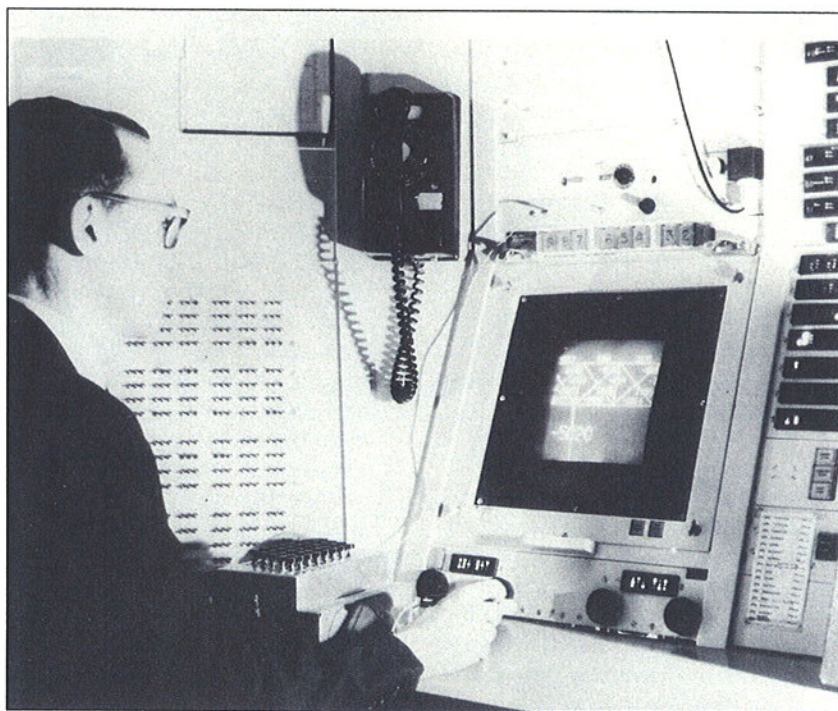
Towards this end, novel tools and techniques are being developed that provide the immense computational power required to process large amounts of data, frequently in real time, and to permit a better understanding of phenomena under study.

This issue of *RLE currents* offers an overview of projects in the laboratory that seek to exploit computers in their role as an enabling technology for basic research. Generally, efforts in this area aim to improve the reliability or precision of computational techniques, to develop new techniques, and to apply them successfully to various disciplines

Visualizing the Past at RLE

In 1961, doctoral student Ivan E. Sutherland (PhD '63) developed Sketchpad, the first interactive computer graphics program. Here, he is seen implementing the system on Lincoln Laboratory's TX-2 computer. In a 1996 interview with **RLE** currents, Dr. Sutherland reminisced, ". . . I heard Marvin Minsky describe computing at RLE and I wanted to get in on the action. It was a rare opportunity to get my hands on a whole computer. On-line computing was the high point of my MIT experience."
(Photo courtesy of MIT Lincoln Laboratory)

With the growth of computing in the early 1960s, many researchers at RLE naturally exploited the technology's new capabilities. In 1961, graduate student Ivan E. Sutherland (PhD '63) created Sketchpad, the first interactive computer graphics program.

Using a light pen, Sketchpad allowed the user to draw simple shapes on a computer screen. For the first time, highly precisely and geometrically constrained drawings could be created, manipulated, duplicated, and stored. An x-y cathode-ray tube (CRT) display, a light pen, and a bank of switches on Lincoln Laboratory's TX-2 computer comprised the interface on which the first interactive computer graphics were made. A separate TX-2 output instruction was needed to plot each of the hundreds of points that made up a single graphic display.

The tip of the light pen contained a small photoelectric cell that emitted an electronic pulse when placed in front of a CRT. The CRT's electron gun then fired directly at the pen. By timing the pulse with the location of the electron gun, the user could precisely pinpoint the location of the pen on the screen. Once the pen's location was determined by the computer, it would then draw a cursor at that point.

Sketchpad pioneered the concepts of graphic computing and visualization, including the ability to constrain objects, rubber-band lines, zoom in and out on a display, and model objects. Now acknowledged as the first graphical user interface or GUI, Sketchpad became the standard for many of today's graphic interfaces.

and emerging technologies. Many methods and tools used for computational modeling, simulation, and visualization are not only created, but also frequently applied in RLE's interdisciplinary environment. The broad range of both applications and basic research spans the fields of biomedical imaging and signal processing, as well as the development of tools for new technologies such as semiconductor lasers, microelectromechanical systems (MEMS), and energy-efficient computation.

MODELING AND SIMULATION

Computer modeling and simulation methods are used to study systems and events with the goal of understanding, controlling, or modifying them. Essentially, modeling and simulation entails identifying a system or event to be studied, applying tools from physics and mathematics to establish a mathematical model, applying tools from numeric analysis and computer science to build a model, and then visualizing and interpreting the results. Models may be used as a basis to simulate an object or event by building numerical representations of processes such as mechanical stress on structures, emerging weather patterns, or how changes in interest rates affect the economy.

Computer simulation is then applied to emulate the behavior of the real-world systems as they change over time from one state to another. In addition to helping investigators understand why certain effects or events occur, simulation can help to predict the behavior under various conditions for systems that either already exist or are under design. By exploring the effects of modifications to a system and confirming that all variables are known, simulation can identify problems before implementation or design is carried out.

Building a model generally entails representing real-world objects or phenomena as a set of mathematical equations. Some computer models of physi-

cal phenomena are based on three-dimensional grids, where specialized software can calculate each point on the grid and where changing numerical values represent changing real-world conditions. Exploiting the capabilities of today's computers to perform massive numerical calculations, computer modeling techniques can accurately represent three-dimensional objects or an event by carrying out a set of equations on a data set. Virtually any object or event that can be reduced to mathematical data can be modeled and simulated. However, because natural phenomena are subject to a countless number of influences, simulation can become difficult. Hence, it is important to determine the most essential factors that could influence the object or event under study.

A good illustration of computer modeling and simulation is in the design of airplanes, where it is crucial to control many different factors, particularly lift force. This force relies on the plane's geometry and different flying conditions, both of which must be understood in a highly complex way. In the past, engineers had to perform many wind tunnel experiments in order to measure lift force under various conditions. Using modern techniques, engineers can now study the lift properties and the other principal features of an airplane by means of theoretical computational models. During the process of simulation, they can change the plane's geometry and other important factors with a simple mouse click, without the need to build an actual physical model of the airplane.

Another advantage of some computer models is that they can speed up extremely slow processes, such as long-range weather forecasting or the formation of a galaxy, in order to predict results. Computer models are also indispensable when phenomena are too small to be examined with traditional physical techniques. For example, molecular dynamic simulations and three-

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dimensional models of chemical compounds help scientists to understand the underlying physical properties of chemical structures. Computer models are also used to explore phenomena that cannot be directly experienced, such as probing the nature of black holes in space or determining the factors necessary to predict severe weather conditions. In cases where uncertainty plays a large role, models help to assess what factors need to be observed and what kinds of data are necessary to solve a difficult problem.

While models enable complex phenomena to be understood and their behavior to be predicted, they are approximations only, and rely heavily on the data used to build them. Many mathematical and statistical concepts are required to produce a valid computer model for effective simulation. These include statistical theory, probability distribution, and random-number generation. Various factors, such as reducing the source of possible errors and determining the degrees of uncertainty in the data, can also affect the results of modeling and simulation.

VISUALIZATION

Computer simulation methods typically generate an enormous amount of numerical output, which can be transformed and presented in a more understandable graphic display. The "art" of visualization employs high-resolution computer graphics to display and control complex computerized output. Instead of analyzing numerical output, scientists use visualization techniques to understand relationships that may be embedded in these outputs and to observe subtle trends. New technologies, such as three-dimensional x-ray and magnetic resonance imaging (MRI) tomography systems, Doppler velocity field measurement systems, and super-computer simulations of physical phenomena, have increased the demand to interpret, analyze, and display massive quantities of data. Using well-designed visualization tools, investigators can efficiently analyze the enormous data sets generated by these new technologies. Visualization also affords a clearer understanding of the multiple forces or variables at work in such phenomena as nuclear and chemical reactions, large-scale gravitational interactions, hydraulic flow, load deformation, and physiological systems. In this regard, it permits the high-quality display of simulated objects

A Sampling of Computational Modeling and Analysis

Most computational modeling and analysis is carried out with the *finite-element method* (FEM), in addition to several other time- and frequency-domain techniques. FEM is one of the most powerful tools used to compute complex structures. As a mathematical technique that is commonly used to analyze stress, FEM breaks down a physical structure into separate and distinct substructures called finite elements. The finite elements and their relationships are then converted into equations and solved mathematically.

First described in 1943 by mathematician Richard Courant, FEM was applied in the 1950s by several aeronautical engineers to solve differential equations and structural analysis problems. FEM was originally used on large mainframes, but it can now be implemented on workstations and PCs for applications in structural engineering, heat conduction, hydraulics, electrical field theory, and fluid dynamics. The advantage of FEM is that all problems, regardless of their complexity, can be decomposed into small, regular subdomains or elements. The process of assembling a complex device by small elements is called *spatial discretization*. Using FEM, the geometry and mechanical behavior of these structures and their elements can be accurately described.

FEM characterizes the behavior of a complex structure by calculating factors such as stiffness, applied loads, and restraints at each element or node within the structure. Initially, the structure is discretized into nodes and elements. Stiffness matrices and load vectors are calculated for each element to obtain a structural or global stiffness equation. Boundary conditions are then applied, and stress-strain relationships and nodal displacements are obtained. As many simultaneous equations can be generated for all the possible degrees of freedom in any one FEM model.

Graphics-based FEM software can display the model on screen as it is being built and, after analysis, it can show the structure's behavior under load conditions.

Using somewhat different approaches are other methods that are part of a general class of differential time-domain numerical modeling methods:

The *finite-difference time-domain* technique (FDTD) is a popular electromagnetic modeling method since it is a time-domain technique that can cover a wide frequency range in a single simulation run. In FDTD, Maxwell's differential form equations are modified to central-difference equations, then descretized and implemented in the modeling software. Equations are solved in an alternating manner, where the electric field (E) and the magnetic field (H) are alternately solved for given instants in time. Initially, a computational domain or space must be set up with boundary conditions to compute Maxwell's differential form equations. The grid material of each cell within the domain must be specified. Typically, materials to be modeled are either free-space (air), metal (perfect electrical conductors), or dielectrics. However, any material can be modeled as long as its permeability, permittivity, and conductivity are specified. Finally, a source is specified. Depending on what is modeled, the source can be an impinging wave plane, a current on a wire, or an electric field between two metal plates.

The *partial element equivalent circuit* (PEEC) technique is a most versatile and flexible approach for handling the hybrid nature of integrated electronics. In contrast to other methods, PEEC facilitates the seamless integration of traditional circuit simulators with electromagnetic analysis tools. Thus, it enables electrical modeling and simulation to be performed for any degree of complexity at either the chip, package, or board level. A time-domain technique, PEEC is used to model three-dimensional geometries and is frequently applied to VLSI interconnects on chips and packages.

The *method of moments* (MoM) frequency-domain technique is commonly used to analyze antenna structures, since it models only the metal structure and not the space around it. However, it is also used in other electromagnetic applications. MoM analyzes a single frequency at a time, although most popular software codes allow the solution to iterate over several frequencies. MoM requires that the entire structure to be modeled be broken down into wires or metal plates or both. Each wire is subdivided into several wire segments that must be small when compared to the frequency's wavelength. This is so that the assumption of a constant value of current across

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or phenomena that cannot normally be seen, such as the shape of molecules, air and fluid dynamics, and weather patterns.

Visual displays can include anything from a simple x-y graph of one dependent variable against one independent variable to a virtual reality environment that allows the user to navigate around or manipulate objects. Simple displays may involve two-dimensional graphs of lines or dots, while displays that are more complex use three-dimensional renderings of objects, contours, and surfaces.

A major challenge to improving high-quality visualization is the development of efficient algorithms to manipulate the countless geometric components (lines, triangles, and polygons, for example) that make up a computer image. In order to display realistic images, the problems faced in approximating objects as a set of planar units must be solved. The edges of objects also must be smoothed so their underlying construction is not visible, and the representations of surfaces must be capable of being textured.

More advanced displays include real-time animation with realistic color, reflections, and shading. Color is essential in enhancing images and emphasizing details that are not readily apparent. With color enhancement, engineers can view air currents and turbulence around automobile designs and architects can detect regions of material stress in structures.

OPTIMIZING SCIENTIFIC COMPUTATION

The use of supercomputers and massively parallel computer systems is essential to solving large-scale scientific and engineering problems that need extensive amounts of memory and rapid speed. Data-intensive calculations run much faster when parallel processing is combined with significant amounts of memory on a single chip, typically a digital signal-processing (DSP) chip. Parallel processing involves the simultaneous use of more than one central processing unit (CPU) or engine to execute a program. The CPU contains the circuits for interpreting program instructions and executing arithmetic and logic operations in proper sequence. A DSP chip is a special-purpose programmable CPU placed on a single chip. It provides
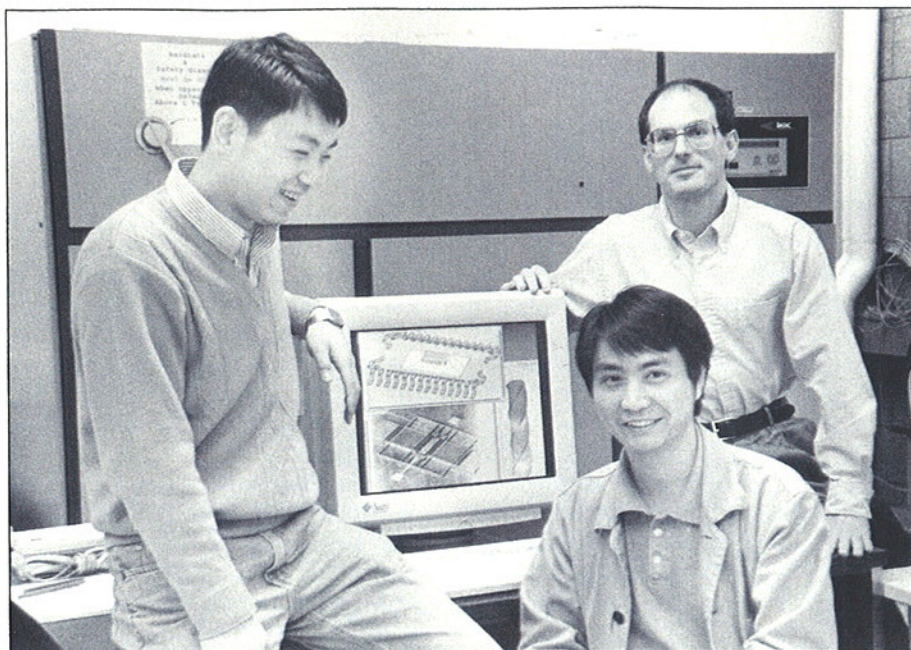
From left: Research Assistants Xin Wang and Junfeng Wang discuss with Professor Jacob K. White the types of structures to which fast three-dimensional solvers have been applied. The monitor displays an integrated-circuit package (top), a micromachined gyroscope (bottom left), and a spar structure used for offshore platforms (bottom right). The spar structure can be seen in more detail on page 9. (Photo by John F. Cook)

Current Density Magnitude

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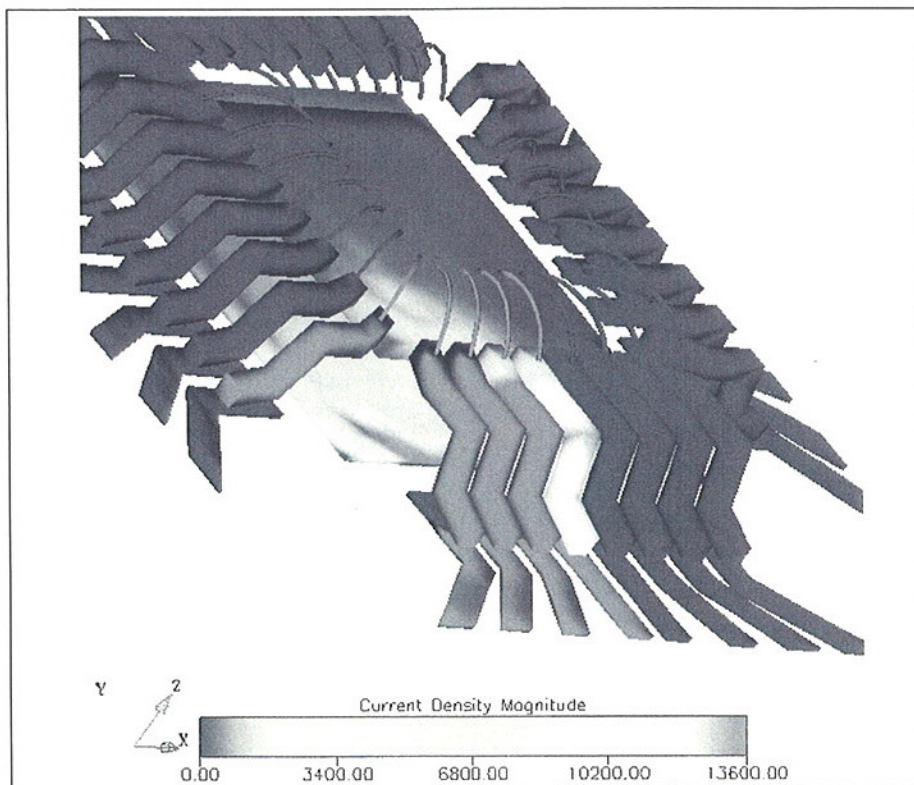
In this example of an integrated circuit package, one can observe the brightest pin being driven, the induced current in the adjacent pins, the wire bonds, and the ground plane. Algorithms like those used in the FASTCAP and FASTHENRY programs, which were developed in Professor Jacob K. White's group in RLE, enable complete package simulations in a matter of hours instead of months. (Courtesy of Microcosm, Inc.)

ultrafast instruction sequences used in math-intensive signal-processing applications. A major research activity in this area is the development of parallel processing algorithms and software, where programs are divided into components that are executed simultaneously by the separate processors. Dividing a program in such a way can make it run faster. To use a parallel computer effectively, an algorithm must have parallelism. That is, it must require the simultaneous performance of certain mathematical operations and determine the number of nonoverlapped operations that are needed. In this way, the number of arithmetic operations needed to solve a problem reliably is minimized, thus minimizing the computational cost and solution time associated with large-scale scientific computation.

COMPUTATION BY THE NUMBERS: NUMERICAL METHODS

Numerical analysis involves the study of problems by computing their numerical values. In this way, mathematical models or equations that describe the behavior of an object or event under study can be solved. In addition, numerical algorithms are developed to determine the values and to analyze the properties used in the models.

Mathematical models are the starting point for the development of computational models that can aid investigators in many tasks, such as predicting future behavior or events for various phenomena, or determining an optimal design for a new system. Computed values can also be compared with experimental observations to test the validity of a theory represented by a model or to estimate the values of unknown constants in a model.

Using numerical analysis, values that are not directly observable can be determined from other known values. However, many models are so complex that it is not possible to solve them or understand the relationships expressed by the model. Here, numerical methods can be used to compute specific solutions or to study the model's behavior as it changes.

## Computational Prototyping Tools and Techniques

In RLE's Circuits and Systems group, Professor Jacob K. White heads an effort directed at computational prototyping tools and techniques. His group develops novel numerical algorithms used to solve design problems in integrated circuits, micromachined devices, and offshore structures. A dual focus on methodology and applications helps his students to become "numerical engineers." That is, students take a design problem, extract the issues that can be addressed by simulation, and then develop sophisticated numerical techniques to solve the simulation problem. The diverse applications addressed by the group ensure that the students focus on fundamental numerical issues. In addition, students often work together to develop approaches that are effective across several different applications.

A major contribution by Professor White's group is computationally efficient numerical techniques used to simulate complicated three-dimensional structures. Applications of these techniques include the electrostatic and fluidic analysis of sensors and actuators, electromagnetic analysis of integrated-circuit interconnects and packaging, and potential flow-based analysis of wave-ocean structure interaction.

