RLE
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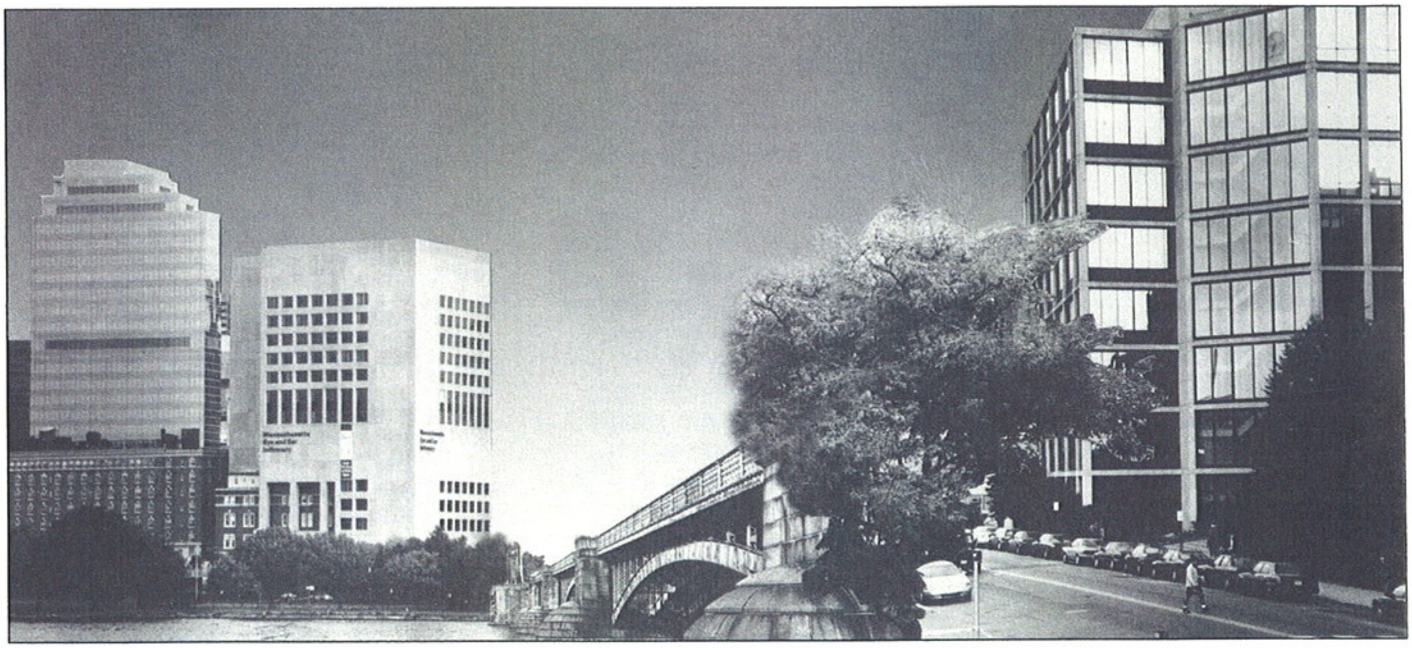
The Research Laboratory of Electronics at the Massachusetts Institute of Technology

CROSSING THE BRIDGE TO BIOMEDICAL AND BIOENGINEERING RESEARCH



This imaginative photographic sleight of hand illustrates RLE's connection to biomedical and bioengineering interests at the Massachusetts Eye and Ear Infirmary and Massachusetts General Hospital across the Longfellow Bridge in Boston. RLE's innovative work in these fields is no illusion though. The laboratory's traditional multidisciplinary approach to electronics has contributed to beneficial collaborations with scientists and clinicians in a wide range of basic and applied research at other institutions. (Photo by John F. Cook)

Many people are surprised to learn that RLE brings together a wide range of activity in biomedical and bioengineering research. In the beginning, RLE's investigators focused on the physical phenomena of electronic devices in systems such as radar. These interests quickly expanded to coding and the representation of information, which led to a basic theoretical understanding of communication in human-made systems. Fueled by Professor Claude Shannon's classic papers on signals and noise, and by Professor Norbert Wiener's work on cybernetics and statistical theory, RLE's early investigations into the field of communication sciences was far ranging. It included information and communication theory in both humans and machines, and expanded into the biological sciences, which included the physiology and development of the human nervous system. During the late 1940s and early 1950s in RLE, communication engineers, neurophysiologists, biologists, linguists, economists, social scientists, and psychologists attended lively dinner discussions arranged by Professor Wiener.

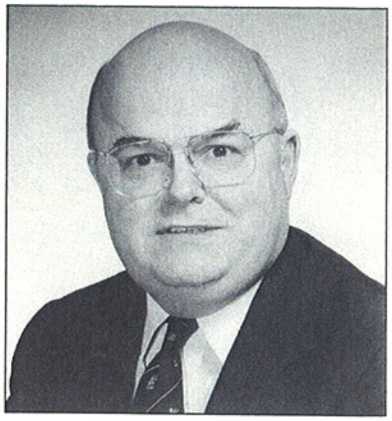
During the 1950s, innovative collaborations with Massachusetts General Hospital (MGH) and the Massachusetts

(continued on page 2)

Director's Message

While the name of our laboratory gives no hint of biomedical or bioengineering research, in fact, it is a very large thrust that is led by twenty principal investigators, and one which spans a wide range of more than fifty projects. These basic and experimental studies probe the fundamental behavior of human visual, auditory, and tactile perception; the complex process of human speech production; and several applications of this basic understanding to practical prosthetic devices for clinical needs. In addition, high-resolution optical probes of biological structures have been developed, as well as novel techniques for efficient biological analysis. The techniques devised and the understanding gained from these projects have led to large investigations of virtual environments and the characterization of microelectromechanical systems, thus demonstrating the wide-ranging impact of RLE's biomedical and bioengineering research.

Not surprisingly, RLE investigators have reached out to several other universities to collaborate on various projects, and these efforts now extend to three local hospitals in the Boston area. The highly interdisciplinary nature of RLE's biomedical and bioengineering research is also very attractive to students, who learn basic biological



Jonathan Allen, Director, Research Laboratory of Electronics

systems not only from an engineering perspective, but also from a complementary medical academic view. Many RLE investigators and students contribute strongly to the Harvard-MIT Division of Health Sciences and Technology, and particularly to the division's Speech and Hearing Sciences program. This unique educational environment has attracted outstanding students from many different backgrounds.

As you read this issue of ***currents,*** you will appreciate the extraordinary depth and breadth of RLE's research in biomedical and bioengineering research. RLE is proud of its intellectual strength and heritage in this area, and is eager to extend its understanding through our current research projects.

Inside This Issue

CROSSING THE BRIDGE
(continued)

Eye and Ear Infirmary (MEEI) were established (see related articles on pages 4 and 13). New research groups were also forming in RLE that touched on the fields of biomedicine and bioengineering: Communications Biophysics, Neurophysiology, Visual Replacement, and Speech Analysis. Professor Jerome Y. Lettvin and his colleagues in RLE's Neurophysiology group developed highly unorthodox methods that have contributed to the underlying properties of perception in humans and animals. In RLE's Sensory Prostheses group, Professor Norbert Wiener, Dr. Edward E. David, Jr. (SM'47, ScD'50) and Professor Jerome B. Wiesner conducted experiments to convert speech signals into a sequence of tactilely perceptible patterns that a deaf person might learn to understand. The experimental device, called Felix, used several band-pass filters to subdivide the range of the spoken voice. In the Visual Replacement group, research staff member Dr. Clifford M. Witcher and Professor Samuel J. Mason conducted studies on reading systems for the blind, computer-based optical character recognition, and the psychophysics of tactile and auditory displays. Later, as head of RLE's Cognitive Information Processing group, Professor Mason continued work on a reading machine for the blind. In 1958, the design and construction of the Average Response Computer (ARC-1) by Wesley A. Clark (EE'55) in RLE's Communications Biophysics group and colleagues at Lincoln Laboratory, was

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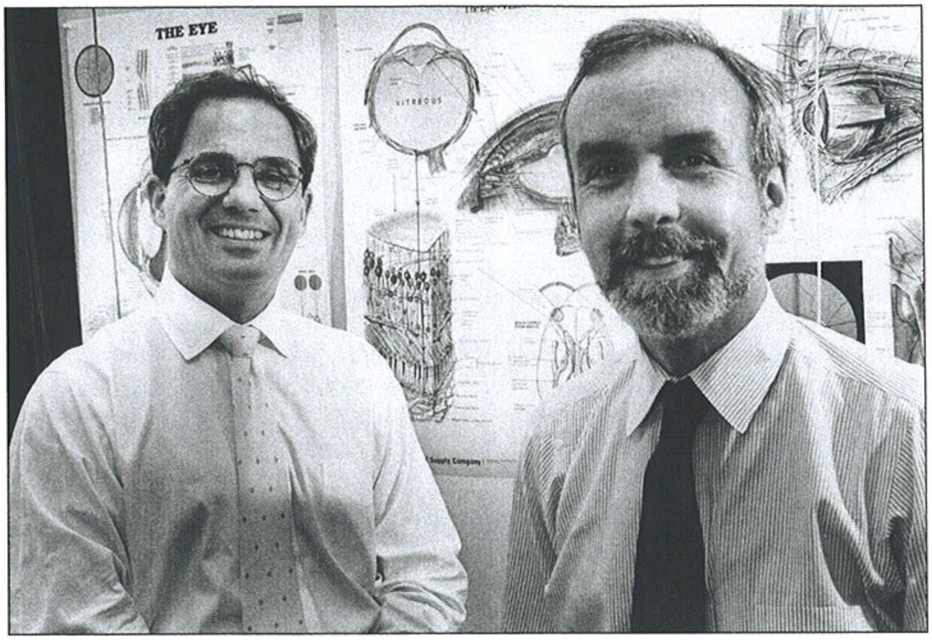
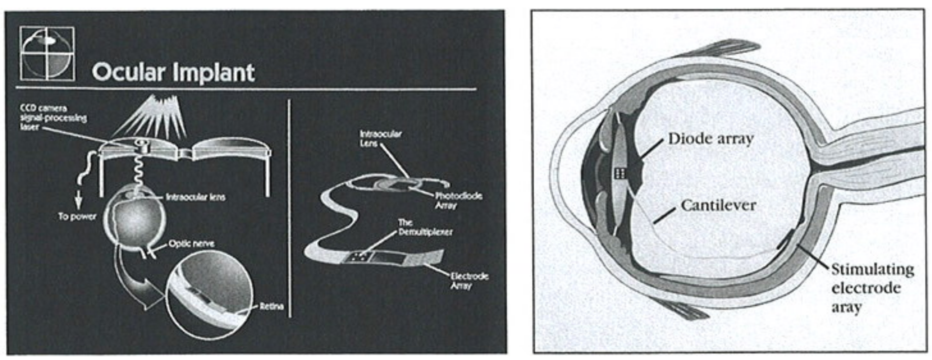


Dr. Joseph F. Rizzo, a physician and faculty member in the Department of Ophthalmology at Harvard Medical School and the Massachusetts Eye and Ear Infirmary, and Professor John L. Wyatt, Jr. of RLE's Optics and Devices group are leading a research team that is working to design and construct an implantable microchip that may restore sight to patients suffering from retinitis pigmentosa and macular degeneration. The Retinal Implant Project is one of four related projects conducted in the new W.M. Keck Foundation Neural Prosthesis Research Center. (Photo by John F. Cook)



In the design of the system for the Retinal Implant Project, the scene in front of a patient will be captured by a tiny camera mounted on the patient's eyeglasses. A signal-processing microchip mounted on the glasses will use visual information from the scene to modulate a low-power laser beam that enters the eye. The laser will illuminate a photodiode array implanted in the forward region of the eye just behind the iris. Current from the photodiode will power the implant. Small high-frequency changes in the current, in response to the modulation on the laser beam, will digitally represent the image. A thin ribbon cantilever, containing wire traces and stimulating electrodes, will extend from the photodiode array to the inner surface of the retina. This design conveys both signal and power to the implant with no need for wires to penetrate the eye. The implanted system contains only "slave" electronics that respond to the camera/laser system located on the glasses. This will allow researchers to alter the stimulation procedure by simply changing the external circuitry and without the need for further surgery.

an important step into the biomedical instrumentation field. Programs were also written at RLE for the TX-0 and TX-2 computers developed at Lincoln, and contributed substantially to a new style of neurophysiological experiments.

An important new direction for RLE research was forged when Dr. Walter A. Rosenblith came to MIT in 1951. He had worked at Harvard's Pscyho-Acoustic Laboratory and, when he joined both RLE and MIT's Acoustics Laboratory, he encountered Professor Wiener. Dr. Rosenblith, with his background in communications engineering and physics, started research in a field then known as communications biophysics. This research attempted to connect the work on mathematical modeling of electrical brain activity and human communication processes. As the field grew rapidly in RLE, Dr. Rosenblith was appointed professor of communications biophysics in the Department of Electrical Engineering, and RLE established the Center for Communication Sciences in 1958. Here, electrical communication scientists, neurologists, and neurophysiologists, as well as scientists with interests in speech, hearing, learning, linguistics, sensory processes, and logic, worked in an interdisciplinary manner to solve the mysteries of natural and human-machine communications.

Today, RLE's interests in biomedical and bioengineering research encompass a broad spectrum of investigation in speech communication, auditory physiology, and sensory communication. RLE's investigators in these areas have successfully collaborated with scientists and clinicians at several Boston-area hospitals and other academic institutions to advance basic understanding and provide new technology in the biomedical and bioengineering fields. In one example, scientists, clinicians, students, and patients at MIT, the Massachusetts Eye and Ear Infirmary, and Harvard Medical School have worked together on neural prostheses for hearing over the last sixteen years, and on the development of an experimental retinal implant over the last eight years. These collaborations have successfully brought together valuable efforts and resources to develop prostheses for deaf individuals, and they now hold promise to improve the vision of those who are blind.

In this issue of ***RLE currents,*** we provide an overview of the many projects conducted by investigators in RLE that continue the laboratory's tradition of interdisciplinary research in the biological sciences.