In terms of engineering design across a variety of disciplines, one of the most numerically challenging problems is to solve for three-dimensional potentials when a domain-specific Green's function for a linear initial value problem is given. Until recently, the primary tool used to solve complicated three-dimensional problems was finite-element analysis as applied to the differential formulation of equations. The difficulty with the general finite-element approach is that generating the three-dimensional finite-element mesh and then solving the associated equations is too expensive for
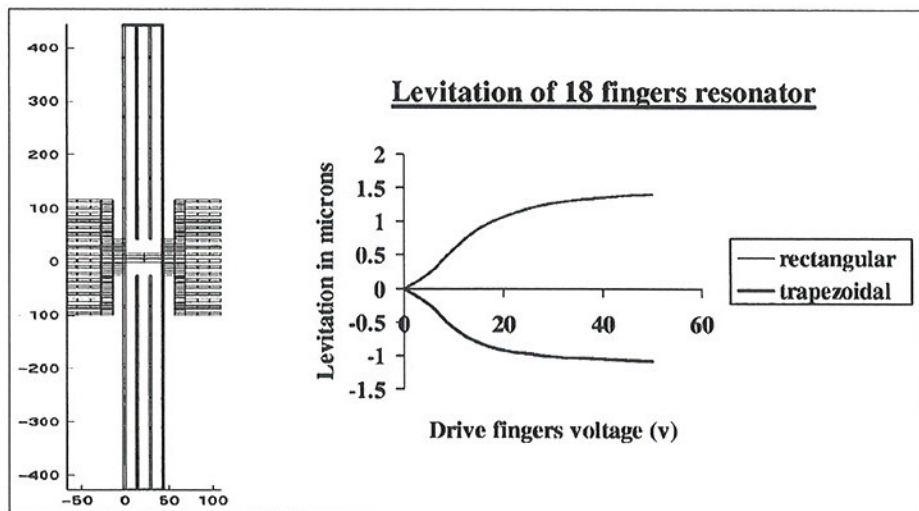
The levitation of a comb-drive resonator realized in Professor Jacob K. White's group, where an efficient multilevel Newton approach was developed. This method makes it possible to perform coupled electromagnetic simulation of complicated structures in less than two hours. The structure's mechanical behavior is treated with finite-element analysis, and electrostatic forces are computed with accelerated boundary-element methods.
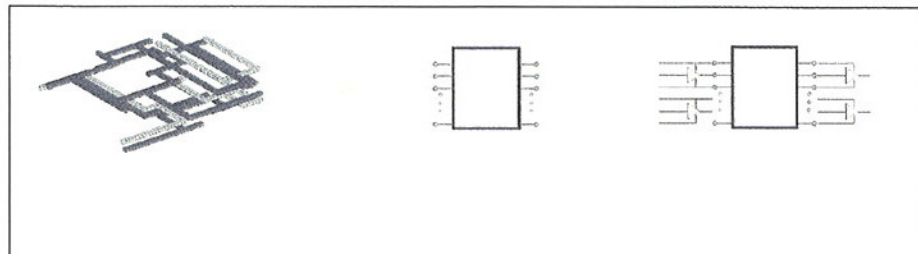
A diagram of the model-order reduction approach developed in Professor Jacob K. White's group. In this approach, accelerated boundary-element methods are used to generate reduced-order models for circuit simulation.

complicated geometries.

Using a different approach, which began with pioneering thesis research in Professor White's group in the late 1980s, so-called "fast" methods were developed to solve the integral formulations of three-dimensional problems. The advantage of integral formulations is that the unknowns are only on the surfaces of structures, which eliminates the need to generate volume meshes. The common numerical approach used to solve integral equations is boundary-element methods (BEMs). Unfortunately, BEMs increase computational cost, which becomes equivalent to the cube of the number of unknowns, and use massive amounts of memory, which are equivalent to the square of the number of unknowns. For example, 100,000 unknowns may be needed to solve a complicated three-dimensional problem numerically. In this case, standard BEMs would require 100 gigabytes of memory and nearly a year of computer time.

In 1988, a three-dimensional capacitance extraction program called FAST-CAP was developed in Professor White's group, based on multipole-accelerated iterative methods. These methods solve boundary-element equations by using time and memory factors that grow linearly with the number of unknowns. Such methods can solve 100,000 unknown problems in a matter of hours instead of years and use only a gigabyte of memory. Dr. F. Thomas Korsmeyer, previously with MIT's Ocean Engineering Department, developed FASTLAP. This program generalized FASTCAP in order to solve general Laplace problems for applications that included the computation of torque by micromotor designers. Next, an accelerated inductance extraction program called FASTHENRY was developed (see illustration on page 6). Finally, the precorrected-fast Fourier

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transform (FFT) approach was developed, which made it possible to use general Green's functions with fast algorithms. This work is now the core algorithm in a collection of fast analysis programs used for offshore structure analysis (FAST WAMIT) and the fluid analysis of micromachined devices (FAST-STOKES). Dr. Korsmeyer, now a research engineer in Professor White's group, directs an effort to develop algorithms for the efficient hydrodynamic analysis of structures and ships (see section on ocean structures below).

In another area related to Professor White's research, micromachining technology has enabled the fabrication of novel microsensors and microactuators. Because of the specialized processing involved, the cost to prototype even simple microsensors, microvalves, and microactuators is enormous. In order to reduce the number of prototype failures, designers of these devices frequently use simulation tools. These tools must account for the interaction between electrical, mechanical, and fluidic forces to enable the performance of micro-electromechanical systems (MEMS) to be predicted efficiently.

Simulating this coupled problem is difficult because most MEMS devices are innately three-dimensional and geometrically complicated. By using domain-specific solvers, it is possible to simulate these devices efficiently, provided the coupling between domains can be handled effectively. Professor White and his collaborators at MIT's Microsystems Technology Laboratories have developed algorithms for coupled-domain simulation.

In another effort, Professor White and his coworkers have also developed an efficient multilevel Newton method that makes it possible to perform coupled electromechanical simulation of complicated structures in less than an

hour. An example of a comb-drive resonator can be seen on page 7. The multilevel Newton approach allows each domain (in this case, mechanics and electrostatics) to use the most efficient simulation approach.

Although accelerated BEMs enable the simulation of extremely complicated structures (such as an entire package or an entire microsensor), the analysis of these structures is only part of the problem. It is also necessary to generate low-order models of the dynamic behavior of these structures so that the models can be incorporated into a higher-level system simulator. Recent work in Professor White's group has focused on fast automatic techniques that automatically generate low-order models of an interconnect directly from discretized Maxwell's equations (see diagram on page 7). The group has developed Arnoldi-based methods and combined them with accelerated boundary-element methods to produce an overall algorithm that efficiently generates accurate models suitable for coupled circuit-interconnect simulation.

During the past decade, Professor White's students have worked on many numerical techniques in a broad range of applications, often collaborating with investigators in other laboratories at MIT and elsewhere. This research includes the development of simulation techniques for transient and hot-carrier effects in semiconductor devices, switching power converters, and inductive effects in Josephson junction arrays.

Computational Prototyping of Ocean Structures

Research Engineer Dr. F. Thomas Korsmeyer and his colleagues in RLE's Circuits and Systems group develop algorithms for the efficient hydrodynamic analysis of structures and ships. The algorithms are then built into software used by oil companies, offshore construction companies, shipbuilders, and the U.S. Navy.
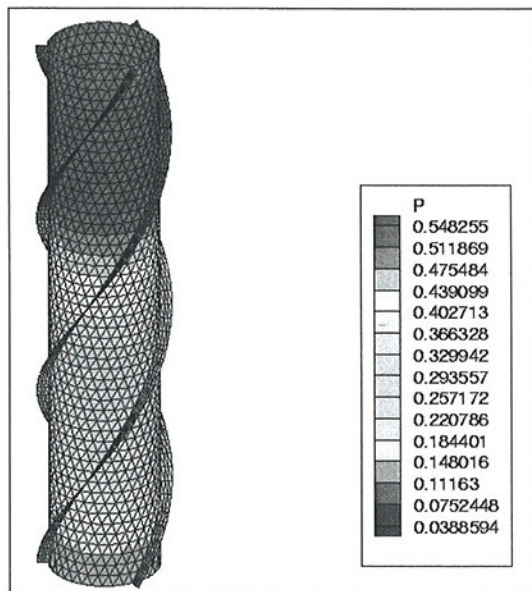
The hydrodynamic analysis of ocean structures, such as offshore oil production platforms, is characterized as a potential flow problem governed by the Laplace equation with nonlinear free-surface and body boundary conditions. The preferred approach to these problems is the boundary element method (BEM), since they may have moving boundaries and may be unbounded in physical extent. Unfortunately, BEM requires solving
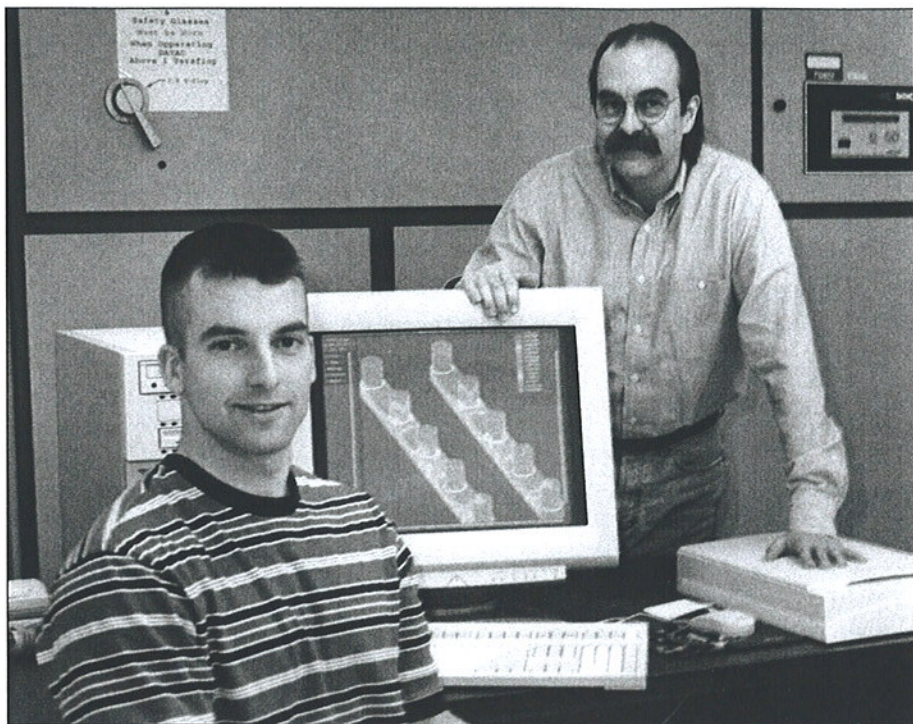
Research Assistant Thomas J. Klemas (left) and Research Engineer Dr. F. Thomas Korsmeyer work together to calculate the diffraction pressure on the wet surface of a semi-submersible section of the U.S. Navy's proposed mobile offshore base. Carrying out the research needed to determine pressure attributed to surface waves on large, complex ocean structures is computationally intensive. However, acceleration algorithms for boundary-element methods can make such computations easier to perform on engineering workstations. Mr. Klemas uses a boundary-element method accelerated by the precorrected-fast Fourier transform algorithm (FFT) to calculate the surface pressure displayed on the monitor.
(Photo by John F. Cook)

dense linear systems and, because ocean structures tend to be large when compared to a wavelength, these systems can have tens and sometimes hundreds of thousands of unknowns.

For N unknowns, the so-called fast algorithms used in BEM can reduce CPU time and memory allocation from order N-squared to order N log N for time and to order N for the memory. In this area of research, Professor Jacob White's group has developed novel methods over the last decade. (See the previous section on prototyping tools and techniques.) Although the original BEM application for fast methods was directed towards electronic packaging, Dr. Korsmeyer and his group have extended the use of these algorithms to hydrodynamic analysis.

Dr. Korsmeyer's group continues research originated by Professor J. Nicholas Newman in MIT's Ocean Engineering Department. This research has resulted in the hydrodynamic analysis codes WAMIT (Wave Analysis MIT) and its high-order element successor HIPAN. These codes are widely used in industry. While WAMIT requires the usual low-order element discrete input, HIPAN uses the exact computer-aided

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	0.220786
	0.184401
	0.148016
	0.11163
	0.0752448
	0.0388594

Left: First-order diffraction pressure on a spar with helical strakes computed with FAST WAMIT (Wave Analysis MIT) program developed in Dr. F. Thomas Korsmeyer's group. The spar is used with a catenary mooring system as the buoyant support for oil production platforms. Dimensions of the actual spar would be approximately 40 meters in diameter and 200 meters high. When using the boundary element method (BEM), computational difficulty arises in analyzing these structures because of the disparate scales of the cylinder and strakes. Small elements are needed to determine the influences across the thin dimension of the strakes accurately. However, if similarly sized elements were used on the entire structure, the total number of elements would be too great for computation by conventional methods. Computations for this structure have been made with a maximum of 250,000 low-order elements. Adequate convergence is obtained with approximately 70,000 low-order elements, for which the computation requires 30 minutes and 900 Mb on a Sun Ultra 30 workstation.

elapsed time= 10 periods
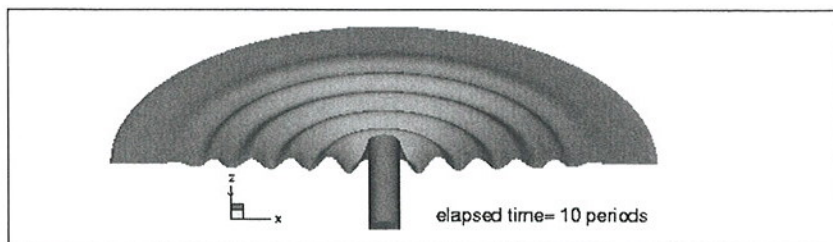
Right: A nonlinear simulation of a heaving cylinder computed by the high-order Rankine element code AEGIR developed in Dr. F. Thomas Korsmeyer's group. Ten periods have elapsed, so waves have filled the computational domain to the numerical beach where they are absorbed. This simple simulation demonstrates the stable evolution of the nonlinear free-surface boundary condition. Simulations of large and complex structures will require the implementation of a fast algorithm using the boundary element method.

design representation of the structure geometry and a B-spline basis for the unknown potential. The result is an improvement in computational efficiency over WAMIT, especially when high-accuracy solutions are required. For either code, large and complicated structures require computational time and memory that can be prohibitive.

Addressing these computational burdens has been the focus of Dr. Korsmeyer's research. For general Laplace problems, FASTLAP was developed from the FASTCAP capacitance extraction code produced by Professor Jacob White's research. FASTLAP uses a multipole acceleration algorithm. However, for frequency-domain analysis of WAMIT and HIPAN, the precorrected-FFT (fast Fourier transform) algorithm is more appropriate due to the wavy nature of the frequency-dependent kernel. Dr. Korsmeyer and his collaborators are also designing a fast algorithm to use with the group's new nonlinear, time-domain hydrodynamic analysis code AEGIR (named for the Norse god of the sea). An example of results from FAST WAMIT and AEGIR are shown in the illustrations on page 9.

Computational Methods for Quantum Physics

Since they were first theorized in the early 1800s, scientists have sought methods to understand the function of atoms in molecular bonds. The emerging study of quantum mechanics in the early 1900s held promise for the development of methods to calculate molecular properties and their interactions, but applications to other scientific fields were slow in coming. One reason was that it was not possible to deal with the complicated mathematical relationships in quantum mechanics for systems as complex as molecules. In 1929, physicist P.A.M. Dirac, a founder of quantum physics and Nobel laureate, addressed the problem: "The fundamental laws necessary for the mathematical treatment of large parts of physics and the whole of chemistry are thus fully known, and the difficulty lies only in the fact that application of these laws leads to equations that are too complex to be solved."

Beginning in the 1960s, computers were used to solve these equations, and the successful application of quantum mechanics to chemistry established the new field of quantum chemistry. Today, computational calculations typically support experimental techniques in many
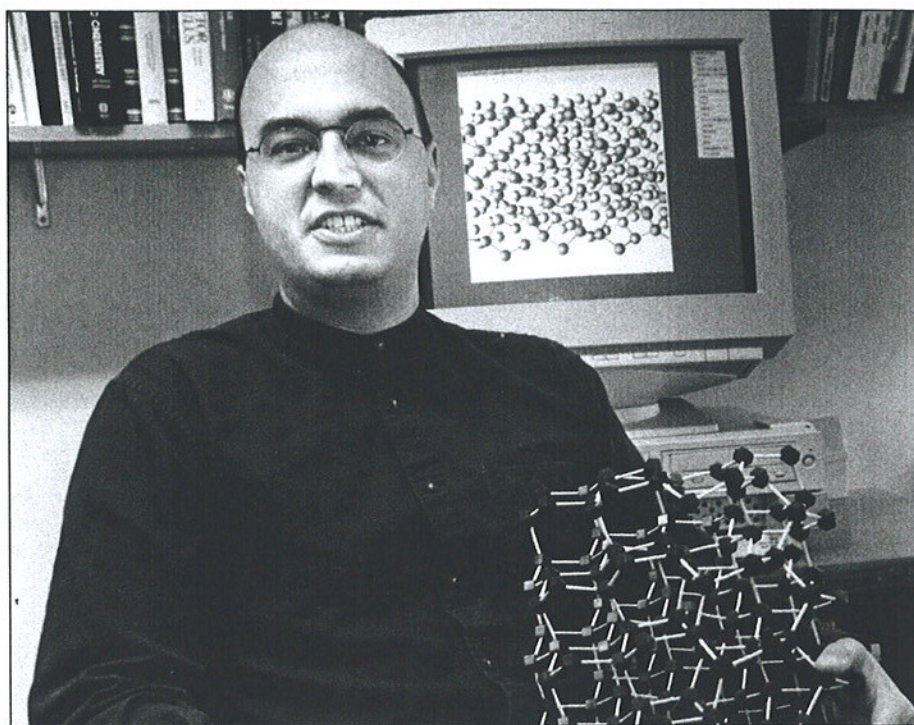
Professor Tomás A. Arias' research activities in RLE's Surface and Interfaces group include the development of new computational techniques for quantum physics. Projects involve the novel use of wavelets to solve Schrödinger's equation, the development of innovative programming methods that allow the same platform-dependent software to quickly explore different physical effects on parallel machines, and the creation of new representations for many-body physics that are well suited for computation. (Photo by John F. Cook)

branches of physics, and it is now possible to analyze the structure and properties of matter in detail. However, since the conventional method used to calculate molecular properties is based on a description of the motion of individual electrons, some computational methods become mathematically intractable.

Nobel laureate Walter Kohn demonstrated that it is not necessary to consider the motion of each individual electron; that it is only necessary to know the average number of electrons located at any one point in space. This has led to *density-functional theory* (DFT), a simple computational method that makes it possible to study large molecules and other complex structures. Although it has taken more than thirty years to make these calculations feasible, the DFT method is one of the most widely used in computational quantum physics today.

Professor Tomás A. Arias' research activities in RLE's Surface and Interfaces group includes the development of new

computational techniques for quantum physics. Projects involve the novel use of wavelets to solve Schrödinger's equation, the development of innovative programming methods that allow the same platform-dependent software to explore different physical effects quickly on parallel machines, and the creation of new representations for many-body physics that are well suited for computation.

A fundamental issue that underlies such diverse fields as computational quantum mechanics and image processing is how to use numerical data to represent mathematical functions efficiently, such as Schrödinger's wave function or the intensity map of an image. In much the same way that one image can have regions of great detail (such as leaves on a tree) and other regions that show little detail (such as the side of a building), the electronic wave functions in a solid or molecule tend to vary smoothly in the valence or bonding regions and tend to have more structure in the cores of atoms near the nuclei. In this area,
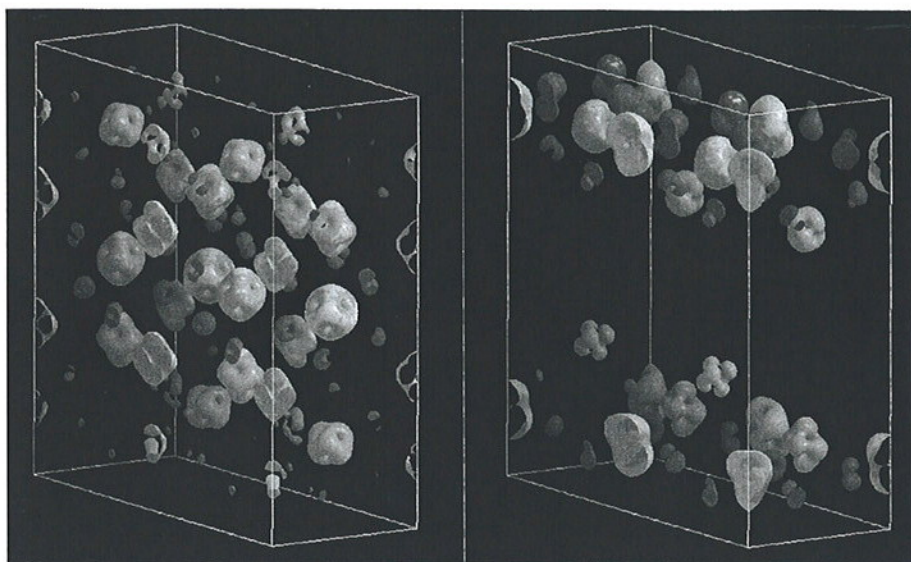
This plot of the highest occupied (at left) and lowest unoccupied (right) molecular orbitals in a two-dimensional horizontal slab of chromium (III) oxide was produced on a Silicon Graphics Origin 2000 computer using the new DFT++ language developed in Professor Tomás A. Arias research group. One benefit of this new computational language is that physics can be expressed independently of the underlying mathematical transforms and how they are computed. Professor Arias works with chemical engineering graduate student Jason A. Cline and Professor Angeliki Rigos of Merrimack College to investigate chromium (III) oxide in order to probe the energetics of surface reactions related to localized corrosion (pitting and cracking) and catalyst poisoning. Here, the unoccupied molecular orbits congregate at the surface, indicating that the oxide may be reactive in a reducing environment.

Professor Arias' group is pursuing a promising direction: the adaptation of wavelet image compression techniques to represent electronic wave functions efficiently. Wavelet theory is used by other RLE investigators for image compression, and Professor Arias seeks to adapt these techniques for quantum-mechanical computation.

Based on the elegant and powerful mathematical idea of *multiresolution analysis,* wavelet theory can be used to build a description of a mathematical function from its coefficients. These coefficients describe the variation of a function on different levels of detail and in different regions of space. One can ignore the coefficients that correspond to a high degree of detail in regions of space where there is no such detail (such as the valence regions of a solid). Thus, multiresolution analysis provides an economical representation of quantum mechanics. In contrast to other techniques with similar capabilities, such as finite-element techniques, wavelet

theory is promising because multiresolution analysis ensures that the representation provided by the information on all different scales is uniform. Thus, the representation is unbiased in a precise mathematical sense, and ultimately leads to results that are more reliable. This is critical since Professor Arias uses these quantum calculations to predict the behavior of atoms when no direct experimental measurement is possible.