CIRCUITS AND SYSTEMS

Retinal Implant Project

In a highly experimental project, Professor John L. Wyatt, Jr., of RLE's Circuits and Systems group, and Dr. Joseph F. Rizzo, physician and faculty member in the Department of

MASSACHUSETTS GENERAL HOSPITAL

Massachusetts General Hospital conducts the largest hospital-based research program in the United States. As New England's oldest and largest hospital, MGH provides diagnostic and therapeutic care in almost every medical and surgical specialty while maintaining a superior program in teaching and research. As the oldest and largest teaching hospital of the Harvard Medical School, more than 90 percent of MGH's staff physicians are on the HMS faculty. The following article depicts the beginning of RLE's relationship with MGH.

Electroencephalography involves the recording and interpretation of the brain's electrical activity. In 1929, Hans Berger of Germany developed the first electroencephalograph to measure and record brainwave patterns. Using printed recordings from the instrument, called electroencephalograms or EEGs, scientists and clinicians can examine how the brain functions and determine its relationship to the central nervous system.

In 1946, W. Grey Walter demonstrated his EEG frequency analyzer in MGH's famous Ether Dome. This instrumentation prompted the application of auto- and cross-correlation to EEGs. According to James U. Casby (SB'52), who was then an engineer in the MGH EEG Laboratory, the application to EEGs had been conceived by Professor Norbert Wiener about 1949. Many years earlier, Professor Wiener had been introduced to several Boston encephalographers by physiologist Arturo Rosenblueth, and he became intrigued with applying statistical communication techniques to this field. This interest sparked the first collaborations between MGH and RLE investigators.

At RLE, Thomas P. Cheatham, Jr. (SM'47, PhD'52) built the first analog correlator in 1948, followed by Henry E. Singleton (SB/SM'40, ScD'50), who constructed a digital correlator in 1949. These machines were designed to perform auto- and cross-correlation analysis of various signals such as speech, music, and random noise. To accommodate the Walter EEG frequency analyzer, a magnetic tape recorder was designed and built at RLE to record the very low frequencies of the EEGs. These were recorded at MGH and then analyzed at RLE using Singleton's digital correlator. Unfortunately, since the correlator's output was in raw binary form, it required laborious manual conversion to graphical form.

When Professor Walter A. Rosenblith joined RLE in 1951, he was encouraged by then-RLE director Professor Jerome B. Wiesner to study sensory communication. Special electrophysiological and psychophysical facilities were set up for both animal and human experiments. Two special-purpose computers were developed in RLE's Communications Biophysics group: a time-gated amplitude quantizer and an analog correlator used to analyze brain potentials. This correlator, which resulted from the redesign of a speech waveform correlator that had been constructed at the Imperial College of Science and Technology in London, was called the Analog Correlator System for Brain Potentials. Developed by Dr. Mary A.B. Brazier and Dr. John S. Barlow at MGH in collaboration with colleagues at MGH and MIT, it detected weak radar signals by cross-correlating the transmitter pulse with the radar return. It provided meaningful and quantitative descriptions in the form of EEG correlograms.

The Analog Correlator System for Brain Potentials was the first of several research instruments used to study EEGs and related brain potentials in RLE. The digital Average Response Computer (ARC-1), built by Wesley A. Clark (EE'55) at Lincoln Laboratory in 1958, was used in RLE's Communications Biophysics group to record the averages of evoked electrical responses of the brain to a given stimulus. In 1962, the Evoked Response Detector was developed by Professor Rosenblith, based on a gating and storage circuit used by Drs. Brazier and Barlow that was used in conjunction with the analog correlator system to average sensory-evoked potentials from the brain. Over the years, although EEGs have become a useful diagnostic tool, they have had limited use in research since they can only record a fraction of the electrical activity that occurs on the brain's surface and cannot measure the brain's more complex function such as thoughts and emotions.

Ophthalmology at Harvard Medical School and the Massachusetts Eye and Ear Infirmary, are leading a research team that is attempting to design and construct a silicon retinal implant chip for the blind. The goal of this work is an implantable microchip that may restore sight to patients suffering from retinitis pigmentosa and macular degeneration.

The retina is a delicate and complex tissue that is considered part of the brain. Vision loss associated with the retina is usually permanent. Retinitis pigmentosa is the leading type of inherited blindness and afflicts approximately 1.2 million people worldwide. Macular degeneration is a form of progressive vision loss that afflicts approximately 10 million Americans. Some patients can use special low-vision glasses, but there is currently no medical treatment available to repair retinal damage.

The prosthesis being designed by the Retinal Implant Project team is a two-sided silicon microchip that will be implanted adjacent to the retina. It is expected that the surgically implanted microchip will be part of a system that includes a miniature camera and a laser fitted to the patient's eyeglasses. Light passing through the eye's lens will be focused on a photoreceptor laser array located on the chip. Electrical impulses will be sent to the retina through an array of stimulating electrodes also on the chip. Healthy optic-nerve ganglion cells in the retina will be stimulated by the impulses, causing them to fire. Because this research is in its early stages, many issues must be addressed. One concern is how to design and mount the device properly so there is no discomfort or further damage to the retina, yet close enough to ensure sufficient electrical stimulation. Questions about the device's possible toxicity and the effects of electrical stimulation on the retina must also be answered.

Over the last eight years, the Retinal Implant Project team has included investigators from the Massachusetts Eye and Ear Infirmary, Massachusetts General Hospital, Lincoln Laboratory, the Charles Stark Draper Laboratory, the Southern College of Optometry in Memphis, Tennessee, the Cornell National Nanofabrication Facility, and RLE's Circuits and Systems group. The Retinal Implant Project is now one of four being investigated as part of the new W.M. Keck Foundation Neural Prosthesis Research Center.

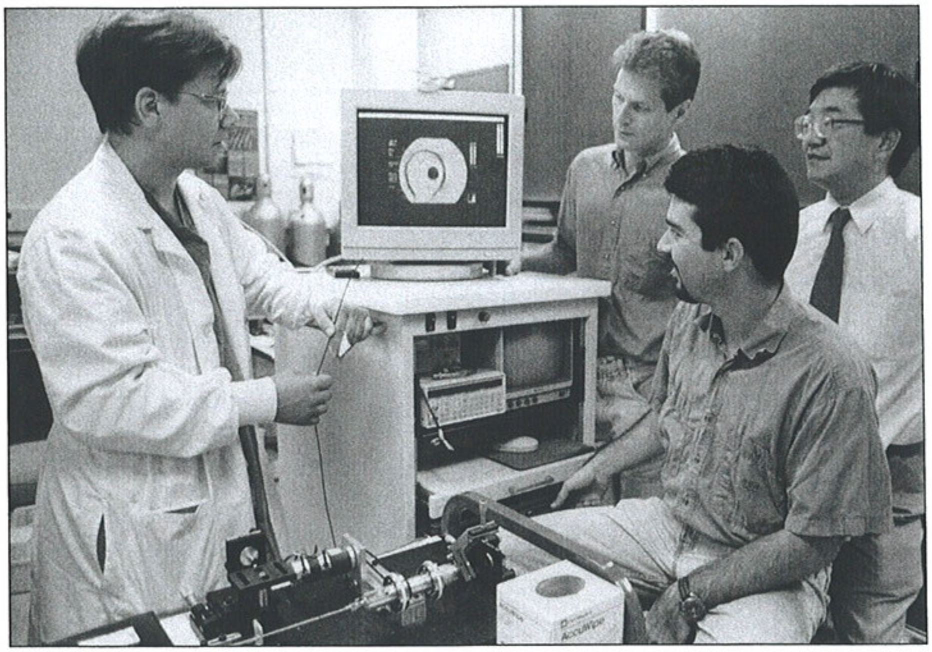
OPTICS AND DEVICES

Biomedical Imaging and Diagnostics

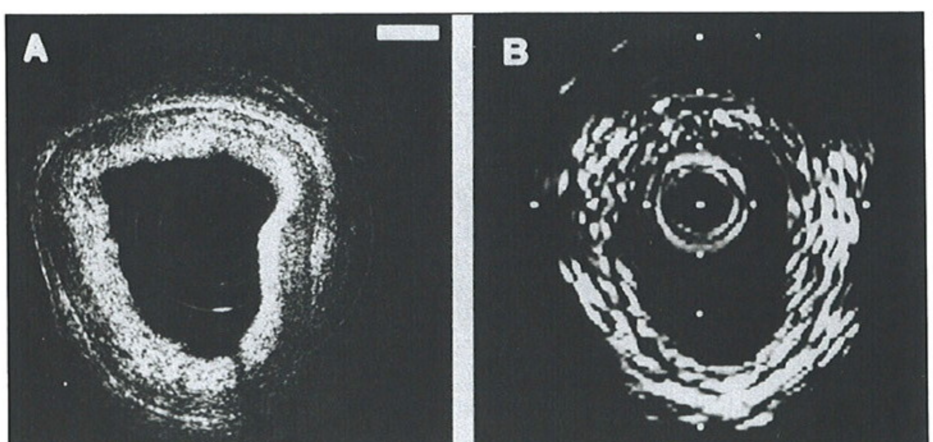
A novel laser technique called optical coherence tomography (OCT) is being pioneered by a research team in RLE's Optics and Devices group led by Professor James G. Fujimoto. OCT is somewhat analogous to ultrasound or radar imaging techniques, except it uses light. Tomographic imaging is performed by measuring the echo delay of back-reflected light from internal biological microstructures. Thus, OCT 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-scale imaging, and catheter/endoscopic delivery systems. Professor Fujimoto and his group have collaborated with Dr. Mark E. Brezinski, a physician in Massachusetts General Hospital's Cardiac Unit and Harvard Medical School, to develop this new type of medical imaging technology.

Initial investigations were performed in the field of ophthalmology. Working with Dr. Carmen A. Puliafito, director of the New England Eye Center and chairman of ophthalmology at Tufts University School of Medicine, OCT has been used to examine more than 5000 patients. OCT technology has also been transferred to industry, and a commercial product for the ophthalmic diagnostic market was introduced last year. OCT now holds promise for improving the diagnosis and management of a wide range of retinal diseases. These include diabetic retinopathy and glaucoma, where OCT may be capable of detecting early disease progression before vision damage occurs.

OCT uses a low-coherence light source in conjunction 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 bounced off the target organ's surface. Photons backscattered by the tissue are returned through the catheter and go to the interferometer, where they interfere with another beam. This interference



From left: Dr. Mark E. Brezinski of Massachusetts General Hospital, RLE postdoctoral associate Brett E. Bouma (now at MGH), graduate student Constantinos Pitris, and Professor James G. Fujimoto discuss the display on the computer monitor, which shows a real-time, catheter-based optical coherence tomography image. (Photo by Donna Coveney)



A comparison of imaging performed in vitro *by optical coherence tomography (A) and standard intravascular ultrasound (B) shows intimal hyperplasia in a human coronary artery. The improved resolution achieved by OCT permits clearer imaging of arterial pathology.*

provides information on where the photons were backscattered from inside the tissue. The data is then converted by computer into an image with a resolution of up to 20 times better than that of magnetic resonance imaging or ultrasound.

Working in collaboration with Dr. Brezinski, Professor Fujimoto's group continues to investigate the potential of OCT as a clinical diagnostic tool for other human organ systems such as the cardiovascular, pulmonary, and gastrointestinal systems. They are currently investigating OCT for various medical applications, including imaging for vascular disease and early cancer detection. It is anticipated that OCT may replace conventional biopsy in cases where traditional methods would be hazardous. The investigators believe that OCT may provide better results in the early diagnosis and detection of cancer, and may be used to guide sensitive surgical procedures in the future.

SPEECH COMMUNICATION

Understanding the Links between Language, Speech, and Hearing

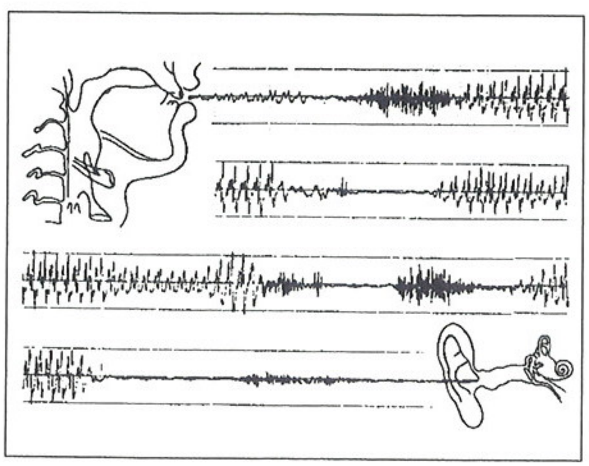
Speech communication is an exclusively human process that has several levels of activity, and is far more complex than one would imagine. The transmission of speech involves the following processes: encoding the speaker's thoughts, motor control of the articulators; the vocalization of speech sounds; vibrations of sound waves at the acoustical level; stimulation of the listener's auditory mechanisms; and nerve impulses that relay the encoded message to the listener's brain, which ultimately decodes the speaker's message. RLE's research in speech communication attempts to piece together the many questions involved in solving the mysteries of the speech puzzle.

RLE's Speech Communication group began when the MIT Acoustics Lab, led by Leo L. Beranek, disbanded in 1957. Some of the Acoustic Lab's work in speech was transferred to a new group in RLE under the direction of Professors Morris Halle and Kenneth N. Stevens. Although there had been earlier investigations into speech analysis at RLE, this influx of new people brought a fresh perspective to this work. Linguists began collaborating with acoustical engineers and phoneticians to analyze the relationship between the acoustic, linguistic, and articulatory properties of speech. Initial studies included the acoustics of speech production, the electrical synthesis of speech, and the development of systems for the bandwidth compression of speech.

Since its inception, the goal of RLE's Speech Communication group has been to uncover the relationship between the discrete linguistic representation of an utterance, the sound pattern that is produced by a speaker, and how that pattern is decoded by a listener. The group's experimental work contributes to the development of models of human production and perception of natural speech. Articulatory movements and sound patterns are measured for both individual speech sounds and larger phrasal units, and the variations of these patterns across contexts and speakers are examined. Models are developed for the production and perception of speech sounds, words, and phrases. Investigators also study the speech of individuals with several kinds of communication disorders, including impaired hearing and laryngeal disorders.