While multiresolution analysis makes wavelet theory a powerful tool for quantum-mechanical calculations, the traditional wavelets used to represent digital images in signal-processing applications are not suited to the continuous electronic wave functions in physical calculations. In addition, it is awkward to express the interactions that occur commonly among functions in physics (known as nonlinear local and semilocal) when using traditional wavelet bases. Finally, traditional wavelet algorithms focus on transforms that use a compressed image to produce

a complete, uncompressed image. In most physical applications, however, it is not efficient to store or process the fully uncompressed wave functions. Hence, new algorithms are needed as well. In this area, Professor Arias' group has pioneered new methods to reduce wavelet theory to its essentials and rebuild it in a form better suited to physical calculations. This work has realized several major breakthroughs described below.

Early in this research, a special blend of functions from finite-element theory and wavelet theory was discovered. These functions, which are better suited to physics calculations than traditional wavelet functions, were discovered independently by other investigators in a different context. They are called *interpolets* because of their interpolating, wavelet-like properties.

More recently, a surprising and profound result was discovered when these functions were used to construct a multiresolution analysis. Interpolets have a property that permits a special kind of multiresolution analysis, called semicardinal, to be constructed. In such a multiresolution analysis, nonlinear local couplings are computed with transforms that only work on a limited set of points in space. Semicardinal multiresolution analysis computes the same results that would be obtained in wavelet algorithms when working with a full representation at infinite resolution. This has enabled Professor Arias' group to eliminate one important set of approximations and to obtain more reliable results in critical parts of their calculations.

Another breakthrough was the development of efficient algorithms to implement the necessary transforms and operations. Earlier methods involved a number of floating-point operations that were approximately equal to the square of the number of wavelets in the calculation or the number of points in the full, uncompressed image. Either case required thousands or tens of thousands of operations to be calculated for each wavelet. Although wavelet calculations in physics could be useful in cases where high resolution and accuracy were needed, it appeared that wavelet methods could not compete in efficiency with the more approximate methods. The use of wavelet calculations in physics seemed relegated to a special niche. However, by exploiting the properties of semicardinal multiresolution analyses, new algorithms were devel-

oped that required only a few floating-point operations per wavelet, thus realizing a tremendous advantage over previous methods.

The final stage in making effective use of these new methods was the development of software to implement new algorithms while exploiting modern cached-microprocessor architectures to achieve high performance. In collaboration with investigators from MIT's Laboratory for Nuclear Science and Laboratory of Computer Science, Professor Arias' group has developed software that achieves performance equal to approximately one order of magnitude better than the simple implementation of their algorithms. The software has achieved performance of 270 million floating-point operations per second on a 300 MHz SUN UltraSparc workstation and 50 million floating-point operations per second on 200 MHz Pentium personal computer. Professor Arias plans to make this software available on the Internet for those interested in using wavelets to solve physical problems in three dimensions.

By implementing the new algorithms and software described above, along with the programming paradigm described below, Professor Arias' group is carrying out the first electronic structure calculations using wavelets. These methods are now competitive, in terms of efficiency, with the standard approximate methods previously used.

The development of new algorithms and new basis sets, as well as the exploitation of new computational platforms, has motivated Professor Arias' group to develop powerful innovative programming methods for physical problems. These methods allow researchers in the group to use the same platform-independent software to explore different physical effects on parallel machines quickly. The goal is to develop a new language that bridges the gap between physical thinking and modern computational languages.

Professor Arias and his colleagues typically use the *Kohn-Sham formulation* of quantum mechanics, for which physicist Walter Kohn shared the 1998 Nobel Prize in Chemistry. In this formulation of the density-functional theory (DFT), a set of simple, one-body wave functions describes the ground state of a quantum-mechanical system.

In the early days of quantum mechanics, physicist P.A.M. Dirac developed a powerful notation for thinking about quantum mechanics called "bra-ket." Used as a convenient notation for vectors, "bra" of a quantum state x is written as $| x >$ and "ket" as $< x |$. Unfortunately, this language is suited only to quantum-mechanical formulations based on many-body wave functions. Therefore, the expression of physics in the Kohn-Sham formulation is awkward and involves many summations and integrations. In addition, it frequently results in error-ridden software and poorly performing programs because of the sequence in which data is accessed during computation.

To address this problem, a new language was developed by Professor Arias' group. Similar to what Dirac's notation did for quantum mechanics, this new language simplifies the previously complicated formal manipulations in the Kohn-Sham formulation. The new language, called DFT++, is so compact and simple that physics expressions can be translated verbatim into C++ code by using the overloading of operators. DFT++ has also proven beneficial in developing portable, high-performance software. In this new language, physics is expressed independently of the underlying mathematical transforms and how they are computed. The same software that was implemented for calculations based upon earlier traditional methods can now be used by Professor Arias' group to perform calculations with their newly developed interpolet transforms described above. This clear delineation between the expression of physics and the actual processing of data in DFT++ allows the "physics" components of the software to be developed independently of the core routines that perform most of the actual computation. Thus, users can quickly explore new physics without being required to optimize mathematical operations continually or to update separate software for parallel implementations on different platforms.

In addition, researchers interested in high-performance numerical algorithms and parallelization can focus attention on important computational kernels without concern for the physics software built on top of it. Typically, many months of programming is required to adapt DFT software to parallel environments. For example, using DFT++ in Professor Arias' group, it took only a month for a graduate student to perform an adaptation to threads on a shared memory processor, and the same amount of time for two students to carry out an adaptation on a message passing interface for distributed memory architectures. The group regularly achieves more than 60% of peak for distributed memory architectures. Normally, it is difficult to sustain more than a small fraction of theoretical peak performance on massively parallel machines.

Today, all quantum-mechanical calculations performed in Professor Arias' group use DFT++. This includes the very large-scale calculations used to study the mechanical properties of materials (see the image on page 1). Given the flexibility and efficiency of this new software, other groups at MIT and elsewhere are now using the code. In the future, this software and the interpolet described above will be available to individuals on the group's Web page http://abinitio.org.

EFFICIENT COMPUTATIONAL METHODS IN SIGNAL PROCESSING
The Science of Image Processing

Image processing involves the manipulation and analysis of visual information. Image coding, compression, restoration, and enhancement are some of the research activities carried out in the field of image processing. Algorithms are applied to visual information, enabling it to be processed in real time by digital computer systems or specially designed analog video hardware. New algorithms

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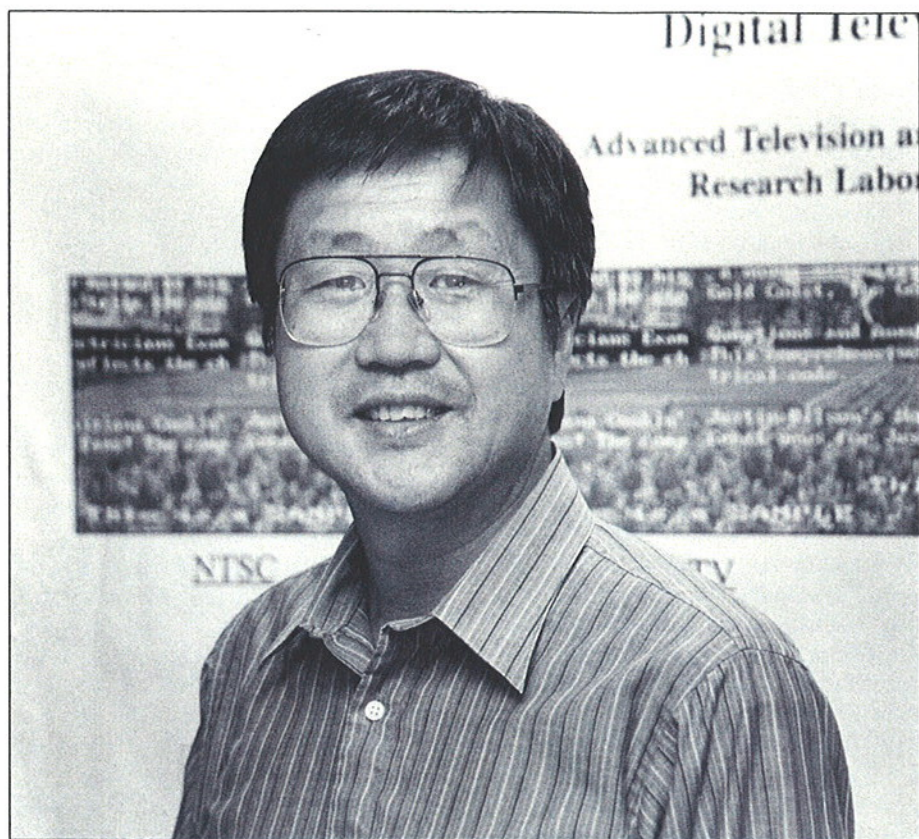
Professor Jae S. Lim heads RLE's Advanced Television and Signal Processing group. In addition to developing a new speech model that is now the basis for the voice coding standard for several international satellite communication systems, Professor Lim and his group have contributed to the design of a high-definition television (HDTV) system adopted by the FCC as the new broadcast transmission standard for the United States. (Photo by John F. Cook)

are continually being developed for image coding and compression, feature extraction, and spatial filtering. Novel computational techniques are also used to analyze, enhance, compress, or reconstruct an image.

One area of image processing involves compressing an enormous amount of video information. To permit a more efficient use of channel capacity (bandwidth) and storage space, redundant information is removed and the image is represented in the minimal number of code bits allowed. These image compression techniques are based on information theory, and many exploit the spatial and temporal relationship between neighboring or adjacent pixels (picture elements).

Mathematical models are used in image restoration to characterize the source of an image's degradation. A degraded image might exhibit noise,

blur, defocus, ghosts, or distortions caused by the image's sensor, transmission, or display. Quantitative techniques are used to measure and remove the degradation. Image restoration entails the selective emphasis and suppression of various picture elements in an image. The image can also be improved or enhanced to a more useable or subjectively pleasing form.

Scientific advances in image processing coupled with technological advances in electronic devices and systems have resulted in a wide range of applications for science, industry, and government. Today, VLSI technology combined with signal-processing theories makes it possible to incorporate frame-store memory and sophisticated signal-processing capabilities into a television receiver at a reasonable cost. The television, computer, and communications technologies are now converging

to produce a high-resolution digital television set capable of receiving high-quality text, video, and audio signals. The earlier participation of RLE's Advanced Television and Signal Processing (ATSP) group in the development of high-definition television (HDTV) standards has generated several important research directions for Professor Jae S. Lim and his students. In addition, the group continues to focus on signal processing for telecommunications and speech enhancement research.

Migration to Higher Resolution Digital TV Systems. Because the new broadcast standard for terrestrial HDTV allows for multiple transmission formats, and because the display formats may differ from the transmission formats, it will be necessary to convert between formats effectively. Issues related to the conversion between the different formats are being examined in Professor Lim's group. Another focus of this research is related to the migration of HDTV to higher resolutions. The need to broadcast at resolutions higher than those now allowed for HDTV has been recognized. A currently acceptable goal for terrestrial HDTV is a progressively scanned video with a resolution of more than 1000 lines scanned at 60 frames per second. However, today's transmission and compression technologies cannot support such a high resolution within the standard 6-megahertz channel, and such a format is not allowed in the digital TV standard adopted by the FCC in 1996.

The ATSP group is investigating several methods to transmit video at higher resolution formats by using video enhancement bits. This approach would transmit two sets of information within the bandwidth allocated for HDTV. Standard video bits would be transmitted at a standard HDTV resolution that the current digital TV standard allows. An advanced HDTV receiver would receive the standard video bits and, with the assistance of video enhancement bits, would convert standard HDTV to a higher resolution. Standard HDTV receivers would ignore the enhancement bits and simply display the video at the standard HDTV resolution. This highly desirable backward-compatible approach would not render standard HDTV receivers obsolete. Understanding the trade-off between the bandwidth allocated to standard video bits and video enhancement bits will enable the

ATSP group to determine the best migration schemes.

Real-Time Video on the Internet.

Packet-switched networks such as the Internet have become an efficient means to transmit data. In these networks, data has no inherent delay constraints and it can handle delay jitter due to variable queuing delays that occur across the network as well as excessive delay from the retransmission of lost data packets. The ATSP group investigates how video compression methods can be applied to video communications over packet-switched networks. Studies focus on how quality real-time video transmission can be achieved over these networks. Since real-time video cannot tolerate excessive delay, data packets that arrive at the receiver after their scheduled playback point are discarded. With the resultant packet loss that occurs on congested networks, it is important to develop video compression methods that anticipate the possibility of packet loss. The ATSP group has developed a method for the optimal selection of parameters for a set of video coders in the presence of potential macroblock loss.

Video Compression with Complete Information.

Video compression and multiplexing systems for bandwidth-limited channels require causal methods to process video data in order to deliver real-time video programs. However, many video sources, such as movies, are prerecorded. Thus, they can be preprocessed before compression and multiplexing are performed for transmission. By exploiting information about each video sequence before compression and multiplexing, improved video quality can be achieved. This research into noncausal processing video compression algorithms in the ATSP group seeks to characterize the gains in video quality that can be realized by acquiring noncausal information about the video programs that are to be compressed and multiplexed. A heuristic iterative algorithm was developed for a buffer-constrained quantization problem in order to minimize the quantization changes in an MPEG-2 intraframe video. Simulations have shown improved and more consistent video quality after the noncausal processing of a video when compared to causal processing.

Multidimensional Rate Distortion-Based Bit-Rate Control.

Bit rates are typically variable at the output of a video encoder. However, when the encoder is part of a communications system, bits can be transmitted through a channel at either a fixed or variable rate. Since the channel's bit rate is different from that produced by the encoder, a buffer is needed to match the two rates. A bit-rate controller is also needed to control the constraint level of the buffer. In most bit-rate control schemes, the buffer level is controlled by adjusting the quantizer parameter. The emphasis in the source coding community is on how to choose quantizers that will maximize video quality under a buffer constraint. Such an approach can degrade video quality significantly, particularly at very low bit rates.

To overcome this problem, the ATSP group has developed multidimensional rate (M-D) distortion-based bit-rate control algorithms. In this approach, a vector of encoding parameters is concurrently adjusted, instead of adjusting only the quantizer parameter. The advantage is that each parameter or quantizer can vary at a much slower rate when compared with a scheme that adjusts only one parameter. From this perspective, the important step in solving video coding problems involves choosing an appropriate operating point in time from a set defined on an M-D grid under a buffer constraint. Since many operating points achieve approximately the same rate, both rate and distortion are considered. The group is currently working to compress underwater images below 10 kilobits per second using this approach. The goal is to transmit these images, taken by an unmanned undersea vehicle, to a ship on the ocean's surface.

Speech Enhancement Systems.

Various techniques have been developed to enhance speech degraded by additive background noise. Model-based enhancement systems, which are based on parameter estimation, have achieved the best results. These techniques, however, are limited by the models upon which they are based. In addition, speech is assumed stationary for a fixed window. It is known that the duration of stationarity varies for different classes of sounds and speakers. One solution is to find the desired stationary regions in the speech before model-based enhancement is performed. Using M-band decomposition and adaptive windowing techniques, the ATSP group has developed an algorithm that segments speech into nearly stationary regions in the time-frequency plane. Noise reduction is achieved by applying a modified Wiener filter based on selective linear prediction. This takes into account the local signal-to-noise ratio of the region under study. Ongoing work in this area is exploring alternatives to this technique that would make it more computationally efficient for real-time applications.
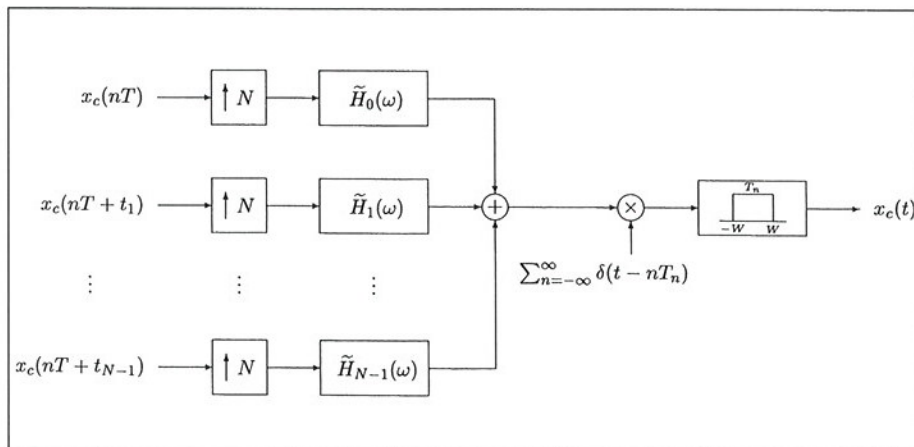
Digital Signal Processing

A strong impetus behind the the emergence of digital signal processing research was the need to process many signals directly in the frequency domain, which required the application of the *discrete Fourier transform* (DFT). In those early days, the computational requirements of the DFT were often prohibitive. However, in 1965, James W. Cooley and John W. Tukey invented the *fast Fourier transform* (FFT) algorithm, a computationally and very efficient implementation of the DFT. As a result, a wide range of FFT-based signal-processing algorithms emerged and the field expanded rapidly. Since then, the methodological foundations of digital signal processing have broadened, and powerful new algorithmic structures continue to emerge for an ever-widening array of applications. Ultimately, algorithm efficiency depends on performance metrics from the application and the computational architecture it will eventually run on.

RLE's Digital Signal Processing (DSP) group carries out basic research on the design of innovative signal-processing algorithms. These algorithms are implemented on a variety of computer architectures, which range from special-purpose hardware to general-purpose microprocessors and programmable digital signal processors. The group's research is motivated by numerous applications such as signal enhancement and active noise cancellation; speech, audio, and multimedia signal processing; signal processing and coding for wireless and broadband multi-user communication networks; and underwater acoustics. New signal-processing algorithms are developed, together with the associated theory, while maintaining a close coupling to target applications and implementation issues.

Recently, new methods have been created by the DSP group for speech

One aspect of the research in RLE's Digital Signal Processing group involves signal enhancement using prototype signals. As part of a project that seeks to extract the human voice from recordings with orchestral accompaniment, (from left) Professor Alan V. Oppenheim and Research Assistants Richard J. Barron and Alan Seefeldt study a spectrogram of two different speakers processed for time alignment. (Photo by John F. Cook)

An essential component to the digital implementation of signal-processing algorithms is the ability to sample a continuous-time signal to obtain a discrete-time representation. This block diagram represents the implementation of a new algorithm for the reconstruction of a continuous-time signal from recurrent nonuniform samples. In this area of research, RLE's Digital Signal Processing group is developing a general sampling framework for the deterministic and random nonuniform sampling of continuous-time signals. Potential applications of this research include randomized sampling for efficient computation, data compression using nonuniform sampling, and efficient quantization methods.

enhancement and acoustic noise cancellation with single- or multisensor measurements. In addition, new methods have been devised to represent and analyze fractal signals for a broad range of applications. The group also studies the potential use of nonlinear dynamics and chaos theory in signal design and analysis for communication and related applications. Other research directions involve the development of broad, new classes of algorithms based on approximate processing and successive refinement paradigms. Another project focuses on robust data hiding and digital watermarking algorithms for multimedia applications (see article on page 26).

A major focus is signal processing and coding for wireless multiuser systems and broadband communication networks. Applications for these algorithms arise in commercial and military mobile radio networks, wireless local area networks and personal communication systems, multimedia networks, and digital audio broadcasting. The DSP group also devises new methods and strategies for code-division multiple-access (CDMA), space-time coding that exploits antenna arrays in wireless systems, modeling and managing traffic in high-speed packet-switched networks, and the backward-compatible digital upgrading of analog communication infrastructures. More generally, new algorithmic structures are created to exploit the potential of networked processors. These include techniques to exploit enhanced communication links between sensors and local processors or base units in sensor networks, low-complexity sequential techniques for sensor signal coding, and techniques to use resources efficiently on dynamically changing networks.

Distributed Signal Processing. As the cost of sensors and processors continues to decrease, distributed sensing and computing networks have become more prevalent. Such networks offer significant advantages over traditional signal-processing platforms. Because information and processing resources can be shared in these environments, the computing capability of each device on the network is increased. Therefore, the overall system becomes more fault tolerant. Additionally, in terms of signal processing, sensors and processors can be integrated into the same network; thus, adaptive interactions between signal collection and processing become possible.

In order to harness the power of distributed networks, several signal-processing problems must be addressed. For example, since resources such as bandwidth, power, and hardware are limited and shared across a network, their availability for any particular processing task can vary greatly over time and geographic location. Hence, for high performance and to guarantee sys-

tem stability, a framework is needed that allows signal-processing algorithms to adapt to the available resources. Another effect of resource limitation is that the heterogeneity among communications channels between sensors and processors can constrain the rate at which information can be transmitted. Consequently, the quality of sensor data streams available at a given processor may vary, depending on the available communication bandwidth from the input sensors. For example, the processor may receive data from a hybrid channel that consists of several parallel channels, each with distinct and dynamically varying characteristics. Efficient algorithms that optimally encode and decode sensor data according to the available channel characteristics are needed for accurate signal estimation at the processors.

The DSP group is studying several problems related to the efficient use of system resources in distributed sensor and processor networks. This work involves methodologies for dynamically adapting signal-processing algorithms to rapidly changing, heterogeneous distributed environments. A versatile framework was built for the design of these low-complexity algorithms, which can efficiently encode measurements at the sensors and accurately perform signal estimation from encoded signals at the processors. The group's formulation of this approach was derived from an innovative interpretation of algorithms as being similar to communication networks. Low-latency and low-complexity algorithms are also being developed for scalar and vector quantizer design in hybrid analog-digital channels.

New Sampling Techniques. In many applications, the ability to implement signal-processing algorithms digitally is advantageous because of the low cost, high speed, and flexibility afforded by programmable DSP architectures. Central to such implementations is the notion of sampling a continuous-time signal in order to obtain a discrete-time representation. Currently, the majority of signal-processing algorithms rely on the uniform sampling and processing of underlying continuous-time signals. However, the sampling process cannot be fully controlled in some applications, and other applications can benefit from more elaborate sampling methods and subsequent processing.

In many cases, the data to be processed can only be obtained at random or deterministic nonuniform points in time. Examples include data loss due to channel erasure or additive noise and data tracked in digital flight control. Therefore, a general sampling framework is needed that includes the deterministic and random nonuniform sampling of continuous-time signals. Such a framework requires efficient algorithms to process digital signals. Once this framework is established, the benefits of deliberately sampling a signal nonuniformly can be explored, and controlled randomization can be introduced to the processing. In addition, once these algorithms are implemented, the different sampling rates in the system must be accounted for. This is important in applications that use nonuniform and randomized sampling, where processing typically involves sampling rate conversion. Consequently, methods that efficiently convert the sampling rate of discrete-time signals are essential to the overall framework. Potential applications include randomized sampling for efficient computation, data compression using nonuniform sampling, and efficient quantization methods.

Different approaches are being explored in the DSP group for nonuniform and randomized sampling, where a general framework is being developed to sample and process the digital signals obtained through the various methods of sampling continuous-time signals. As a result of this research, analytical tools have been introduced to analyze randomized sampling and filtering as well as some forms of nonuniform sampling. Algorithmic structures that are efficiently matched to the processing of signals sampled in this manner are also being examined.

Wireless Communications. Mobile wireless communication links suffer from several types of interference. One type leads to significant signal fluctuations
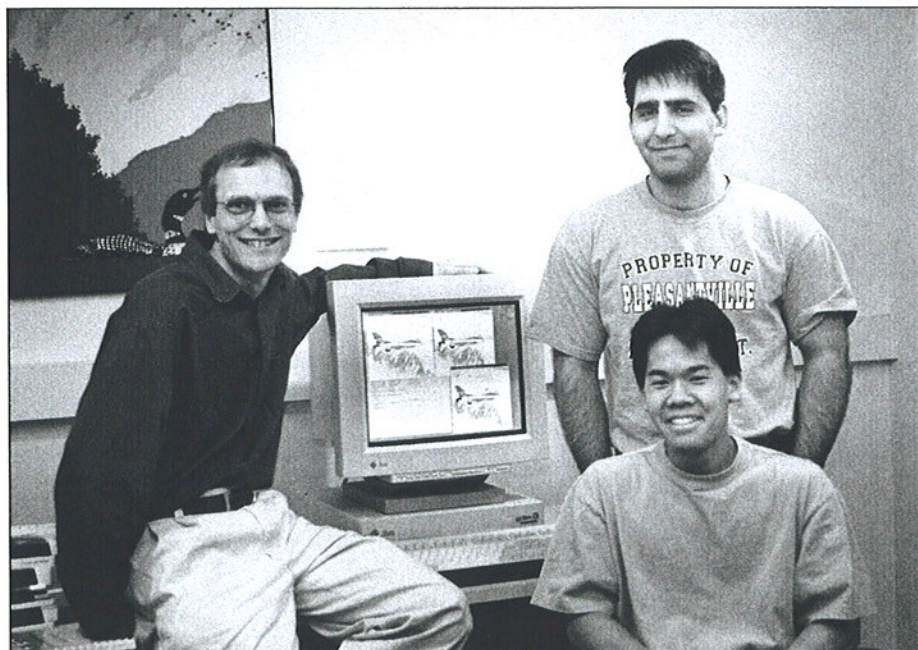

Digital watermarking is emerging as an important computational tool to enable copyright notification and enforcement for digital multimedia content such as audio, video, imagery, and graphics. The watermarking technique involves a digital "fingerprint" that is hidden in some host signal of interest. A next-generation digital watermarking system is being developed in RLE's Digital Signal Processing group by a research team led by Professor Gregory W. Wornell (left) with graduate students Brian Chen (seated) and Emin Martinian. See article on page 26. The underlying technology is based on a new class of provably robust, efficient information-embedding algorithms called quantization index modulation, which was introduced by Professor Wornell's group. Other important applications of the new technology are also being pursued, including data authentication and digital audio broadcasting.
*(Photo by John F. Cook)*

(fading), and arises from multipath propagation and the relative motion of the transmitters and receivers. Another source of interference that occurs between the transmissions of different users is called *multiple-access* or *co-channel* interference. These interference effects severely limit system capacities, which are increasingly stressed by the growing demand for wireless voice and data services. However, system capacities can be increased dramatically with sophisticated signal-processing algorithms that control and mitigate these sources of interference. From this perspective, high-speed computation is a major enabler of higher capacities. The development of such algorithms is a focus of the DSP group's research in wireless communications. Much of this work is aimed at low-complexity, bandwidth-efficient, and power-efficient techniques that can be implemented on flexible, low-power DSP-based architectures.

In mobile transceivers, power is consumed in radio-frequency (RF) transmission and by on-board processing. Algorithmic techniques to reduce RF transmission are emphasized in the DSP group to achieve target performance specifications. This shifts power dissipation from the transmission to the processing circuitry, where further power reductions are possible through implementations that take advantage of the energy-efficient computation techniques developed in Professor Anantha P. Chandrakasan's research group (see page 25).

Many of the signal-processing algorithms under development in the DSP group that dramatically reduce transmitter power requirements involve the creation and exploitation of diversity on wireless links. One example, spectral diversity, is created by using wideband transmission formats such as the IS-95 commercial CDMA standard, and can be exploited by suitably designed receiver processing. A second example is receiver antenna arrays, which create diversity by exploiting suitably designed combining algorithms. The group has introduced powerful, low-complexity classes of iterative and recursive receiver structures to exploit these forms of diversity. Temporal diversity methods spread information across multiple time slots, thus trading off system delay for diversity gain and generally requiring addi-
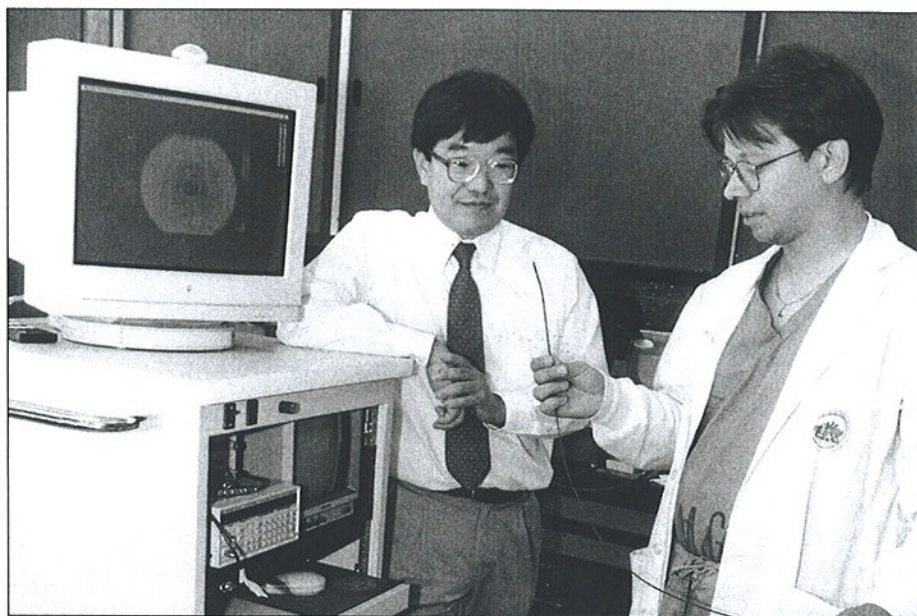

Professor James G. Fujimoto (left) of RLE's Optics and Devices group and Research Affiliate Dr. Mark E. Brezinski of Massachusetts General Hospital examine the fiber-optic catheter used in optical coherence tomography (OCT) procedures. The computer monitor displays a real-time, catheter-based OCT image. (Photo by Donna Coveney)
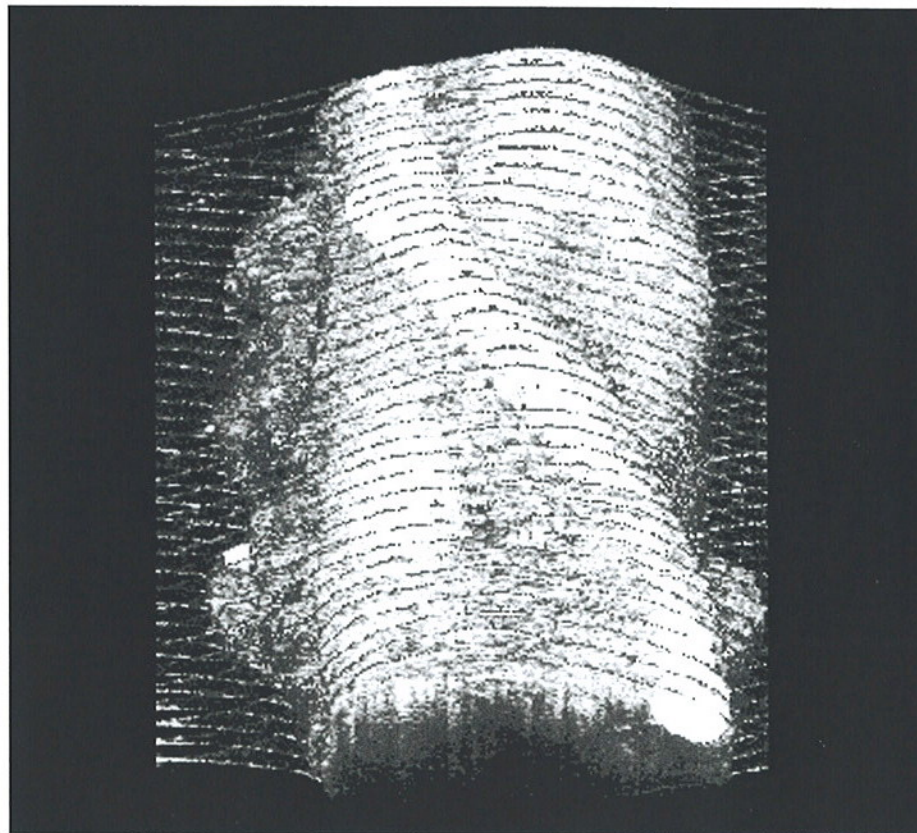
Eighty images with 50-μm spacing were used to construct this three-dimensional optical coherence tomography (OCT) rendering. The figure shows a vertical view of a peripheral nerve. The data set includes segmented images to illustrate longitudinal tracking of a fascicle (a bundle of nerve fibers) in three dimensions. OCT was originally developed to image the eye's transparent tissues, and Professor James G. Fujimoto's group has adapted this technique to image the interior of more opaque parts of the body.

tional power or bandwidth to preserve the transmission rate. *Spread-response precoding,* a technique devised in the DSP group, achieves temporal diversity through low-complexity linear encoding without additional power or bandwidth requirements. A variety of linear and iterative equalization algorithms have also been formulated, along with a powerful multiuser generalization called *spread-signature CDMA.*

Another class of computational techniques that reduces power requirements in wireless systems is being studied for use with multiple-element transmitter antenna arrays. To realize the available diversity benefit requires computationally intensive space-time coding algorithms at the transmitter and efficient equalization and decoding algorithms at the receiver. The DSP group has been developing various powerful linear and nonlinear space-time coding and decoding strategies for these applications. Achievable performance limits of space-time coding algorithms with practical implementations are also being examined. Results have shown that the use of computation in the form of such space-time processing can reduce the transmitter power needed to meet typical target performance specifications by several orders of magnitude when compared to traditional signaling strategies.
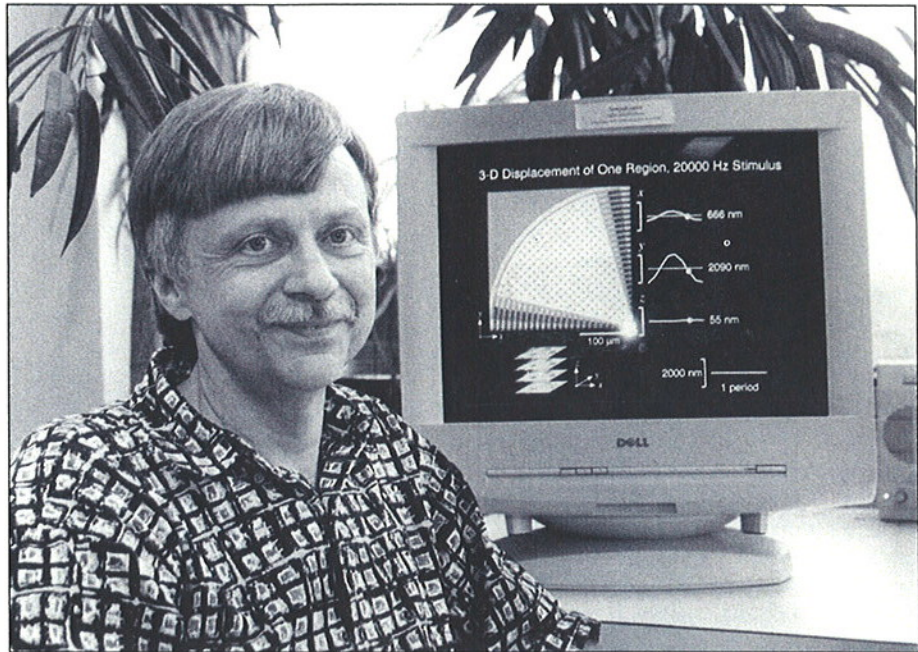
Professor Dennis M. Freeman and his coworkers have developed "dots," a simple, general-purpose motion analysis tool that can be used for a variety of different machines. The user starts the analysis by specifying a particular point on a machine. The analysis tool then extracts a cube of data surrounding that point for each time step in the data set. Professor Freeman demonstrates the dots motion analysis tool in this photograph, with the cube and four planes of a section in pseudo-perspective projection displayed on his computer monitor. In this view, the user can see the motions of all images as the software cycles through each measured point in time. A motion analysis of that region provides estimates of the three-dimensional translations of the corresponding part of the machine. The estimates are shown on the monitor as plots with dots, thus indicating the time corresponding to the image being displayed. (Photo by John F. Cook)

HUMAN DIMENSIONS OF SCIENTIFIC COMPUTATION
Biomedical Imaging

One important challenge to using computers for biomedical imaging is the ability to reconstruct the various biological shapes (organs, bones, or tumors) from the lower-dimensional data gathered by medical instruments such as CAT scans. Using signal-processing techniques, one-dimensional CAT scan images can be transformed into two dimensions. However, reconstructing three-dimensional shapes can be a more formidable task. Another challenge is compressing medical images so that they can be efficiently transmitted and stored, since there is almost no tolerance for information loss in compressed biomedical images.

A novel laser technique called optical coherence tomography (OCT) is being developed by a research team in RLE's Optics and Devices group led by Professor James G. Fujimoto. Originally developed to image the eye's transparent tissues, Professor Fujimoto's group adapted this technique to image the interior of more opaque parts of the body. (See photograph and figure on page 17.)

OCT is somewhat analogous to conventional ultrasound or radar imaging techniques, except it uses light to produce images. In OCT, tomographic imaging is performed by measuring the echo delay of back-reflected light from internal biological microstructures. Thus, it functions as a type of optical biopsy to provide cross-sectional images of tissue microstructure on a micron scale. In contrast to conventional biopsy methods, OCT can image tissue *in situ* and in real time. Current applications include real-time imaging, subcellular imaging, and catheter/endoscopic delivery systems. Professor Fujimoto and his group have collaborated with Research Affiliate Dr. Mark E. Brezinski, a physician in Massachusetts General Hospital's Cardiac Unit

and Harvard Medical School, to develop this new medical imaging technology.

OCT employs a low-coherence light source combined with interferometry to perform high-resolution measurements of the echo time delay of backscattered light. One light beam is directed through a fiber-optic catheter inserted into the patient's body and is reflected off the surface of the target organ. Photons backscattered by the organ's tissue are returned through the catheter and are directed to the interferometer, where they interfere with another beam. This interference supplies information on where the photons were backscattered from inside the tissue. Data converted by computer produces an image with a resolution of up to 20 times better than that of magnetic resonance imaging or ultrasound.

Professor Fujimoto and Dr. Brezinski continue to investigate other potential uses of OCT as a clinical diag-

nostic tool for the cardiovascular, pulmonary, and gastrointestinal systems. In the future, OCT may replace conventional biopsy in cases where traditional methods would be hazardous. The group is also investigating OCT for various medical applications including imaging for vascular disease and early cancer detection, as well as a guide for sensitive surgical procedures. Recently, Professor Fujimoto was nominated as a 1999 *Discover Magazine* Award finalist for technological innovation in medical diagnostics, and Dr. Brezinski (see page 28) was awarded a Presidential Early Career Award for Scientist and Engineers.

Turning Sound into Motion

Professor Dennis M. Freeman and his colleagues in RLE's Auditory Physiology group have developed a computer video system that measures the mechanical properties of inner-ear structures. The sensory receptor cells of the inner ear are typically stimulated by sound-induced motions of microscopic sensory hairs that protrude from the surface of the cell. These sensory hairs and other structures in the inner ear comprise a complex hydromechanical system that contributes to the sensitivity of the ear and performs important signal-processing functions.

Using novel microscopic photodetection methods and high-resolution image-processing techniques developed in his group, Professor Freeman records images using a computer video system. The computer then analyzes the images so the basic three-dimensional inner-ear structures and their submicron motions can be visualized and measured. These methods have shown for the first time how the microscopic hairs in the inner ear move in relation to its other structures and promises a better understanding of the inner ear's mechanical processes.

The group is extending these experimental methods to characterize the motion of synthetic microelectromechanical systems (MEMS), including microfabricated silicon structures that measure acceleration and angular velocity as well as microfabricated mirrors for fiber-optic communications. These systems promise to revolutionize the design of sensors and actuators, in much the same way that microfabrication has revolutionized electronic design.

Several projects in this area involve the development of inexpensive and reliable tools for *in situ* visualization of the motions of internal MEMS structures. Although MEMS are fabricated by batch techniques, which are similar to the techniques used to fabricate microelectronic devices, there are no simple methods to test and characterize the internal failure modes of micromechanical devices. In Professor Freeman's group, images of MEMS are magnified with a light microscope and projected onto a CCD (charge-coupled device) camera. Stroboscopic illumination is used to take temporal sequences of images at multiple planes of focus. Recorded images are then viewed at playback speeds chosen to facilitate human interpretation of the motions. Quantitative estimates of the motions are also obtained directly from the recorded images using algorithms originally designed for robot vision.

A variety of motion analysis tools for MEMS is currently being developed by Professor Freeman's group, including an interferometric video system that combines the subpixel in-plane resolution of computer microvision with the superior out-of-plane resolution of interferometry. This new system, called *interferometric computer microvision,* provides information for full three-dimensional motion estimation. Another general-purpose analysis tool called "dots" was also developed by the group to analyze motions in different systems (see photograph on page 18).

Virtually Tangible

In RLE's "Touch Laboratory," headed by Principal Research Scientist Dr. Mandayam A. Srinivasan, the focus is on *haptics.* This rapidly emerging field is concerned with the scientific as well as the technological aspects of manual exploration and manipulation in the real and virtual worlds. The goals of this research are to increase the basic understanding of human haptics and to apply this knowledge to novel haptic interfaces for enhanced human-machine interaction in virtual reality systems. Haptic interfaces enable users of virtual reality systems to touch, feel, and manipulate computer-generated virtual objects.

To gain a deeper understanding of human haptics, Dr. Srinivasan and his coworkers in the Laboratory for Machine and Human Haptics explore all aspects of interactions between the human hand and objects, including mechanics, sensorimotor functions, and cognition. The group's multidisciplinary investigations involve skin biomechanics, neurophysiology, psychophysics, and motor control. As a part of this research, novel computational procedures are devised to control high-precision robotic stimulators; to process optical, magnetic resonance imaging (MRI), and ultrasound image data; and to carry out finite-element analysis of mechanistic models. Research activities include the measurement of human capabilities in manual tasks that employ computer-controlled electromechanical apparatus, as well as the determination of the biomechanical, neural, and perceptual mechanisms that underlie performance in these tasks.

In particular, investigation of the mechanistic basis of the tactile sense (which enables us to discriminate shapes, textures, and compliance of objects) involves complex computations. Realistic three-dimensional models of human and monkey fingertips have been developed and nonlinear finite-element analysis is performed to probe the mechanics of contact between the fingerpad and objects. Here, supercomputers are employed to gain a better understanding of the spatiotemporal loads imposed on the skin, how they are transmitted through the skin, and which mechanical signals are transduced by each type of spatially distributed mechanoreceptor populations. Models are validated by biomechanical data obtained from robotic stimulators and various imaging methods (including magnetic resonance imaging and ultrasound), and by neurophysiological data recorded from peripheral neural fibers in monkey fingertips stimulated by robotic devices. (See photograph on page 20). This research contributes to applications in hand therapy, intelligent prosthesis design, and the development of autonomous robots that perform human-like functions in unstructured environments.