Dr. Kenneth N. Stevens, Clarence Joseph LeBel Professor of Electrical Engineering, has devised methods to study the basic mechanisms of human speech production and perception, speech recognition and synthesis, and hearing- and speech-related problems

Professor Kenneth N. Stevens, Senior Research Scientist Dr. Joseph S. Perkell, and Research Scientist Dr. Reiner Wilhelms-Tricarico in RLE's Speech Communication group laboratory check the design of EMMA, an electromagnetic midsagittal articulometer system. This apparatus is used during experiments to measure the articulatory movements of a subject's tongue, lips, and lower jaw. (Photo by John F. Cook)



Steps in the speech chain: *On the upper left is a cineradiographic tracing of a speaker's vocal tract pronouncing the sound "n." In the center, the sound pressure signal for the utterance "speech communication" is illustrated. On the lower right, the ear represents the first step in the sequence of audition, perception, recognition, and understanding. In RLE, speech communication research includes studies of normal and impaired speech generation processes.*

The Harvard-MIT Division of Health Sciences and Technology: Making Healthy Connections

Although joint efforts in the health sciences between MIT and Harvard date back to the early part of this century, it wasn't until 1977 that the bond was formalized in the Harvard-MIT Division of Health Sciences and Technology. This deep commitment by both schools to address society's needs in the health sciences has been the most long-lasting functional collaboration between the two preeminent institutions.

The Harvard-MIT School for Health Officers, established in 1912 to educate public health officials in preventative medicine and sanitary engineering, became the Harvard School of Public Health in 1922. Collaborative research efforts between Harvard and MIT continued informally for several decades. In 1966, the National Institutes of Public Health approached MIT and proposed that the Institute establish a medical school. After careful consideration, MIT officials determined that a medical school would not be feasible. However, during their explorations into this possibility, they uncovered a strong interest within the faculty and student body in applying engineering and science to problems in health and medicine. They also found interest at Harvard Medical School to develop a program that would combine medicine with engineering and physics.

An agreement between MIT and Harvard Medical School was reached in 1970 to develop a joint research program in medical education and health care, and in 1971, a joint curriculum in medical sciences was established that grants an MD degree from Harvard Medical School. The Harvard-MIT Division of Health Sciences and Technology was formally established in 1977, and in subsequent years, three additional academic degree programs were developed to prepare students for research and leadership roles in academic medicine, biomedical sciences, and biomedical engineering. (Editor's note: The term "division" was chosen rather than "school" because the term "school" had different meanings at the two parent institutions.)

Today, the Harvard-MIT Division of HST provides a unique range of multidisciplinary education to MD and PhD students at both institutions. HST's research programs encompass five main areas: integrative biology and quantitative physiology; biomedical engineering and biological physics; imaging sciences and technology; and the application of computer and statistical techniques to information management (bioinformatics and medical informatics). These programs are designed to train students for careers at the interface of the physical and biological sciences.

The MD program prepares students to become physician-scientists who possess a deep understanding of the quantitative and molecular principles of medicine and biomedical research. The Medical Engineering and Medical Physics doctoral program, established in 1978, provides physicists and engineers with medical science training in a clinical environment. HST's Radiological Science Joint program offers training in physical sciences and engineering related to the applications of radiation to biomedicine.

In 1992, HST's Speech and Hearing Sciences program was started through the efforts of Professor Nelson Y.S. Kiang. This highly multidisciplinary program prepares pre- and postdoctoral students for research careers in the physical and biological aspects of speech and hearing. With sixty faculty members from ten different Harvard and MIT academic departments, students in this program are provided with a broad exposure to biomedical issues, from basic physiology to the diagnosis and treatment of communication disorders.

In addition, HST offers a Medical Informatics program that addresses issues related to health care delivery, biomedical science, and imaging, as well as a Clinical Investigator Training program designed to familiarize postdoctoral physicians with the techniques and processes used in patient-oriented research.

The Harvard-MIT HST program integrates the efforts of engineers, scientists, and clinicians who seek to address problems in human health and clinical medicine. By combining the strengths of the faculties and resources at Harvard and MIT, including Harvard Medical School and its teaching hospitals, HST provides a framework for unparalleled intercollegiate and multidisciplinary opportunities in basic research and applied research and development. Its infrastructure preserves the balance between science, engineering, and medicine while promoting collaborative educational and research programs that neither of the two world-class institutions could provide alone.

caused by speech disorders. His recent investigations have focused on the development of models for speech sound generation, and on the variability that occurs in speech sounds from different speakers and from different modes of speaking. Using these models, Professor Stevens and his group are developing procedures to recognize words in speech and to assess disorders in speech production. Finding significant variability in certain English consonant sounds within different contexts, they have explained this variability in terms of "context-conditioned" differences in tongue movements and in other articulatory structures. The group has also devised methods to measure the deviations from normal speech production of certain consonants in dysarthric speakers, who have difficulty in articulating words due to diseases of the central nervous system. This will help define the quantitative procedures needed to evaluate speech production disorders and to suggest approaches to remedy them.

In exploring the relationship between hearing and speech, Senior Research Scientist Dr. Joseph S. Perkell has been examining the extent to which people need to hear in order to speak normally. Once our ability to speak is acquired, hearing is used mainly to fine-tune the elements of speech (such as rate, pitch, and loudness). His subjects have included specific patient populations such as cochlear implant users and those individuals who suffer from auditory nerve tumors. His research also examines the physiological and biomechanical properties of speech production: how these properties influence our speech, how speech is produced mechanically, and how its movements are controlled. Dr. Perkell's work has involved the development of innovative techniques to characterize the movements of the speech articulators. Models can then be developed to convert the input articulator movements of the tongue, palate, jaw, and lips into a speech waveform output. This has enabled investigators to look at variability patterns associated with speech production. In a method developed by Dr. Perkell, probe coils, or pellets, are attached to the articulators in order to track their movement. Each coil generates three or four signals and the amplitudes of these signals must be recorded with great precision. A computer then digitizes the speech, the pellet signals, and possibly other signals related to airflows and pressures in the mouth.

Working with Dr. Perkell, Research Scientist Dr. Reiner Wilhelms-Tricarico uses computational methods to investigate vocal-tract dynamics. He has built software to generate accurate finite-element models of the tongue and the mouth floor. This software, which was developed to visualize data and to carry out measurements, can interactively generate cross-sectional views of a three-dimensional image. This enables users to define and label points, cubic splines, and surfaces in order to determine morphological structure. It is anticipated that the software will also be useful in generating finite-element models of other organs.

Research Scientist Dr. Stefanie Shattuck-Hufnagel is a psycholinguist who explores how humans plan and produce normal speech. Her research involves building models of the speech production planning process that are based on the prosody (or structure) of spoken utterances and the error patterns contained in them. Her investigations have provided new information about the representations and processes used by speakers when they plan an utterance. Dr. Shattuck-Hufnagel explains, "As we learn more about the way we plan our speech, we will be better equipped to find ways to help others who have trouble speaking because of a stroke, head injury, or developmental problems. It is challenging to develop methods to help others when we know so little about the way the normal speech process works and what can go wrong." She and her colleagues continue to develop the MIT Digitized Speech Error Database, which will enable the analysis of prosodic constraints on speech error occurrence, detection, and correction.

Research Affiliate Dr. Harlan Lane, University Distinguished Professor in the Department of Psychology at Northeastern University, works with RLE's Speech Communication group on the role of hearing in speech. He is carrying out analyses to determine how and why speech deteriorates in adults who become deaf, and how speech changes when some hearing is restored to patients with cochlear implants. Dr. Lane also studies the American Sign Language of the Deaf (ASL) and how it influences not only the universal properties of language, but also the social and educational issues about deaf people.