In order to construct virtual reality systems that enable users to touch and feel virtual objects, Touch Lab researchers design electromechanical devices and develop haptic rendering algorithms. Studies on the human perception of computer-generated virtual objects under purely haptic and multisensory conditions are also performed. This effort has contributed to the emergence of *computer haptics,* a new area of research analogous to computer graphics. Computer haptics addresses
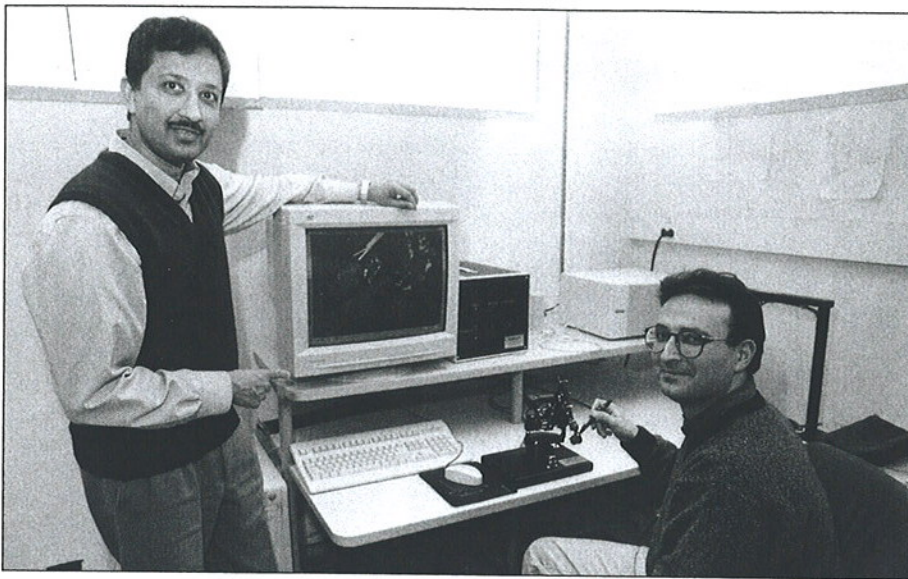
In RLE's Laboratory for Human and Machine Haptics (known as the "Touch Lab"), Principal Research Scientist Dr. Mandayam Srinivasan (left) discusses the computer display of a virtual human liver with Research Scientist Dr. Cagatay Basdogan, who is manipulating virtual objects in the display using the PHANToM haptic interface device. Their research in multimodal virtual reality is contributing to the development of a surgical simulator for minimally invasive procedures in collaboration with Massachusetts General Hospital and Harvard Medical School. (Photo by Donna Coveney)
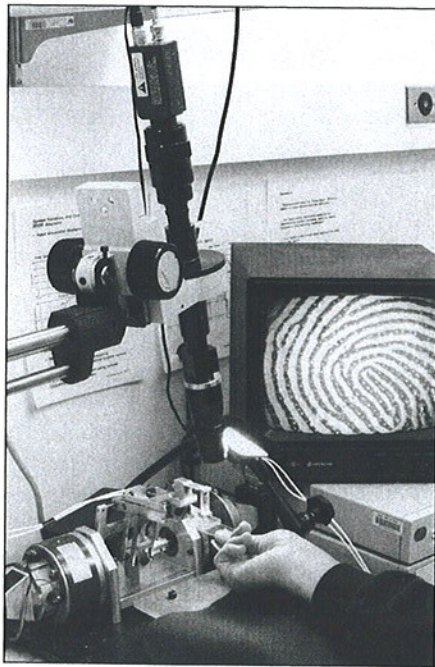
Left: As part of experiments conducted in RLE's Touch Lab to investigate the biomechanics of touch, a high-precision robot with a force sensor applies computer-controlled mechanical stimuli to the human fingerpad. At the same time, a video microscopy system records the real-time deformations of the fingerpad. This experimental set-up is used by Principal Research Scientist Dr. Mandayam A. Srinivasan and his group to determine the mechanical impedance and frictional characteristics of the fingerpad, as well as to investigate the mechanisms underlying the detection of slip and the discrimination of softness. (Photo courtesy Mandayam A. Srinivasan)
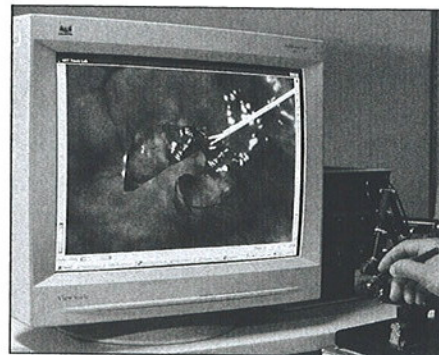
Right: Researchers at RLE's Touch Laboratory are developing a virtual reality training system for minimally invasive surgical procedures. The system can display three-dimensional texture-mapped anatomical models of internal organs and can perform real-time computations that approximate their dynamic behavior. The surgical trainee can see the tissue deformations on a monitor and feel interaction forces through a force-reflecting device while manipulating the soft tissues. (Photo courtesy Mandayam A. Srinivasan)

the real-time generation and rendering of virtual haptic objects. It involves several computational issues such as large database management, efficient collision detection, the rapid computation of mechanistic models, and real-time synchronization of haptics with graphics and sound.

The status of haptic interactions is generally limited to manually exploring and manipulating virtual objects with a rigid tool. In collaboration with researchers at Carnegie-Mellon University, the Touch Lab is attempting to enable users to feel direct contact between the skin and virtual objects by using tactile actuator arrays. These arrays consist of millimeter-sized stimulators that are fabricated with microelectromechanical (MEMS) techniques. Eventually, multimodal virtual-reality systems, composed of visual, haptic, and sound displays are expected to play a significant role in a variety of human activities such as education, training, and entertainment.

In collaboration with Massachusetts General Hospital and Harvard Medical School, researchers in the Touch Lab are developing a surgical simulator for minimally invasive procedures. This project, which is an application of the Touch Lab's research in multimodal virtual reality, is led by Research Scientist Dr. Cagatay Basdogan and involves the creation of force-reflecting tissue models for the real-time simulation of laparoscopic procedures. During a typical laparoscopic procedure, such as gall bladder removal, the surgeon makes several small incisions. With surgical tools inserted into the incisions, the surgeon manipulates the tissues under visual guidance provided by a monitor connected to a miniature camera inside the patient.

In a simulation system currently under development in the Touch Lab, texture-mapped three-dimensional models of internal organs and tissues can be viewed on a computer monitor. The models display viscoelastic behavior of soft tissues in real-time and provide the user with haptic feedback through a force-reflecting device as tissues are manipulated with simulated surgical instruments. Computationally fast collision-detection algorithms and models of laparoscopic instruments have been developed to simulate tissue-instrument interactions, such as the palpating and grasping of soft tissues. Several novel algorithms created for this project are

now being patented. Work is continuing on the simulation software to devise cutting tools and computer models for bleeding. Ongoing work also seeks to obtain *in vivo* data on the mechanical behavior of organs and tissues using instrumented robotic devices, as well as the development of more physically realistic tissue models.

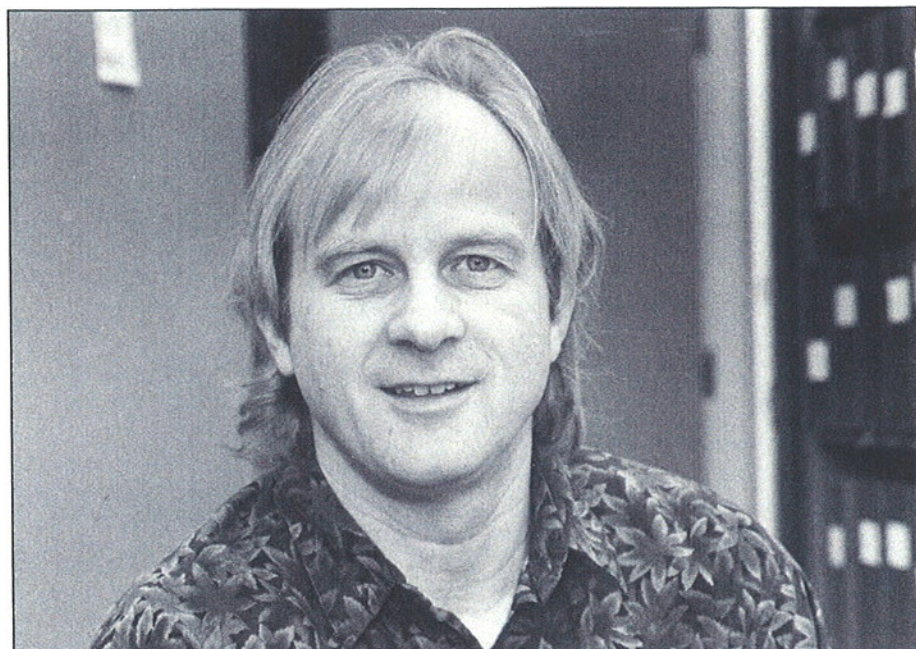## COMPUTER MODELS OF THE HUMAN VOCAL TRACT

In RLE's Speech Communication group, Research Scientist Dr. Reiner Wilhelms-Tricarico has worked on various aspects of vocal tract physics, using mostly computational methods of physics and engineering. His work has included automatic estimation of articulatory parameters from the speech signal, estimation of spectral parameters of speech signals, quasi-articulatory speech synthesis, automatic data flow programming, and physiological models of the glottis. In recent investigations into vocal-tract dynamics and structure, Dr. Wilhelms-Tricarico is developing software to generate accurate finite-element models of the tongue and mouth floor. One software program, developed to visualize data and to carry out measurements, can interactively generate cross-sectional views of a three-dimensional image. This software enables users to generate and edit small rectangles that represent sections through the data. Users can define and label points, cubic splines, and surfaces in order to segment morphological structures geometrically. It is anticipated that the software will also be useful in generating finite-element models of other organs.

ENABLING NEW TECHNOLOGIES

Several projects in RLE seek to develop novel computer techniques and tools for emerging technologies such as semiconductor lasers, microelectromechanical systems (MEMS), and energy-efficient computation.

DISTRIBUTED DESIGN AND FABRICATION FOR ADVANCED MICROSYSTEMS

The design and fabrication of state-of-the-art semiconductor devices and integrated circuits require a diverse and expensive set of resources, including manufacturing equipment and computational tools. Research for advanced semi-

Research Scientist Dr. Reiner Wilhelms-Tricarico has worked on various aspects of vocal tract physics, using mostly computational methods of physics and engineering. In recent investigations, he has developed software to generate accurate finite-element models of the tongue and mouth floor. This software may also be useful in generating models of other organs. (Photo by John F. Cook)
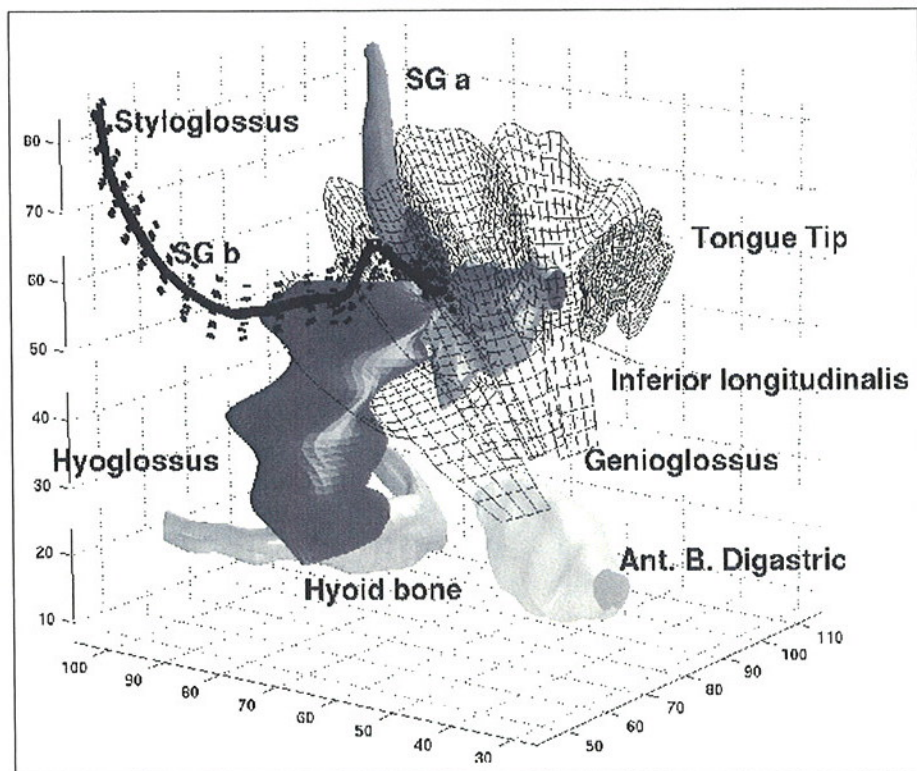

Some of the oral structures of the vocal tract extracted from the male specimen of the National Library of Medicine's Visible Human Project and composed into a demonstration using software developed by Research Scientist Dr. Reiner Wilhelms-Tricarico in RLE's Speech Communication group. The computer image shows the fiber directions of the styloglossus muscle, the matching of a grid template to the tongue body, the hyoid bone, and one side of the hyoglossus and digastric muscles represented as surfaces.

conductors can be even more demanding, and frequently requires special equipment and processing capabilities.

Professor Donald Troxel's group in RLE is developing a flexible, distributed system architecture capable of providing collaborative design, fabrication, and analysis of semiconductor devices and integrated circuits. Distributed fabrication promotes direct, remote, and physical experimentation for leading-edge technology, where manufacturing resources can be costly and scarce. In these cases, the computational resources, software, processing equipment, and people may all be widely distributed. However, their efficient integration is essential to realize new technologies for specific product requirements.

The distributed system architecture developed in Professor Troxel's group defines software interfaces and infrastructure by using existing and emerging standards for network design, computer-integrated manufacturing, and computer-aided design. Using this architecture, process engineers and product designers can access processing and simulation results through a common interface and can collaborate across the distributed manufacturing environment. Professor Troxel and his group are seeking to apply this architecture to collaborative microfabrication research, distributed process control and diagnosis, and the remote inspection and analysis of microelectromechanical system (MEMS) devices.

In one project, Professor Troxel and his colleagues are developing an application where clients (users) can remotely operate a MEMS station from any computer or operating system anywhere on the Internet. The system architecture is based on messaging, Java programming, web browsers and web servers, C programs that control the hardware, and the retrieval of data that has already been captured or computed. A set of messages was defined that provides the form of communication between the clients and the server. These can be modified, and one is capable of returning a complete set of messages supported by the particular server. Clients communicate with the server using their own web browser, which communicates messages by the HyperText Transfer Protocol (HTTP) post-protocol to and from the web server running on the server machine. The server machine is the source of the Java code, which is downloaded to the user by HTTP. The
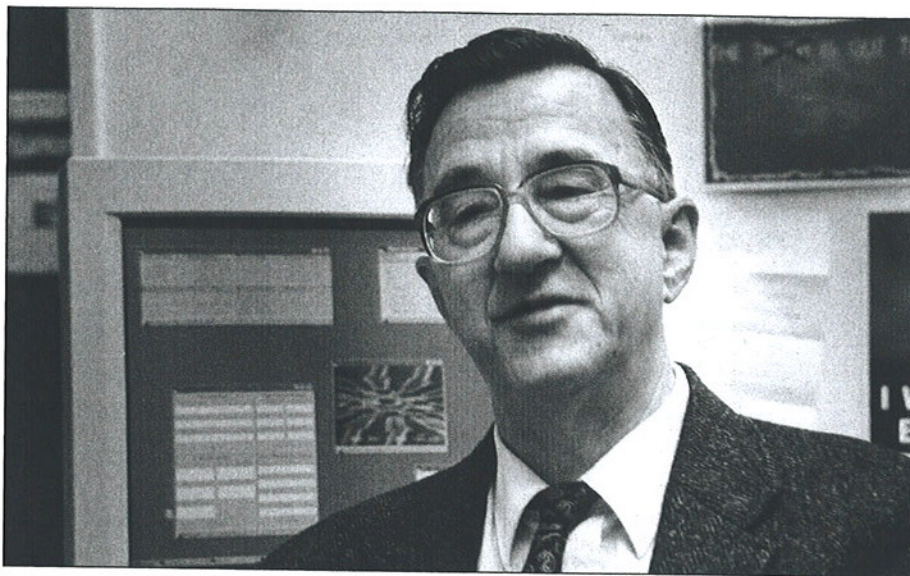
Professor Donald E. Troxel demonstrates one of several selectable MEMS station user interfaces being developed in his group that can be operated remotely from any computer or operating system anywhere on the Internet. The system architecture is based on messaging, Java programming, web browsers and web servers, C programs that control the hardware, and the retrieval of data that has already been captured or computed. (Photo by John F. Cook)
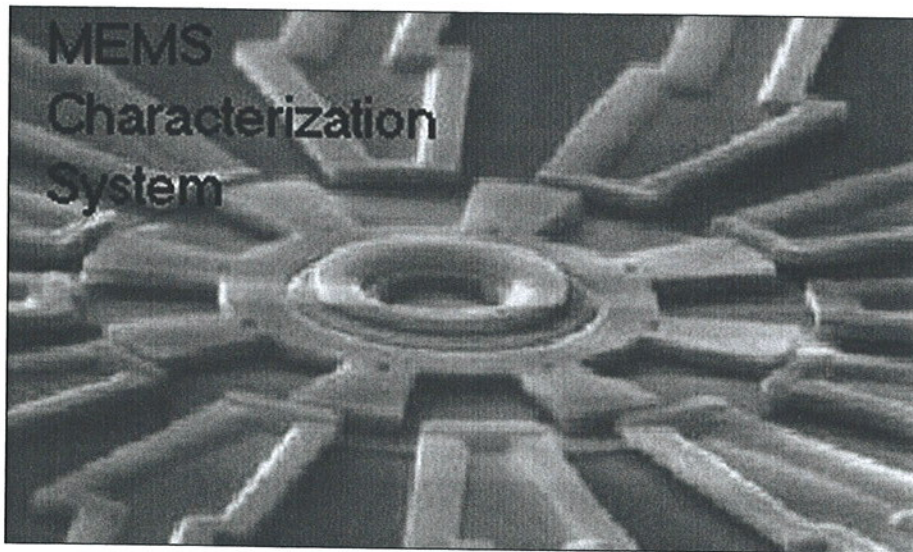
Microelectromechanical systems (MEMS) are integrated microdevices or systems that combine electrical and mechanical components. Fabricated by integrated-circuit batch-processing techniques, MEMS devices can be designed for special purposes so that their mechanical actions are controlled by computer. They range in size from micrometers to millimeters. On a microscale, MEMS can sense, control, and actuate. On a macroscale, they can function individually or in arrays to generate certain effects. Applications for this enabling technology include a wide range of process and control devices such as accelerometers, chemical and flow sensors, optical scanners, and fluid pumps. The performance of MEMS micromotors, such as the one shown in this illustration, can be analyzed using the remote MEMS station user interfaces under development in Professor Donald E. Troxel's group.

server also maintains a list of clients who are logged on to a particular session in a way that is not known to other clients. For example, clients cannot send messages directly to each other, only through the server. The serv-

er implements client session control by a Java servlet. Some of the server's actions are provided by C programs, which are called up from Java by the Java native interface.

MODELING AND SIMULATION FOR SEMICONDUCTOR LASERS

As high-performance semiconductor lasers become increasingly complex, the many physical processes involved in their design require more scrutiny. Unlike passive semiconductor optical devices, semiconductor lasers exhibit a variety of physics that range from the microscopic to the macroscopic level. In order to design semiconductor lasers at the microscopic level, one needs to know the band structure of strained quantum wells, the radiative and Auger recombination rates, carrier leakage rates, and nonequilibrium carrier dynamics. At the macroscopic level, one
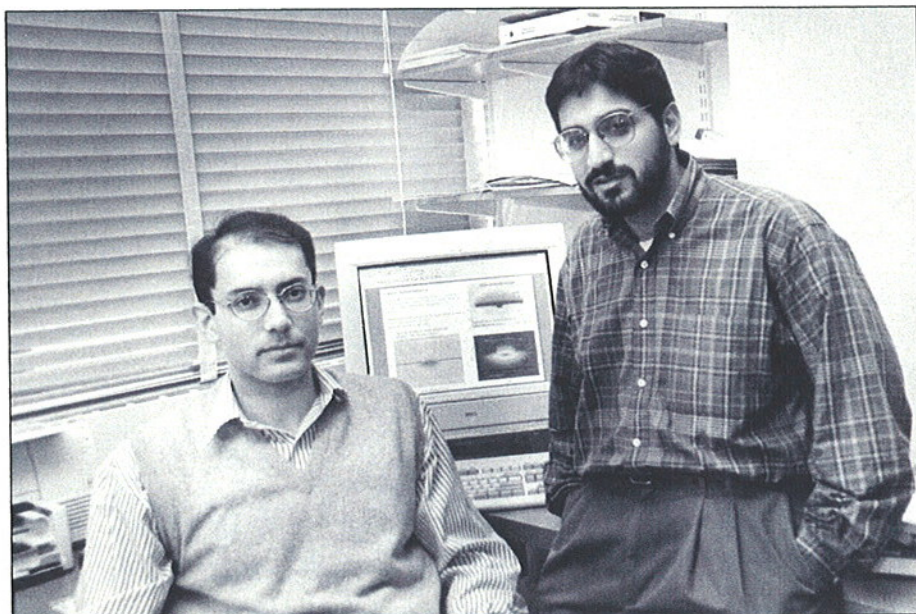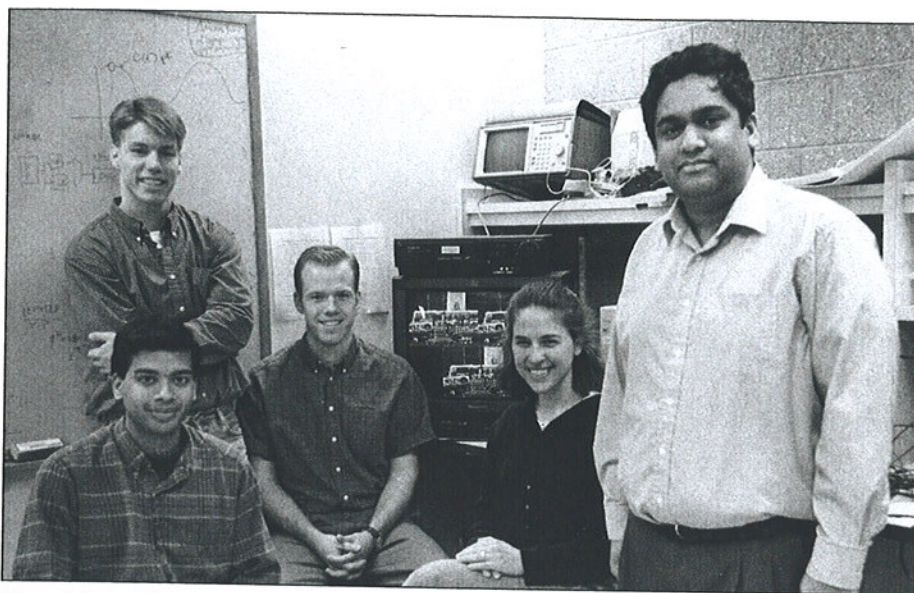

Research Assistant Farhan Rana (left) and Professor Rajeev J. Ram review the set of innovative software tools developed in their group to model and simulate lasers. These tools, shown below, include a laser temperature simulator (top left), a semivectorial mode solver for edge-emitting lasers (bottom left), a finite-difference time-difference (FDTD) simulator for vertical-cavity surface-emitting lasers or VCSELs (below right). (Photo by John F. Cook)
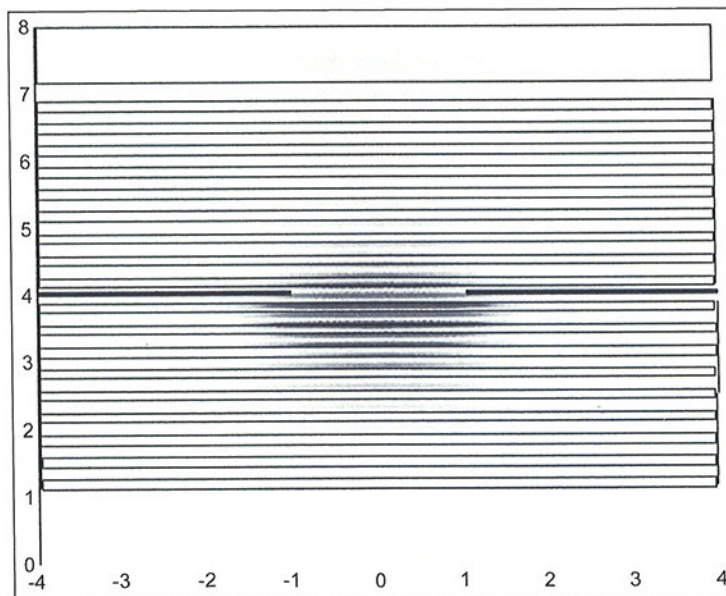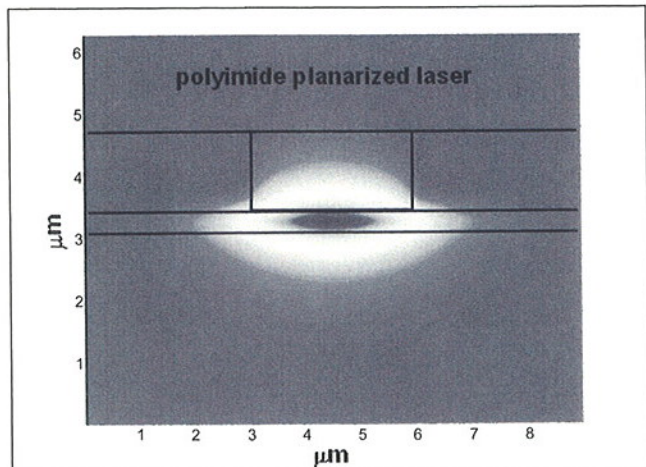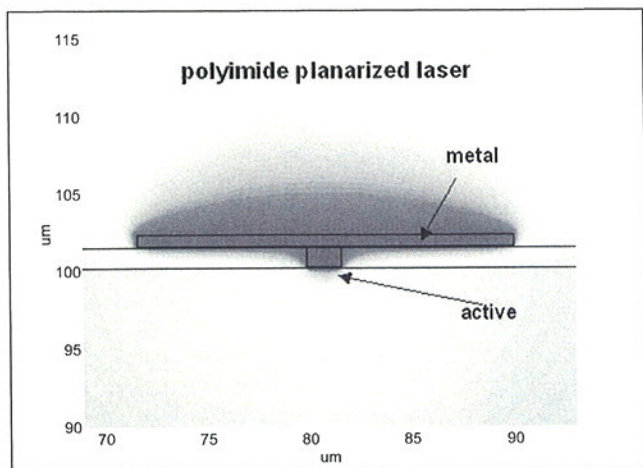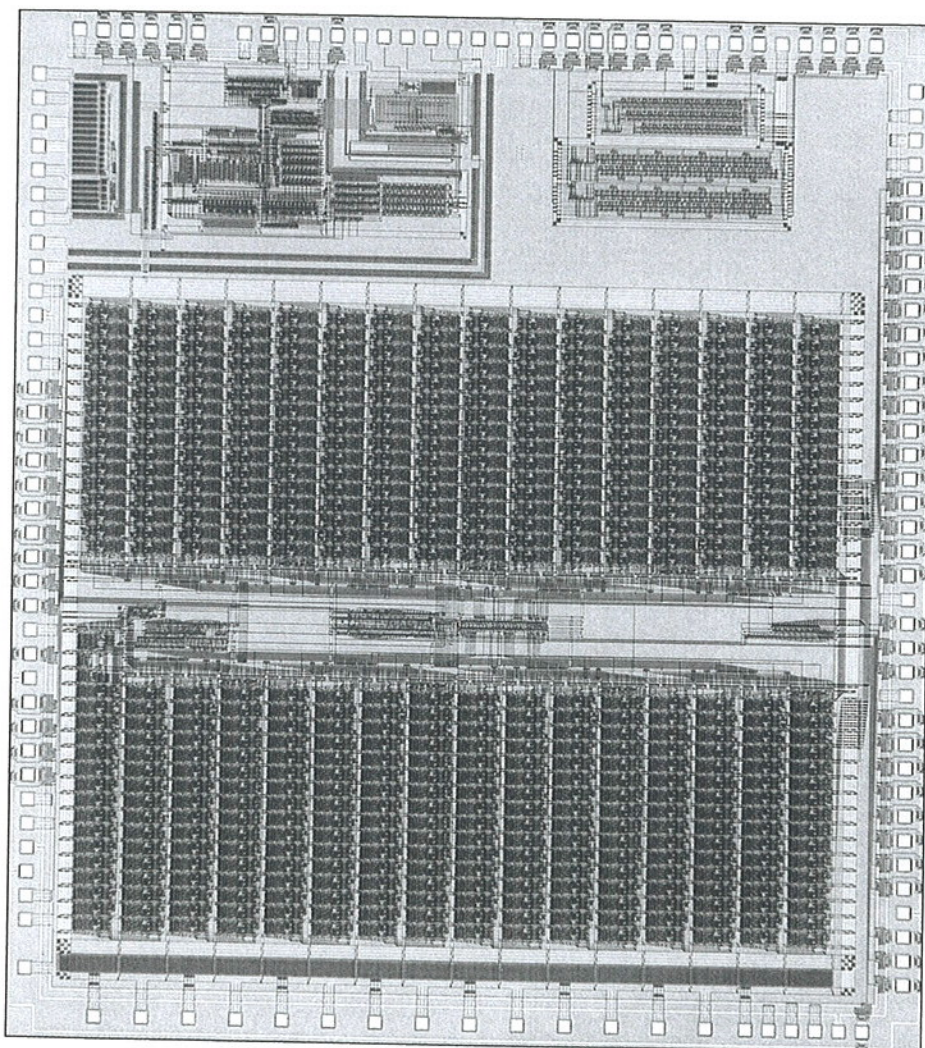

Left: The temperature distribution inside a polyimide planerized laser operating slightly above threshold that was calculated using a laser temperature solver developed in Professor Rajeev J. Ram's group in RLE. The temperature distribution obtained from this program can be used to calculate temperature-dependent laser parameters self-consistently, such as laser gain and differential gain (top left). The program can also be used with optical mode solvers to model the thermal lensing of the laser mode (bottom left).

Above: The first-order mode of an oxide-apertured vertical-cavity surface-emitting laser (VCSEL) calculated using a program developed in Professor Ram's group.

From left: Graduate student James R. Goodman (standing), Research Assistants Rajeevan Amirtharajah, Scott E. Meninger, and Wendi B. Rabiner, and Professor Anantha P. Chandrakasan meet to evaluate the results of various computational partitioning schemes used to transmit video over a wireless network. (Photo by John F. Cook)

needs to model the optical modes of the laser cavity, spatial hole burning, optical losses, the temperature distribution inside the laser, and thermal lensing. In the case of high-modulation bandwidth semiconductor lasers, careful attention must also be paid to electrical parasitics and electrical signal propagation at microwave frequencies.

Problems arise because today's analytical tools used to describe laser physics have limited scope and accuracy. Efficient and powerful computer simulation tools are needed to design these novel high-performance lasers. Professor Rajeev J. Ram and his students in RLE's Optics and Devices group have developed a suite of new modeling tools to address these problems. Several of these models have been implemented as vectorized algorithms and are executed on a Cray T90 supercomputer at the University of San Diego Supercomputer Center.

Using an eight-band $k \cdot p$ theory approach, Professor Ram's group has implemented an efficient finite-difference scheme to solve the band structure of strained quantum wells. The band structures and electron hole wave functions generated by this program are used to calculate various physical processes including laser differential gains, radiative and nonradiative carrier recombination rates, the carrier-dependent refractive index, and laser linewidth.

Using another finite-difference scheme, Professor Ram and his colleagues have implemented a laser temperature solver to address the heat-generation problem that most lasers experience when operating at long wavelengths. Problems associated with heat generation in lasers include an increase in nonradiative recombination rates, a decrease in laser gain and differential gain, thermal lensing, and an increase in

A die photograph of an energy-scalable encryption processor chip for performance feedback systems, which was designed in Professor Anantha P. Chandrakasan's group. The chip features a security-scalable encryption engine and an embedded, high-efficiency variable output dc-dc converter. The embedded converter exploits variations in throughput and quality in order to minimize the average energy consumption.

material degradation rates. Thus, it is important to design lasers that remain well within the thermal budget and to efficiently remove the heat that is generated inside a laser's active region.

Vertical-cavity surface-emitting lasers (VCSELs) were developed in the late 1980s and early 1990s for applications such as optical interconnections and optical information processing. These lasers have low-beam divergence and a circular beam. Individual VCSELs typically exhibit an output power near one milliwatt, while two-dimensional arrays with one-watt output power have been demonstrated. Optical modes in VCSELs can be difficult to compute analytically and numerically. Currently, no method can provide an accurate mode description of these lasers, which is needed in order to determine optical losses and laser threshold. Most methods based on beam propagation are inadequate because of the strong scattering from the laser's dielectric apertures and distributed Bragg reflector mirrors.

To overcome this problem, Professor Ram's group has used a finite-difference time-domain scheme (FDTD) to compute the optical modes in oxide-apertured VCSELs. Their scheme, which employs perfectly matched layer (PML) boundary conditions, is based on a novel scalar formulation of electrodynamics in a quasi-three-dimensional geometry. The scalar formulation with PML boundary conditions results in a saving of computer time and memory by a factor of three when compared to a full vector implementation. The scalar model used breaks down the second-order scalar Helmholtz equation into two first-order equations that can be stepped in time.

ENERGY-EFFICIENT COMPUTATION

Professor Anantha P. Chandrakasan and his colleagues in RLE's Circuits and Systems group focus on the energy-efficient implementation of integrated cir-

cuits and systems. Three current projects involve performance feedback systems, self-powered computation, and optimum computation partitioning in wireless networks.

Performance Feedback Systems. In current digital systems, the power supply voltage is static (or fixed) and chosen to meet a specific timing constraint under worst-case conditions. That is, the feedback around the power converter is established to fix the output voltage. Professor Chandrakasan's group has demonstrated that it is more energy efficient to allow the voltage to vary, such that the timing constraints can be met at any given temperature and operating condition. This is done by establishing the feedback around a fixed processing rate or delay. Many applications can exploit this technique, ranging from traditional signal-processing applications (such as MPEG compression and adaptive filtering) to general-purpose computation.

Professor Chandrakasan and his colleagues have built several integrated circuits and systems to validate this idea. Of particular interest is a 512-bit encryption processor that has an embedded dc-dc converter circuit (see figure on page 24). The dc-dc converter allows the supply voltage to be dynamically varied, based on computational demand. Professor Chandrakasan and his group have also developed techniques to construct algorithms and architectures that have a variable workload. For example, they have fabricated chips where the bitwidth of computation and the number of operations performed per sample varies dynamically.

Self-Powered Computation. With continued advances in power management techniques, the power consumption of future low- to medium-throughput digital-signal processors is projected to consume on the order of tens to hundreds of microwatts. At these low power lev-

With continued advances in power management techniques, the power consumption of future low- to medium-throughput digital-signal processors is projected to consume on the order of tens to hundreds of microwatts. At these low power levels, an interesting question arises: can ambient energy sources be used to power electronic systems?

els, an interesting question arises: can ambient energy sources be used to power electronic systems? Ambient energy is in the environment of a system and is not stored explicitly, for example, in a battery. A circuit powered by ambient sources has a potentially infinite lifetime, as long as the source persists. In long-lived sensor-embedded systems, where battery replacement is difficult, generating power from ambient sources is imperative.

Professor Chandrakasan's group has built a first-generation prototype (based on a moving coil generator) and an integrated circuit that performs control for the transduction of mechanical vibration to electrical energy. The self-powered operation of a low-power subband filter has been demonstrated. The group recently developed a power electronics control processor for a microelectro-mechanical system (MEMS) generator that consists of a proof mass, its suspension, and a variable capacitor. The ultimate vision of autonomous sensor systems is to integrate the generator on the same substrate as the load circuit and to eliminate the need for batteries.

Computation Partitioning in Wireless Networks. Energy dissipation can be dramatically reduced by optimization at the algorithm and system levels. In many wireless sensor systems, it is possible to reduce power dissipation of the battery-operated device by off-loading computation to remote base-station servers that do not have energy constraints. For example, consider an image sensor that performs data compression before transmission to a high-powered base station. Most video-compression algorithms use some form of block-based scene motion estimation/compensation to remove the temporal correlation inherent in natural video sequences. Unfortunately, these algorithms tend to be computationally intensive and result in significant battery drain on the sensor node. An important observation, which can save significant power in the image sensor node, is that the motion of objects is continuous from one frame to the next in natural sequences. Thus, by knowing the location of an object in a few previous frames, it is possible to predict its location in the current frame. Therefore, it is possible to remove the motion estimation computation from the portable encoder and perform it at the receiving base station. This reduces power in the portable encoder by several orders of magnitude.

Leaving a Mark without a Trace

Many authors, photographers, musicians, and artists who publish their work on the Internet are often exploited by pirates who illegally duplicate audio and graphic files without permission. In this online environment, where information flows freely, copyright infringement and distribution control become challenging problems for copyright owners and web managers.

New signal-processing software technology is now available to fight the unlicensed use of copyrighted materials on the Internet. *Digital watermarking,* which has its foundations in the science of steganography and cryptography, involves the embedding of information in the form of a digital "fingerprint" into video, audio, and graphic files. Thus, in some respects, digital watermarks are conceptually similar to the traditional watermarks used to authenticate stationery and currency. Typical digital watermarks, however, consist of a string of bits (0s and 1s) that must be imperceptible to the human eye or ear. Their detection is accomplished by using appropriately designed signal processing software.

A digital watermarking system consists of an information embedding algorithm and an associated information-extraction algorithm. From the system designer's viewpoint, the goal is to embed a watermark that is as unique as possible, to embed it as imperceptibly as possible, and in a manner that is as robust as possible. Robustness ensures that the watermark will survive tampering, distortions (such as noise, compression, and geometric distortion), and other degradations encountered when the material is transferred from one medium to another. However, since these objectives conflict, the quality of a digital watermarking system is ultimately measured by how efficiently it can achieve the performance trade-offs posed by the different objectives.

Various companies are attempting to commercialize first-generation digital watermarking systems. In addition, standards committees in several application areas are working to identify the best candidate systems for standardization. An example of such a system is one in which the copyright information is contained in the visually or aurally least significant bits of the host file. These are called *low-bit modulation systems.* In another example, often called a *spread-spectrum embedding system,* the digital watermark consists of a small pseudonoise signal added to the image or audio waveform.

In a fundamentally new approach, Professor Gregory W. Wornell and graduate students Brian Chen and Emin Martinian in RLE's Digital Signal Processing group are developing a powerful second-generation digital watermarking technology called *quantization index modulation* (QIM). One efficient imple-

The image of the F-16 on the left contains a 512-bit digital watermark that was embedded imperceptibly using the quantization index modulation and dither modulation technologies recently developed by RLE's Digital Signal Processing group. On the right is a noise-corrupted version of the same watermarked image, from which all 512 bits were extracted without error.

mentation of QIM is realized by using what is called *dither modulation*. Here, embedded information modulates a dither signal and the host signal is quantized with an associated dithered quantizer. QIM and dither modulation systems have considerable performance advantages over previously proposed spread-spectrum and low-bit modulation systems. Moreover, existing first-generation systems can be easily upgraded to take advantage of the dramatic performance enhancements made possible by this technology.

Digital watermarks are also exploited in an increasing array of commercial products. For example, they are being integrated into the design of secure digital videodisk (DVD) players. These players prevent the unauthorized viewing and dupli-

RLE (LAB) SCOPE

cation of movies distributed in DVD format without paying the required fees. However, applications for digital watermarking technology extend well beyond the realm of copyright notification and enforcement. For example, it can also be used for hidden annotation and indexing. In the case of a photograph, information about the image, such as the photographer, the f-stop and shutter speed used, camera type, and time of exposure can be embedded.

Other applications of digital watermarks include photo ID authentication, in which the embedded digital watermark is the mechanism by which forgeries and tampering are detected, and digital audio broadcasts (DAB). The latter is a newer application of digital watermarking that has been proposed by RLE's Digital Signal Processing group. In this context, digital watermarking provides the means to upgrade an existing analog format to a higher fidelity digital format in a backward-compatible manner and within existing spectrum allocations. In this case, the embedded digital watermark consists of bits that newer digital receivers can use, in conjunction with the analog signal, to reconstruct the audio signal in a higher fidelity. At the same time, since the watermark is imperceptible, older receivers can still successfully decode the existing lower fidelity analog signal.
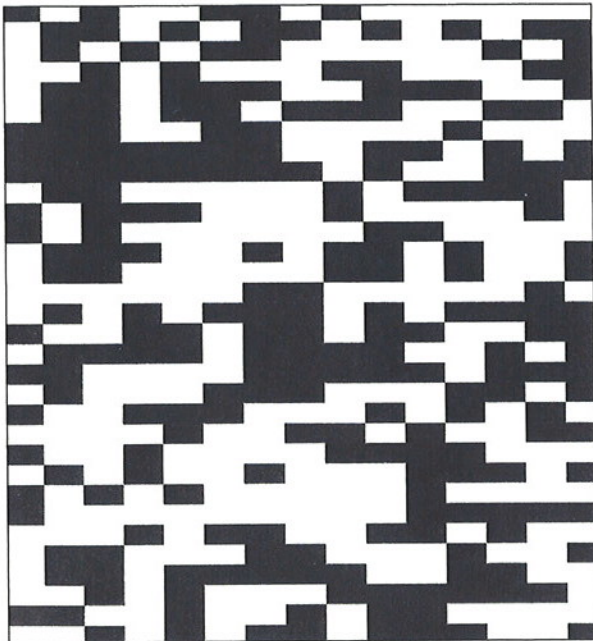

A symbolic representation of the imperceptible digital watermark that is embedded in the image of the F-16 aircraft on page 26. This representation shows the location of each of the 512 bits that comprise the digital watermark. Black represents the 0 bits and white represents the 1 bits.

the wire segment is valid. Each metal plate is subdivided into several surface patches that must be small when compared to the wavelength; again, so the assumption of constant current is valid. Once the model is defined, a source is imposed (such as an approaching plane wave or a voltage source on a wire segment). The MoM technique then determines the current on every wire segment and patch due to the source and all other currents, or the other wire segments and surface patches. Once these currents are known, then the electric field at any point in space can be determined from the combined contribution of all the wire segments and surface patches. Although MoM is easy to use for wires and metal plates, it is difficult to use for dielectric and special magnetic materials.