Research Affiliate Dr. Robert E. Hillman is principal investigator for the Voice Project, which is part of the new W.M. Keck Foundation Neural Prosthesis Research Center. The Voice Project seeks to develop a prototypical artificial larynx that can supply a natural voice and intelligible speech to individuals with impaired laryngeal function. It is anticipated that the voice prosthesis will provide an improved sound source that will more closely approximate the normal human voice. Dr. Hillman's research includes studying mechanisms for normal and disordered voice production, the treatment and rehabilitation of voice disorders, and physiologic and acoustical measures for voice and speech production. He serves as director of the Voice and Speech Laboratory at the Massachusetts Eye and Ear Infirmary, as director of the graduate program in Communication Sciences and Disorders at Massachusetts General Hospital's Institute of Health Professions, and as director of the Voice Disorders Center of the Harvard Medical School. In addition, he is associate professor in the Department of Otolaryngology at Harvard Medical School.

SENSORY COMMUNICATION

New Dimensions in Sensory Research

We normally think of language as the backbone of human communication and cognition. However, human sensory capability is essential for many communication tasks. Our five senses convey the information we need to perceive the sensations caused by stimuli in our environment. It is only through our sensory systems that we gather knowledge from the world around us. What can be learned by exploring our sensory mechanisms and their relationships to physiological and psychological phenomena? Although the physical events around us can be measured, we perceive them in a way that is difficult to measure. The field of psychophysics examines this relationship between physical stimuli in our environment and our psychological reactions to our behavior towards them. Psychophysics research has provided clues to how the mind works by examining how it processes physical stimuli from our environment, and its techniques are a key to unlocking the mysteries of human perceptual processes. Today in RLE's Sensory Communication group, psychophysical studies of human sensory perception encompass the auditory, visual, and tactile modalities.

Aids for Deaf and Hard-of-Hearing Individuals

Hearing impairment affects more than 30 million Americans, thus making it the third most common chronic affliction that affects people of all ages in this country. The largest group that suffers from hearing loss is the elderly, and approximately one-third of individuals older than 65 is affected. However, hearing impairment and, more importantly, deafness, also affect the very

RLE's Sensory Communication group is involved in the study of multimodal sensory perception for a variety of applications. Investigators in this group include (from left): Senior Research Scientist Nathaniel I. Durlach; Principal Research Scientist Dr. Charlotte M. Reed; Research Scientist Lorraine A. Delhorne; Dr. Louis D. Braida, Henry Ellis Warren Professor of Electrical Engineering; Research Affiliate Dr. Richard M. Held, Professor of Brain and Cognitive Sciences; and Principal Research Scientist Patrick M. Zurek. (Photo by John F. Cook)

young. Approximately one to two children in 1000 is born deaf, and less severe impairments are diagnosed in many more during childhood. Prelingual loss of hearing, that is, the loss of hearing before one acquires speech and linguistic skills, can have major effects on the acquisition of these skills as well as on the education and development of a deaf child. Scientists in RLE's Sensory Communication group are attempting to develop improved acoustic hearing aids and communication aids for the deaf community.

Hearing Aid Research

Dr. Louis D. Braida, Henry Ellis Warren Professor of Electrical Engineering; Senior Research Scientist Nathaniel I. Durlach; Principal Research Scientist Dr. Patrick M. Zurek; Research Scientist Dr. Julie E. Greenberg; and Research Associate Dr. Paul Duchnowski lead the Sensory Communication group's research on hearing aids. Their work is directed at improving speech reception for people with sensorineural hearing impairments, who constitute the majority of hearing aid users. The goal of this work is to determine and understand fundamental limitations on the improvements in speech reception that can be achieved by processing speech; and, within these limitations, to develop optimal processing schemes for use in hearing aids. The aim of the group's basic research is to determine both the characteristics of the hearing impairment and of the speech signal that are responsible for a reduced ability to understand natural and processed speech. The group seeks to embody this understanding in models of speech intelligibility in order to guide the development of improved aids. Applied research attempts to determine and evaluate promising signal-processing methods for improved hearing aid performance.

Selective functional simulations of hearing loss are being developed that allow listeners with normal hearing to evaluate factors such as: loss of sensitivity and reduction in auditory area; degraded resolution in the amplitude, frequency and time domains; and perceptual distortions. These simulations are carried out in order to assess how the various changes in auditory function associated with hearing impairments can contribute to reduced speech-reception capacity.

How speaking style affects the speech reception of hearing-impaired listeners is being studied to gain better insight into new signal-processing schemes for hearing aids. Clearly enunciated speech is more intelligible than conversational speech under various presentation conditions. Differences in the acoustical properties of clear and conversational speech are examined to isolate the factors responsible for the high intelligibility of clear speech. Using this knowledge, it may be possible to develop signal-processing algorithms for hearing aids that can mimic the changes made when someone speaks clearly.

Analytical models are being developed and evaluated to predict intelligibility scores for specified waveforms and listener characteristics. These models seek to understand the effects of alterations of the speech signal on speech reception. Used in conjunction with functional simulations of sensorineural hearing impairment, such models can predict the effects of perceptual distortions on speech reception. These models may also be capable of predicting the effects of promising, new signal-processing schemes for hearing aids.

Signal-processing techniques based on new methods to automatically control gain and frequency-gain characteristics are being developed and evaluated. These techniques present amplified sounds to hearing aid users at levels that are comfortable for long-term listening and are nearly optimal for speech understanding. Studies are aimed at new methods for measuring differences among subjective attributes of processed sound that are important to hearing aid users, such as comfort, quality, and annoyance.

In order to improve the intelligibility of speech in the presence of noise and reverberation, algorithms are being developed to process signals from a head-worn array of microphones. Several issues are being investigated in this project, including: the benefits and costs of fixed (time-invariant) algorithms versus adaptive algorithms, the impact of directional systems on the ability to localize sound sources, the speed of adaptation, and the benefit of adaptive systems in reverberant environments.

A field study is being conducted to evaluate advanced signal-processing algorithms under realistic conditions.

Subjects are outfitted with wearable digital signal processors, microphone arrays, and insert receivers. This equipment allows the subjects to judge the effectiveness of experimental algorithms in their daily environments. The signal-processing algorithms that will be implemented in these devices are being determined in preliminary laboratory evaluations. These experimental algorithms seek to improve speech reception in background noise, to prevent loudness discomfort, and to increase maximum gain without feedback.

New types of hearing aids are being developed that extract the amplitude envelopes of speech bands and then convey them by modulating the amplitudes of audible tones. These new aids may help individuals with hearing loss so severe that amplified speech is used primarily as an aid to speechreading. Such signals can supplement speechreading effectively, but they also must be adapted for hearing-impaired listeners, taking into account the perceptual distortions associated with their limited auditory area and reduced auditory resolution.

Aids for Deaf Individuals

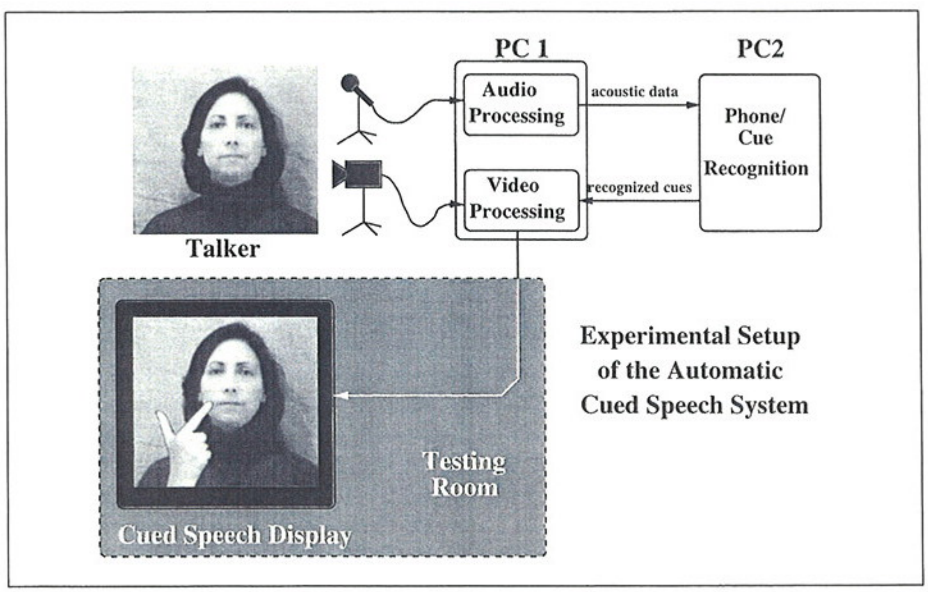
In order to help individuals who are unable to benefit from the acoustic presentation of amplified sound, scientists in the Sensory Communication group study techniques based on electro-auditory, tactile, and visual stimulation.

In collaboration with the Cochlear Implant Research Laboratory at the Massachusetts Eye and Ear Infirmary (see section on CIRL on page 17), research on cochlear implant devices is carried out by Research Affiliate Dr. William M. Rabinowitz and Research Scientist Lorraine A. Delhorne. Cochlear implant devices, which address the condition of total deafness, involve the surgical implantation of an electrode array into the inner ear. In response to sound, this array is driven to stimulate the auditory nerve directly. Using existing devices, the majority of implant users receive a substantial benefit to lipreading, which allows them to communicate better and more easily. With improved signal-processing schemes recently introduced into wearable devices, many implant users can now understand speech moderately well using the implant alone. Work on cochlear implant devices in the Sensory Communication group has focused on the documentation of speech reception performance in implant users, interpreting performance limitations in terms of the underlying aspects of speech signals, and comparing performance among different implant systems and other prostheses for deaf individuals. Ongoing work includes the development of an auditory simulation of speech perception using a cochlear implant device, as well as a comparative performance evaluation using a variety of promising signal-processing schemes.

Research on the tactual communication of speech is conducted by Principal Research Scientist Dr. Charlotte M. Reed, Senior Research Scientist Nathaniel I. Durlach, Research Affiliate Dr. William M. Rabinowitz, Research Scientist Lorraine A. Delhorne, and Visiting Scientist Geoffrey L. Plant. This research involves the development of tactual aids that serve as substitutes for hearing in speech communication for deaf and deaf-blind individuals. These tactual aids enable deaf people to achieve substantially improved speech perception, speech production, and overall linguistic competence. In addition, research is aimed at increasing knowledge about the nature of speech

Dr. Hong Z. Tan, former researcher in RLE's Sensory Communication group, developed the Tactuator, a sensory stimulation device that delivers two types of sensory stimulation to the hand: kinesthetic via motion and cutaneous via vibration. Many earlier artificial tactual displays were limited to cutaneous stimulation and were not applied to the hand, which is rich in nerve endings. In contrast, the Tactuator provides a perceptually richer display that may lead to higher information transfer rates of at least 12 bits per second. This is comparable to estimated rates achieved in speech reception using the Tadoma method. The Tactuator is capable of producing "abstract" stimuli that can be used as codes for speech sounds, which must then be learned by its user. (Photo by John F. Cook)

Two experienced Tadoma method users who are deaf and blind (Leonard Dowdy on the left and Raymond Boduch on the right) communicate with each other and Senior Research Scientist Nathaniel I. Durlach (center), who is able to hear and see. In this method, speech is received by placing a hand on the talker's face and then monitoring the mechanical actions associated with the speech production process. This tactile communication method is studied in RLE's Sensory Communication group to determine its effectiveness in speech reception. (Photo by Hansi Durlach)



Studies of the reception of automatically cued speech as a speechreading supplement are being investigated by RLE's Sensory Communication group. This illustration demonstrates an automatic cued speech system, where the acoustic waveform and an image of the talker are processed by PC1, while PC2 recognizes the spoken phones. Phones are speech sounds considered as physical events without regard to their place in the sound system of a language. PC2 also implements a finite-state machine that converts the sequence of recognized phones into cues that specify the shape and position of the hand superimposed on the image of the talker's face. PC1 delays the image of the talker's face so that the cues are synchronized with facial actions.

communication, the capabilities of the tactual sense, the underlying principles of display design, and sensory substitution and human plasticity. Plasticity refers to the phenomenon that allows information to be transmitted over several different sensory modalities.

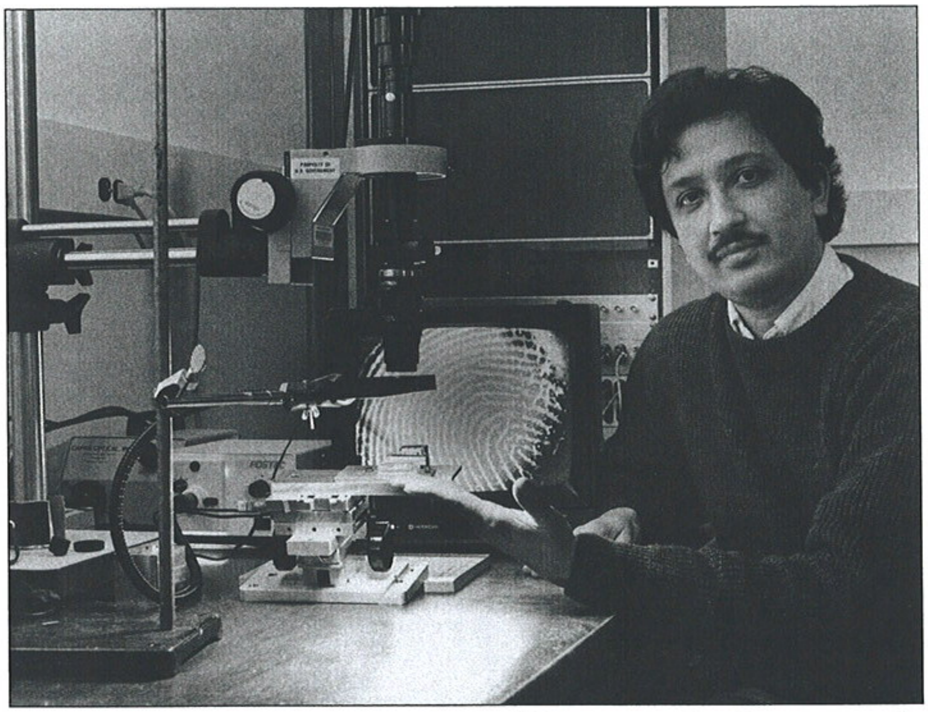
Earlier research conducted by the group has demonstrated the effectiveness of various natural methods of tactual communication used by deaf-blind individuals. These methods include the Tadoma method of speech communication (in which a deaf-blind individual monitors speech by placing his or her hand on the speaker's face and neck), the tactual reception of fingerspelling, and the tactual reception of sign language. Studies involving experienced deaf-blind users of each method have indicated that not only is good speech reception possible through the tactual sense, but also that high levels of communication efficiency can be achieved without monitoring the articulatory processes of speech and without having exceptional tactual sensitivity. The properties common to successful natural methods of tactual communication include perceptually rich displays that include both cutaneous and kinesthetic stimulation of the hand and strong motivation and training to communicate successfully with the display. These results provide a general framework for ongoing work involving the basic study of encoding and display schemes, tactual supplements to speechreading, and the evaluation of practical tactual aids.