Transmission line modeling (TLM) is a general numerical technique suitable for solving field problems. Its main application is in electromagnetics, but it can also be applied to thermal or diffusion problems as well as acoustics. Its basic approach is to obtain a discrete model, which is then solved exactly by numerical means. Approximations are introduced at the discretization stage, in contrast to the traditional approach in which an idealized continuous model is obtained and then solved approximately. For electromagnetic systems, the discrete model is formed by conceptually filling space with a network of transmission lines in such a way that the voltage and current give information on the electric and magnetic fields. The point at which the transmission lines intersect is called a *node*. The most commonly used node for three-dimensional models is the symmetrical condensed node. At each time step, voltage pulses are incident upon the node from each transmission line. These pulses are scattered to produce a new set of pulses that become incident on adjacent nodes at the next time step. The relationship between the incident pulses and the scattered pulses is determined by a *scattering matrix*, which is set to be consistent with Maxwell's equations. Additional elements, such as transmission-line stubs, can be added to the node so that different material properties can be represented.
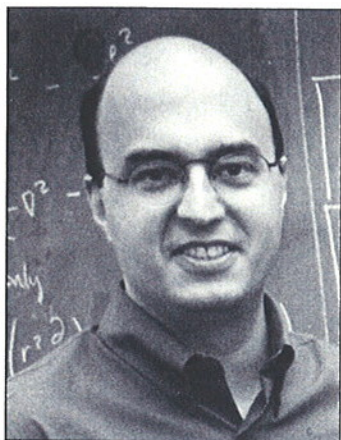
Dr. Tomás A. Arias (SB '86, PhD '92), assistant professor of physics, was promoted to associate professor without tenure in the department, effective July 1, 1999. Professor Arias is a principal investigator in RLE's Surfaces and Interfaces group, where his research is focused on several projects in the field of condensed-matter theory, including *ab initio* calculations and massively parallel computation (see page 10). Professor Arias uses *ab initio* methods to develop connections between the quantum-mechanical description of materials and their behavior. In this research, he seeks to exploit theoretical techniques and supercomputer architectures in order to perform large-scale quantum calculations. He also develops new theoretical techniques to link *ab initio* calculations of complex solid and liquid systems with phenomena on larger scales. Professor Arias joined the MIT faculty in 1993, after receiving his academic degrees in the Department of Physics and serving as a postdoctoral associate in RLE. His recent honors and awards include an Alfred P. Sloan Foundation Research Fellowship (1995), the Department of Energy Defense Programs Young Scientist award (1996), and the MIT School of Science Undergraduate Teaching Prize (1997). *(Photo by John F. Cook)*
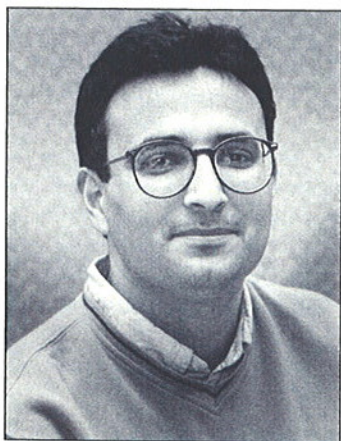
Dr. Cagatay Basdogan was appointed as research scientist in RLE's Sensory Communication group, effective November 1, 1998. Since 1996, Dr. Basdogan has been a visiting scientist in the group's Laboratory for Human and Machine Haptics and a research fellow at the Massachusetts General Hospital. His background in biomechanics, the modeling of biological systems, and computer graphics for virtual reality systems has contributed to the development of novel techniques for graphic and haptic displays. One technique, developed in RLE, enables the user to touch and feel the shape, texture, and compliance of three-dimensional objects in virtual environments. Another project involves collaboration between RLE and MGH to develop a virtual-reality-based surgical simulator that surgical trainees can use to touch, feel, and see computer models of biological tissues and organs (see page 19). Dr. Basdogan is a member of the American Society of Mechanical Engineers and

holds degrees in mechanical engineering from Middle East Technical University (BS '88, MS '91) in Ankara, Turkey, and Southern Methodist University (PhD '94). *(Photo by John F. Cook)*

From left: Congressman Paul E. Kanjorski (D-PA) of Dr. Brezinski's hometown district, PECASE award recipient Dr. Mark E. Brezinski, and Assistant to the President for Science and Technology Dr. Neal F. Lane at February's White House awards ceremony. (Photo courtesy of U.S. Department of Defense)

Dr. Mark E. Brezinski, a research affiliate in RLE's Optics and Devices group, was named a recipient of a Presidential Early Career Award for Scientists and Engineers (PECASE). The award was presented to sixty young researchers at a White House ceremony on February 10, 1999. It is the highest honor given by the U.S. government to outstanding scientists and engineers who are beginning independent research careers. Dr. Brezinski, an assistant professor at Harvard Medical School and a cardiologist at Massachusetts General Hospital, was cited for his involvement in creating a new imaging technology called *optical coherence tomography* (OCT). The technique was originally developed to image the transparent tissues of the eye. However, Dr. Brezinski, in collaboration with Professor James G. Fujimoto's research group in RLE, adapted OCT to image nontransparent biological tissues such as joints (see page 18). The non-invasive technique

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SHORT CIRCUITS
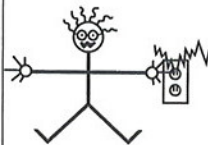
The staff of **RLE currents** would like to note the following corrections:

The Web page cited in the caption for the visualization learning pipeline on page 3 of the fall 1998 issue was incorrect. The correct URL is http://enpc1644.eas.asu.edu. Thanks to Laurie Luckenbill at Arizona State University for the correct information.

The "RLE Connections" photo caption describing Professor Alan V. Oppenheim's research group on page 12 of the spring 1998 issue mistakenly identified Research Assistant Huan Yao as graduate student Lee Li. Thanks to Professor Oppenheim for checking the error.

The name of physicist Albert A. Michelson was incorrectly printed as Alan Michelson in the "Tools of the Trade" article on page 4 of the spring 1997 issue. Thanks to Christopher A. Fuchs at the California Institute of Technology for the correction.

uses infrared laser light and fiberoptic technology to produce a high-resolution optical biopsy. Studies are underway to extend OCT's capabilities to detect early joint disease.
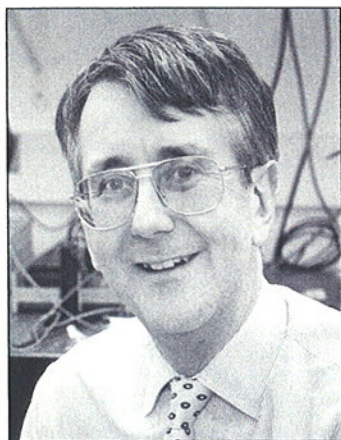
Dr. Charles H. Cox, III (ScD '79) was appointed as research scientist in RLE's Optics and Devices group, effective February 8, 1999. Dr. Cox has been a research affiliate with RLE since 1997 and has collaborated on optoelectronics research focused on radio-frequency signal transmission. Most recently, he was a senior staff member at MIT Lincoln Laboratory, where he headed a group investigating the potential system applications of photonics. Dr. Cox had served on the Lincoln Laboratory staff since 1979 and conducted research in microwave photonics with several research groups there. At his new position in RLE, Dr. Cox will work with the semiconductor laser group on the design of high-fidelity optical links. A graduate of the University of Pennsylvania (SBEE '70, SMEE '72), Dr. Cox is a member of the Institute of Electrical and Electronics Engineers. *(Photo by John F. Cook)*

Dr. Leslie A. Kolodziejski, the Esther and Harold E. Edgerton Career Development Associate Professor, was promoted to the rank of full professor in the Department of Electrical Engineering and Computer Science, effective July 1, 1999. Since joining the MIT faculty in 1988, Professor Kolodziejski has established an important facility for the epitaxial growth of II-VI and III-V semiconductor materials. Her research in RLE's Materials and Fabrication group involves the use of compound semiconductors to fabricate various optoelectronic devices such as optical emitters and filters, photonic microcavities, and optical detectors. As part of a collaborative effort in RLE on photonic bandgap microcavities, Dr. Kolodziejski's group has helped to fabricate the first photonic bandgap air-bridge resonator that operates at the 1.55-micron wavelength. A graduate of Purdue University (BS '83, MS '84, PhD '86), Dr. Kolodziejski is a member of the American Physical Society, the Materials Research Society, the Optical Society of America, and the Institute of Electrical and Electronics Engineers. *(Photo by John F. Cook)*

Dr. David E. Pritchard, professor of physics, was elected to the National Academy of Sciences in May 1999. Professor Pritchard, a principal investigator in RLE's Atomic, Molecular, and Optical Physics group, was recognized for his distinguished and continuing achievements in original research. Membership in the NAS is considered one of the highest honors accorded a scientist or engineer in the United States. In RLE, Professor Pritchard pursues experiments in ultrahigh-precision mass spectroscopy of single trapped ions, traps for neutral atoms using light and magnetic forces, and atom interferometry. His research group explores the fundamental properties of atoms and their interactions, using supercooled atoms to carry out ultrahigh-precision measurements of mass, time, and rotation. In seeking to provide advances in fundamental measurement accuracies, individual atoms are isolated by interacting lasers at low temperatures. These techniques promise to improve atomic clock accuracy by several orders of magnitude. A graduate of the California Institute of Technology (BS '62) and Harvard University (PhD '68), Professor Pritchard is a fellow of the American Physical Society and a member of the American Association for the Advancement of Science and the Optical Society of America. *(Photo by John F. Cook)*
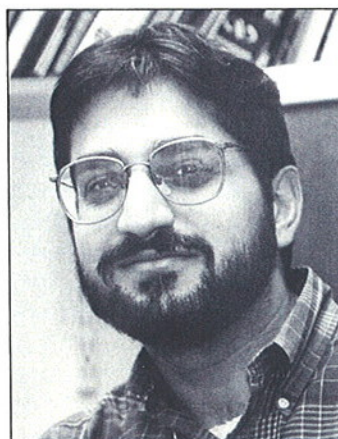
Dr. Rajeev J. Ram, assistant professor of electrical engineering and computer science, was selected to receive a 1999 Office of Naval Research Young Investigator Program Award. The ONR Young Investigator Program recognizes young scientists and engineers who show exceptional promise for outstanding research and teaching careers. These awards are given based on prior professional achievement, the submission of a creative proposal, and evidence of strong support by the investigators' respective universities. Since joining RLE's Optics and Devices group in 1997, Professor Ram has conducted a wide range of theoretical and experimental research, including the development of high-speed semiconductor lasers and studies of the dynamics of microcavity polaritons (see page 23). His ONR award will be used to investigate highly efficient cascade interband laser receivers, which have the potential to cost less and perform better than other arrays used for communications. *(Photo by John F. Cook)*

IN MEMORIAM
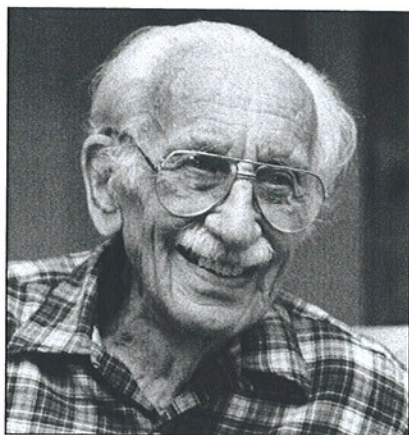
Dr. William P. Allis, 98, professor emeritus of physics, died March 5, 1999, at Mt. Auburn Hospital in Cambridge after a brief illness. During more than forty years on the MIT faculty, Professor Allis conducted theoretical research on plasmas in magnetic fields and the behavior of partially ionized gases. His collaborative work with the late Professor Sanborn C. Brown encompassed all aspects of gaseous electronics and was instrumental in establishing RLE as a premier laboratory in this field.

Professor Allis was born in Menton, France, in 1901. Home educated, he came to MIT and graduated in three years with a master of science degree in 1924. His postgraduate studies included research at the University of Nancy in France, Princeton University, and the University of Munich. His affiliation with MIT continued as a research associate (from 1925 to 1929) and a physics instructor (from 1931 to 1934). He joined the MIT physics faculty in 1934 as an assistant professor and was appointed to full professor in 1950.

Briefly with MIT's Radiation Laboratory, Professor Allis carried out research on magnetron theory and then served as the liaison officer between the Pentagon and the RadLab for the duration of World War II. He achieved the rank of lieutenant colonel and received the Legion of Merit by the War Department.

Following the war, he joined the faculty at the newly established RLE and directed Project Ashby, focusing on the properties of plasmas. Professor Allis was responsible for starting the American Physical Society's Gaseous Electronics Conference. After serving as its chairman from 1949 to 1962, he was named honorary chair in 1966. He also served as NATO's assistant secretary general for scientific affairs from 1962 to 1964.

Since retiring from MIT in 1967, he traveled extensively as a visiting professor and lecturer. Keeping active in recent years, Professor Allis continued to enjoy bicycling, blazing trails at his Yonder Farm property in Dublin, New Hampshire, and mountain climbing at nearby Mount Monadnock.

A fellow of the American Physical Society and the Physical Society of London, Professor Allis was also a vice president of the American Academy of Arts and Sciences and a member of the American Association for the Advancement of Arts and Sciences and the American Association of Physics Teachers. In addition to writing many articles for scientific journals, his books include: *Thermodynamics and Statistical Mechanics* (1952); *Nuclear Fusion* (1960); *Waves in Anisotropic Plasmas* (1962, with Solomon Buchsbaum and Abraham Bers); *Electrons, Ions and Waves* (1967); and *Principles of Laser Plasmas* (1976).

Professor Allis is survived by a daughter, Amedine Allis Bella, of Peterborough, New Hampshire; a son, John Cotton Allis II, of Belmont, Massachusetts; and grandchildren William Phelps Allis II, Padget G. Allis, Gallen Allis, Alyssa N. Bella, and Ivan N. Bella.

A memorial service was held at MIT on March 22, 1999. Memorial donations can be made to the Appalachian Mountain Club, 5 Joy Street, Boston, MA 02108, and the Gaseous Electronics Conference of the American Physical Society, 1 Physics Ellipse, College Park, MD 20740. *(Photo by John F. Cook)*
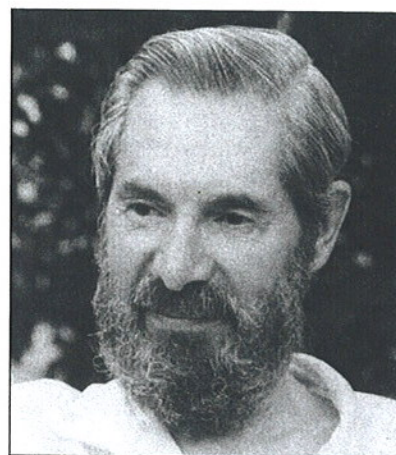
Fred Rosebury, 97, died February 20, 1999, in Framingham, Massachusetts, of complications from a hip fracture. Mr. Rosebury came to MIT's Radiation Laboratory in 1942 and, as a member of Group 53 (Radio Frequency), he was involved in the design of radar equipment. He joined the MIT Vacuum Tube Laboratory in 1945 and became a staff member in RLE when the tube lab became part of RLE in 1946. Until his retirement in 1970, Mr. Rosebury supervised personnel and helped to construct the special vacuum tubes required by RLE investigators.

Born in London, Mr. Rosebury immigrated to New York with his family in 1910. His early career included work as a laboratory assistant at Cornell Medical School and traveling widely as a shipboard radio telegrapher. He was also a graphic design artist in New York City and a

IN MEMORIAM

medical electronics technician at Columbia-Presbyterian Hospital before joining MIT's Radiation Laboratory.

As the author of several technical books, including the *Handbook of Electron Tubes and Vacuum Techniques* (American Vacuum Society, 1993) and *The Wireless Almanac* (Society of Wireless Pioneers), Mr. Rosebury was also a successful artist. His work, which included watercolors, pen and ink drawings, silkscreen printing, and jewelry design, was exhibited in Boston's Museum of Fine Arts in the early 1960s. Several drawings were also published in the *Boston Globe Sunday Magazine* in 1968.

Following his retirement from MIT, he established an engineering consulting firm, Intertech, Inc., in Natick, Massachusetts, where he had lived for many years. Mr. Rosebury was a member of the Society of Wireless Pioneers and a ham radio operator.

Mr. Rosebury is survived by a daughter, Ruth R. Trussell of West Newbury, Massachusetts, and a grandson, Jacob H. Trussell of South Boston. *(Photo courtesy Ruth R. Trussell)*

Laya W. Wiesner, 79, civic leader and champion of an expanded role for women at MIT, died on September 28, 1998, of complications from polymyositis, a degenerative muscle disease. Mrs. Wiesner was the widow of Professor Jerome B. Wiesner, former RLE director and MIT president.

Her many activities included the founding of the Metropolitan Council for Educational Opportunity, working with the Massachusetts League of Women Voters, and organizing the KLH Day Care Center in Cambridge. She also served on the Massachusetts

Laya W. Wiesner

Governor's Advisory Committee on Child Development and on the board of the Cambridge School in Weston. At MIT, Mrs. Wiesner was a supporter and leader of many projects for women including the Women's League, the Advisory Committee on Women and Work, and the Child Development Center.

On April 7, 1999, the MIT Women's League held an on-campus tribute to Mrs. Wiesner and announced the establishment of the Laya Wiesner Community Award. The award will be presented for the first time in 2000 to a member of the MIT community for conspicuously effective service that reflects Mrs. Wiesner's concerns for enhancing life at MIT and the world at large.

Mrs. Wiesner leaves three sons, Stephen J. of Mitzpeh Ramon, Israel, Zachary K. of West Tisbury, Massachusetts, and Joshua A. of Somerville, Massachusetts; a daughter, Elizabeth A. of Branford, Connecticut; and two brothers, Piery W. Wainger of Williamsport, Pennsylvania, and Yale Wainger of West Palm Beach, Florida. A memorial service was held in Brookline, Massachusetts, on October 1, 1998.

Memorial donations may be sent to the Myositis Association of

America, 1420 Huron Court, Harrisonburg, VA 22801-8004. Donations to the Laya Wiesner Community Award fund may be sent to the Recording Secretary, MIT Office of the Treasurer, 238 Main Street, Cambridge, MA 02142-1012. *(Photo courtesy Tech Talk)*

Jacqueline M. Fano, 78, died of cancer at her summer home in Chatham, Massachusetts, August 6, 1998. Mrs. Fano was the wife of Radiation Laboratory staff member and RLE faculty member Professor Emeritus Robert M. Fano (EE'41). A noted fashion designer, Mrs. Fano attended Simmons College and the Modern School of Fashion Design in Boston. A memorial service was held at MIT on October 3, 1998.

She is survived by her husband; brother Paul S. Crandall (SB'42) of Littleton, Massachusetts; daughters Paola F. Nisonger (SM'79) of Milford, Michigan, and Linda C. Ryan (SM'82) of New Canaan, Connecticut; son Carl S. Fano of Chatham, Massachusetts; and five grandchildren. Memorial donations may be sent to the MIT Medical Department Inpatient Fund, c/o Mary Smith, Room E23-308, 77 Massachusetts Avenue, Cambridge, MA 02139-4307.

(Photo courtesy Robert M. Fano)

TECHNOLOGICAL INNOVATION IN EDUCATION:
Computers as Learning Environments

Advances in computer technology, such as hypertext and multimedia capabilities, have begun to change pedagogy—the way educators teach and how students learn. Although these technologies have not yet reached a stage where they can be used to teach all educational disciplines to all students, an interactive multimedia learning environment can provide additional support and resources to both students and teachers. By exploiting multimedia computer technology and the vast resources . of the Internet, students can effectively manipulate or graphically view learning material, thus stimulating their understanding of concepts, environments, and systems. Combined with networking technologies, computer-assisted learning is also a vehicle for distance learning. In many situations, students can learn not only by doing, but also by exploring the content of the lesson or problem presented, thus having increased interaction with the learning material. Self-paced learning and individualized instruction are important aspects of these computerized learning environment, enabling educators to better accommodate varied learning styles and to set the pace of learning in the classroom.

In terms of science and engineering education, many computer techniques that investigators use to discover new properties in the laboratory are also employed to educate students in the classroom. These same techniques can display interactive demonstrations, represent information dynamically, and retrieve or extract data. For example, scientific visualization combined with computer simulation has proven to be a successful teaching method because of the nonlinear nature of many scientific phenomena. Another important aspect of visualization is its ability to interpret large amounts of quantitative data obtained from computer simulation models and to present a physical picture of the phenomenon under study.

On its own, computer simulation provides an authentic form of practice in which students can manipulate various elements displayed on the computer screen, thereby exploring the content of
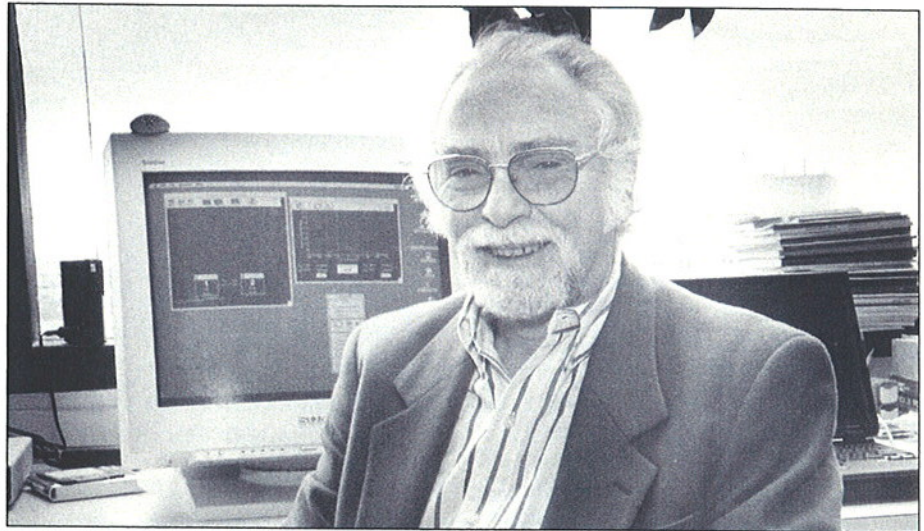
Professor Thomas F. Weiss of RLE's Auditory Physiology group has used computers to teach cellular biophysics as well as traditional electrical engineering subjects such as signal and systems theory. The computer in the background is running a software package developed by Professor Weiss and his colleagues that enables users to design voltage-gated ion channels, which is one of the major mechanisms of ion flow through cell membranes. A detailed view of the display is shown on page 33. (Photo by John F. Cook)

the intended lesson. It enables the testing of abstract concepts and the ability to experiment with scientific processes that may not be possible in a traditional classroom setting. The timing of a simulation can be slowed while explanations and feedback are supplied. In addition, invisible events or processes, such as the flow of electrons, can be observed in order to increase understanding of how a device or system works.

Professor Thomas F. Weiss of RLE's Auditory Physiology group has used computers to teach cellular biophysics, as well as traditional electrical engineering subjects such as signal and systems theory. In 1984, together with several students, Professor Weiss began developing highly successful software packages to teach cellular biophysics in MIT's Department of Electrical Engineering and Computer Science. One of their software packages received national recognition when it won the 1990 Higher Education Software Award for Best Engineering Software from EDUCOM/National Center for Research to Improve Postsecondary Teaching and

Learning (NCRIPTAL). The award-winning software allowed users to compute the response of the Hodgkin-Huxley model of nerve-cell membranes to electrical stimulation for different environmental variables.

Other software packages developed by Professor Weiss and his students include the random-walk model of diffusion, solutions to the macroscopic diffusion equations, carrier-mediated transport through membranes, and single voltage-gated ion channels. Originally, these packages were designed for UNIX workstations using C and X-Windows, and were available only to MIT students and faculty through Project Athena. However, in 1995, Professor Weiss received support from the National Science Foundation to rewrite these programs to run in MATLAB, a commercially available mathematical and visualization software language. MATLAB is maintained by a commercial vendor and runs on all major platforms such as UNIX workstations, and PC-compatible and Macintosh computers. In addition, a complete software manual is available

that contains exercises and projects.

Professor Weiss and his colleagues are now developing a new software package for cellular homeostasis. This project seeks to produce a simulator that will teach cellular homeostasis to students and researchers in bioengineering, biophysics, cell biology, and physiology. The goal of the software is to allow users to design a cell that consists of several compartments separated by membranes. Users can then select the composition of each compartment from databases of simple solutes, pH buffers, metal ion chelators, dyes, indicators, and macromolecules. Some of these solutes bind others, and the chemical reactions describing the relations are characterized in the software. In addition, users will be able to design the membranes in order to include a constellation of transporters from a list of channels, carriers, and pumps. Each element of the model is selected from a user-selectable, expandable library of transporters and binding mechanisms, each of which can be edited by the user. Once the cell is designed, users can then perform simulation experiments.

In creating an interactive learning environment (ILE) for very large-scale integration (VLSI) circuit design, Professor Jonathan Allen, RLE's director and an investigator in the Circuits and Systems group, and Dr. Christopher J. Terman, senior lecturer in the Department of Electrical Engineering and Computer Science, have developed software that emphasizes the exploration process in design and promotes a deeper understanding of circuits.

This innovative and powerful software features several tightly integrated components including hypertext, illustrations, a toolkit, libraries, tutorials, video clips, and animation (see illustration on back page). The toolkit, known as JADE (Java Design Environment), enables the design of schematic and layout representations, their extraction to circuits, simulation, and measurement. The various software components encourage students to choose from various design alternatives and to explore the consequences of their choices when designing digital metallic oxide semiconductor (MOS) circuits.

Once a circuit schematic or layout is encountered in the text, students can use the JADE toolkit environment to make changes and explore design choices. Questions can be asked and answers easily obtained at any level within the software. Students can experiment with the circuits, thus building a deeper insight into digital MOS circuit behavior. Combined with the theory supplied in the text, repeated experimentation contributes to a solid background for creating innovative MOS circuits.

An important feature in this ILE is the integration of schematic and layout representations with the text. In a textbook, an illustration usually accompanies the circuit schematic under discussion. In this software, however, instead of a drawing, an embedded window
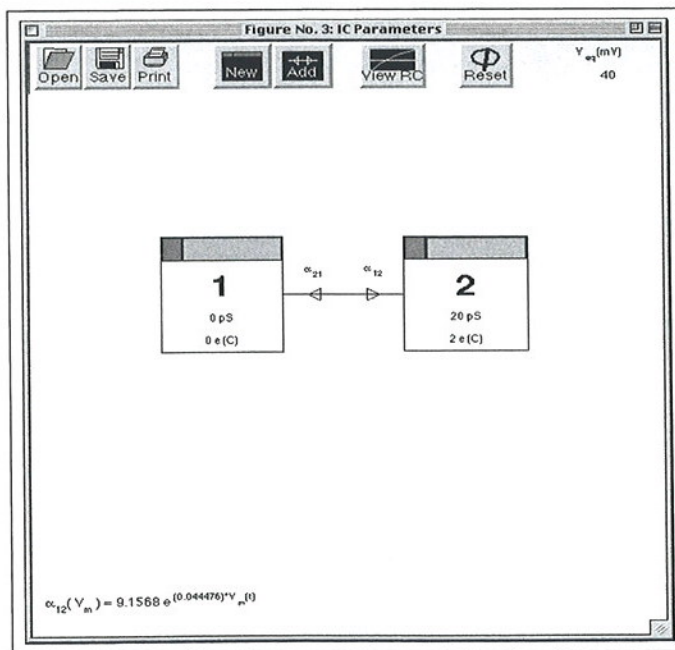
This simple state diagram, which illustrates how ions flow through voltage-gated ion channels, has just two states—1 and 2. Each state has a single-channel conductance and a single-channel gating charge whose value can be edited by the user. State 1 has a conductance of 0 pS and a gating charge of 0 C; whereas state 2 has a conductance of 20 pS and a gating charge of 2e C, where e is the electronic charge. The channel switches randomly between its two states with transition rates α_{12} and α_{21}, which are themselves dependent on the membrane potential. Thus, as the membrane potential changes, the probability that the channel will be in a particular state will also change. As a part of the channel design component of the software, users can add additional states and specify the voltage-dependence of transition rates between states.
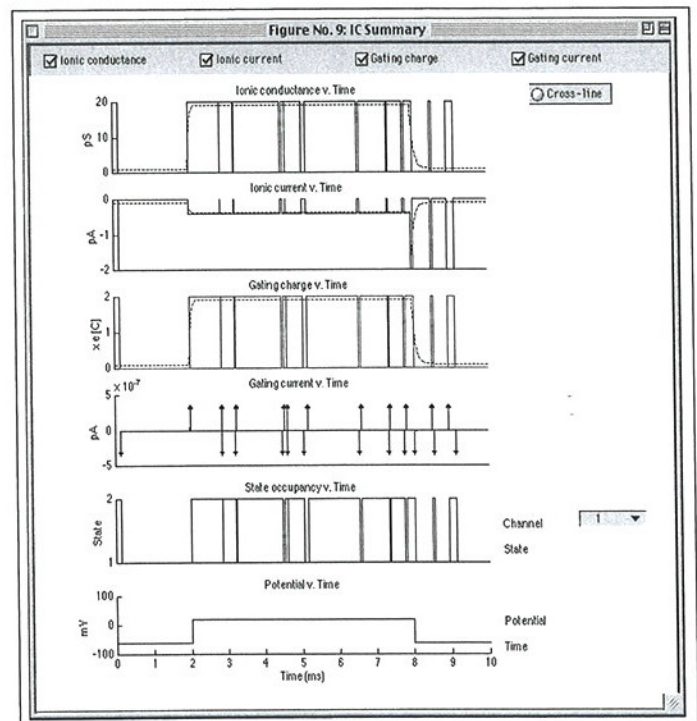
Once a state diagram for a single channel is designed, users can perform simulation experiments with the software. This figure shows several single-channel variables as a function of time associated with the state diagram (at right/top). The bottom panel displays the potential across the membrane that houses the single channel. All the variables are probabilistic. However, when the membrane potential is positive, the channel tends to reside in state 2, which is the conducting state. This is shown by the single-channel conductance and the single-channel current. Thus, this channel is activated by an increase in the membrane potential.
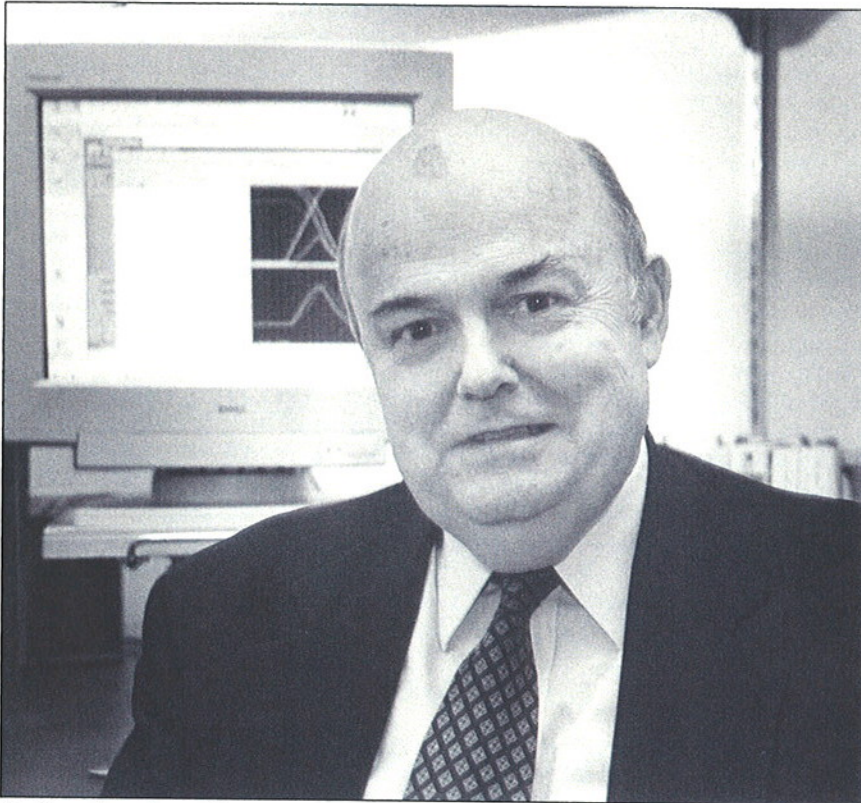
Professor Jonathan Allen, RLE's director and an investigator in the laboratory's Circuits and Systems group, works with the newly developed interactive learning environment for very large-scale integration (VLSI) design, which emphasizes the exploration process and promotes a deeper understanding of circuits. The software features several tightly integrated components including hypertext, illustrations, a toolkit, libraries, tutorials, video clips, and animation. An interactive circuit simulation environment is displayed on the monitor in the background. Here, users can carry out circuit simulation using a set of test waveforms. They can also display any current or voltage of the circuit under design by inserting voltage probes and current meters with the schematic editor feature. (Photo by John F. Cook)

representing the circuit in the JADE toolkit is displayed. Here, the student can edit the schematic and perform circuit extraction and simulation without leaving the text window. The editor and simulator environment of the software animates the text descriptions of the circuits. Tutorials associated with each schematic guide the student in exploring the interesting aspects of circuit behavior.

Layout is approached in a similar way. For schematics or layout, the circuit can be augmented with voltage probes and current meters at any node or branch. Precise measurements can then be made to obtain a better understanding of the circuit's action and important aspects of its performance. The techniques used in this ILE, particularly the integration of editing, extraction, and simulation tools with hypertext, can be applied to other circuit engineering courses and other subjects where understanding depends critically on simulation.

The ILE developed by Professor Allen and Dr. Terman was recently used in an introductory VSLI design class in MIT's Department of Electrical Engineering and Computer Science. The software is implemented in Java, runs under Windows 95/98 or NT, and uses Internet Explorer on a PC. It can also run in stand-alone mode on a notebook computer, thus providing the requisite design resources for substantial projects at one's fingertips. Since it is a Web-based software, it is also well suited for distance learning applications.

Publications

RLE Progress Report

RLE Progress Report Number 141 is available from the RLE Communications group at no charge. *Progress Report Number 141* covers the period January through December 1998. It provides detailed information about the research objectives, projects, and publications of RLE's research groups. Faculty, staff, and students who participated in each project are listed, in addition to current RLE personnel, and funding sources are identified. The *Progress Report* is also available in the Publications section of RLE's website at http://rleweb.mit.edu.

RLE welcomes inquiries regarding the laboratory's research. To request an *RLE Progress Report,* please contact:

RLE Communications Group
MIT
Research Laboratory of Electronics
Room 36-412
77 Massachusetts Avenue
Cambridge, MA 02139-4307
Telephone: 617-253-2566
Fax: 617-258-7864

RLE Technical Reports

The following new RLE technical reports are available from MIT Document Services:

Nonlinear Device Noise Models: Thermodynamic Requirements, by John L. Wyatt, Jr., and Geoffrey L. Coram. RLE TR No. 616. 1997. 30 pp.

A Framework for Low-Complexity Communication over Channels with Feedback, by James M. Ooi. RLE TR No. 617. 1997. 185 pp.

Proceedings of the Second PHANToM Users Group Workshop, by Kenneth J. Salisbury and Mandayam A. Srinivasan. RLE TR No. 618. 1997. 92 pp.

Human Haptic Interaction with Soft Objects: Discriminability, Force Control, and Contact Visualization, by Jyh-Shing Chen and Mandayam A. Srinivasan. RLE TR No. 619. 1998. Touch Lab Report 7.

Multimodal Virtual Environments: MAGIC Toolkit and Virtual-Haptic Interaction Paradigms, by I-Chun Alexandra Hou and Mandayam A.

Professor Kenneth N. Stevens (ScD '52), the Clarence J. LeBel Professor of Electrical Engineering, recently published *Acoustic Phonetics* (MIT Press, 1998). This long-awaited reference book details a comprehensive theory for defining categories of speech sounds used to form distinctions between words in languages. Using a linguistic approach, it describes the basic acoustic features of speech perception, production, and processing. The book includes a review of the anatomy and physiology of speech

Acoustic Phonetics

KENNETH N. STEVENS
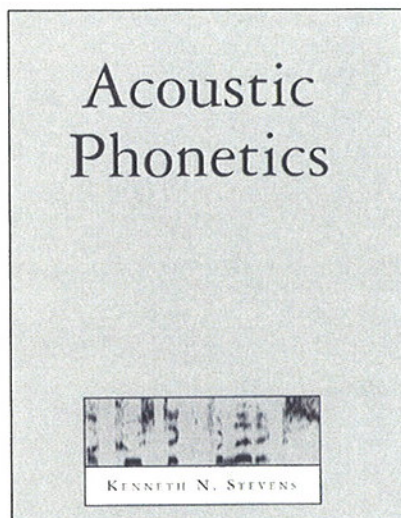
production and source mechanisms; the related aspects of auditory psychophysics and physiology; phonological representations; and an analysis of vowels, consonants, and the influence of context on speech sound production.

A Toronto native, Professor

Stevens came to MIT in 1948 as a teaching assistant in the Electrical Engineering Department after receiving his masters in engineering physics at the University of Toronto. As a graduate student in electrical engineering at MIT, Professor Stevens' interest in acoustics grew under the influence of Dr. Gunnar Fant, who spent about two years at MIT during the 1950s; Dr. Morris Halle, now Institute Professor Emeritus at MIT and former head of the Linguistics Department; and Dr. Leo L. Beranek, former technical director of MIT's Acoustics Laboratory. Since joining the MIT faculty in 1958, Professor Stevens has been central to the development of speech communication research in RLE.

During a recent interview with *RLE currents*, Professor Stevens said that he began to collect the materials for the book fifteen years ago, using them as notes for his course on speech communication. "In this book," Professor Stevens said, "I attempt to build on the earlier work of Gunnar Fant and others over the decades to present a theory of speech sound generation in the human vocal system. I am presenting an approach to modeling the production of speech sounds in general. I show how acoustic theory can make predictions about sound patterns and how these articulatory and acoustic patterns are related to the categories that distinguish the sounds that are used in language."

Discussing the concepts behind the theory of speech communication,
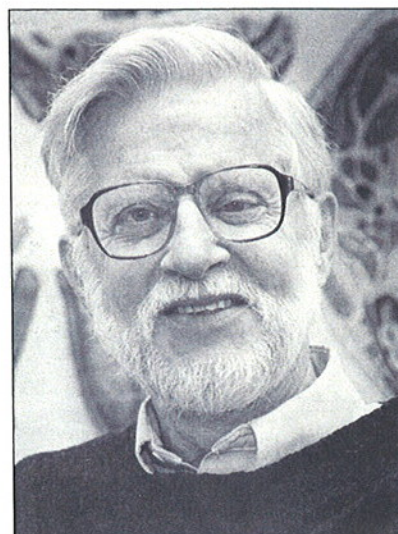
Professor Stevens remarked, "On one hand, from a layman's point of view, speech production seems simple. A child of two years can speak complete sentences without being taught. It looks effortless. But if you examine the basic processes of human speech production from the moment the idea comes into one's mind until the words are uttered, you will begin to understand that the process is very complex."

Professor Stevens' recent work involves the development of models for speech sound generation and the variability that occurs in different speakers and various speaking modes. Procedures are then developed from these models to recognize words in speech and to assess speech production disorders.

(Photo by John F. Cook)

Srinivasan. RLE TR No. 620. 1998. Touch Lab Report 8.

Identification and Control of Haptic Systems: A Computational Theory, by Steingrimur Pall Karason, Mandayam A. Srinivasan, and Anuradha M. Annaswamy. RLE TR No. 621. 1998. Touch Lab Report 9.

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Multiscale Analysis and Control of Networks with Fractal Traffic, by Warren M. Lam and Gregory W. Wornell. RLE TR No. 625. 1998. 55 pp.

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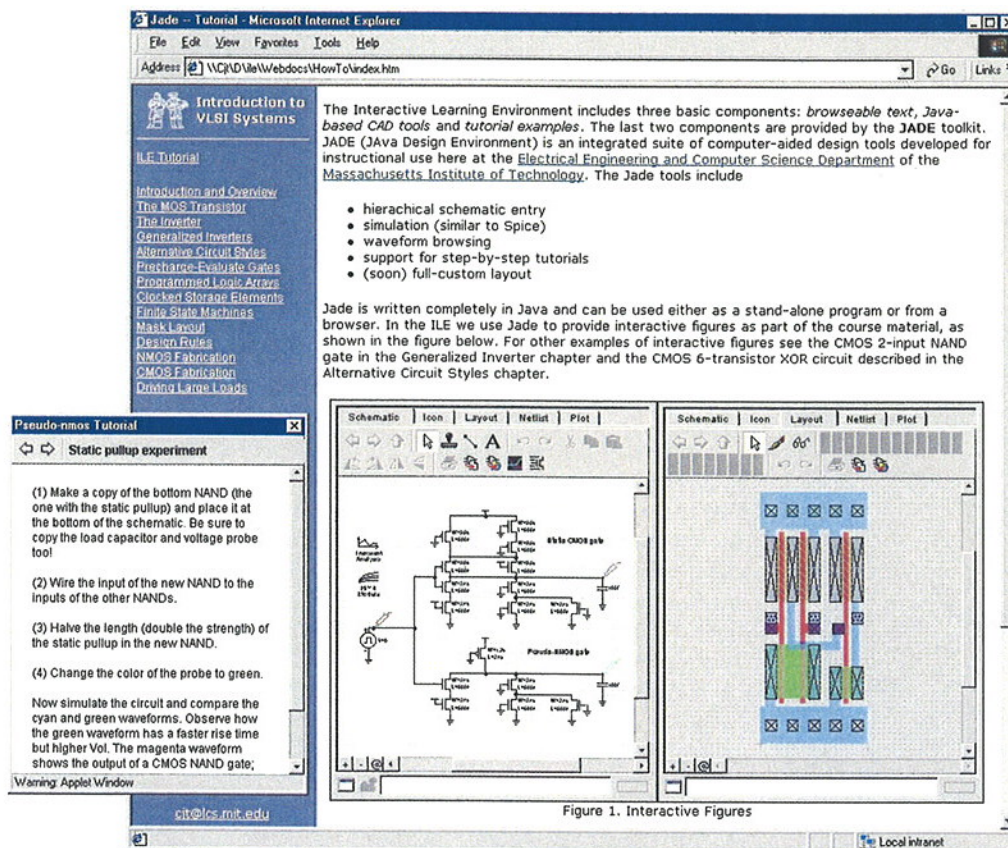Tel: 617-253-5668 Fax: 617-253-1690
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RLE on the Web
Internet users are invited to browse RLE's extensive Web pages, which contain previous issues of *RLE currents*. The laboratory's website is located at http://rleweb.mit.edu/.

TECHNOLOGICAL INNOVATION IN EDUCATION:
Computers as Learning Environments
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Figure 1. Interactive Figures

This screen capture illustrates several components of an interactive learning environment for VLSI circuit design. The software, designed by Professor Jonathan Allen and Senior Lecturer Dr. Christopher J. Terman, closely integrates hypertext, illustrations, a toolkit, libraries, tutorials, video clips, and animation that students can use to explore various design alternatives.