A new multifinger tactual display was developed to deliver multicomponent stimuli that evoke sensations along the entire tactual continuum from the kinesthetic to cutaneous senses. The information transmission capabilities of this display are being assessed in a series of experiments. Results suggest that the information-transfer rates achieved through this display are comparable to those observed in the reception of speech through the Tadoma method (which is approximately 12 bits per second). In another investigation involving speechreading, research is being conducted to compare the benefits of a supplementary low-bandwidth signal (derived from the acoustic speech signal) that is presented through either the auditory or tactual system. Studies are also being carried out on the performance of deaf children and adults who use wearable tactile aids. The studies with children examine the effects of training on the development of speech reception and speech production. In a field study of deaf adults, evaluations are being conducted on speech reception (primarily as a supplement to speechreading) and on the ability to identify sets of environmental sounds. The results of this research suggest that tactile aids not only improve speechreading ability, but they also help in the identification of various environmental sounds.

Speechreading supplements that can be presented visually to deaf individuals are studied by Professor Louis D. Braida and Research Associate Dr. Paul Duchnowski. Their work focuses on the use of automatic speech recognition in order to derive supplements related to the "Manual Cued Speech System," which has been used effectively in educational and communication settings by deaf individuals. Such supplements consist of streams of discrete symbols presented synchronously with the speaker's visible facial actions. It may be possible to adapt these supplements to help deaf individuals acquire and maintain the skills needed for speech production.

Research and Development in Virtual Environments and Teleoperation

Research on virtual environment and teleoperator systems is being conducted by Senior Research Scientist Nathaniel I. Durlach, Principal Research Scientist Dr. Mandayam A. Srinivasan, Research Scientist Dr. Thomas E. Von Wiegand, Visiting Scientist Dr. Cagatay Basdogan, and Research Affiliate Professor Richard M. Held. Work in this area is directed toward the improvement of human-machine interfaces for teleoperator and virtual environment systems, the application of virtual environment systems to training, and an increased basic understanding of human sensorimotor performance, perception, and cognition.



By recording video images of contact regions and their corresponding forces, Principal Research Scientist Dr. Mandayam A. Srinivasan and his colleagues in the "Touch Lab" of RLE's Sensory Communication group investigate the mechanics involved in the contact between the human fingerpad and transparent test objects that differ in their mechanical properties. This data is used to infer mechanisms of tactile information processing by developing biomechanical models of the fingerpad. These models are used to interpret the results of neurophysiological and psychophysical experiments performed with the same test objects. (Photo by John F. Cook)

A teleoperator system consists of a human operator, a human-machine interface, and a remote device called a telerobot. The telerobot's mechanisms can sense signals in its environment, which it communicates to the human operator. The signals are conveyed to the human operator by displays that are part of the human-machine interface. The human operator's responses to the telerobot are detected by devices in the human-machine interface and transmitted back to the telerobot to control its behavior. Thus, in a teleoperator system, the human operator interacts with a real-world environment using an artificially transformed and extended sensorimotor system.

Virtual environments (sometimes called artificial realities) also involve a human operator and a human-machine interface. However, in a virtual environment, a computer replaces both the teleoperator's real-world environment and the telerobot. The human operator interacts with a computer-generated virtual world. In contrast to traditional simulation systems, the simulations in a virtual environment are more intimately tied to the human operator by a general-purpose interface that matches the human sensory systems. Also, these simulations often include virtualization of the near field, that is, the field within reach of the operator. Whereas the objective of teleoperator systems is to sense, navigate through, or operate upon the real environment, the objective of virtual environment systems is to alter the human operator's state or alter the information environment.

Current projects include studies of visual depth perception and auditory localization perception in virtual environments, manual sensing and manipulation of virtual objects, sensorimotor adaptation to intermodal distortions in virtual environments, and the benefits of sensorimotor involvement in the learning of cognitive skills. Applications of virtual environment technology to training are focused on the training of skills required for surface ship handling, piloting remotely controlled (teleoperated) underwater vehicles, and the acquisition of spatial knowledge and it use for spatial navigation.

As is the case with audition studies in the Sensory Communication group, work on haptics goes beyond its connection with virtual environments and teleoperation. The human haptic system includes our tactile and kinesthetic subsystems, as well as the human motor system that enables the control of body posture, motions, and forces. It helps us to identify various textured surfaces, recognize the shape or softness of objects, and generally be aware of our surroundings. Haptic research in RLE seeks to increase our basic knowledge about manual sensing and manipulation, improve the clinical diagnosis and treatment of hand impairments, and contribute to the design of artificial hands used in robotic systems. It may also provide the deaf and blind communities with possibilities for an additional communication input channel and may increase the amount of information that can be acquired.

Principal Research Scientist Dr. Mandayam A. Srinivasan studies the sensorimotor mechanisms in the human hand, particularly in terms of manipulation and the sense of touch in the fingers. He and his colleagues in RLE's "Touch Lab" explore all aspects of the human hand and its interaction with objects as it relates to mechanics, sensorimotor functions, and cognition. The goals of the research conducted in the "Touch Lab" are to understand human haptics, develop machine haptics, and enhance human-machine interactions in virtual reality and teleoperator systems.

In order to gain a deeper understanding of human haptics, multidisciplinary investigations involving skin biomechanics, neurophysiology, psychophysics, motor control, and computational models are employed. Typical projects involve the measurement of human capabilities in manual tasks that employ computer-controlled electromechanical apparatus, and the determination of the biomechanical, neural, and perceptual mechanisms that underlie performance in these tasks. To develop haptic machines that enable the user to touch and feel virtual reality, electromechanical devices and rendering software are designed. Studies are conducted on the human perception of computer-generated virtual objects under purely haptic and multisensory conditions. The benefits of this research include applications to hand therapy, intelligent prosthesis design, and the development of autonomous robots that perform human-like functions in unstructured environments. In collaboration with Massachusetts General Hospital, a new project led by Dr. Cagatay Basdogan seeks to develop a surgical simulator for laparoscopic procedures. Using this simulator, a surgical trainee can not only see the virtual tissues graphically, but also feel and manipulate them haptically.

Principal Research Scientist Dr. J. Kenneth Salisbury works on the design of medical robotic systems to enhance dexterity in laparoscopic procedures. This includes the development of the visual and touch simulation of surgical procedures to enhance real-time telesurgery. It is anticipated that these types of haptic interfaces will allow users to virtually feel the texture and

The Massachusetts Eye and Ear Infirmary: A Clear Vision, A Sound Future

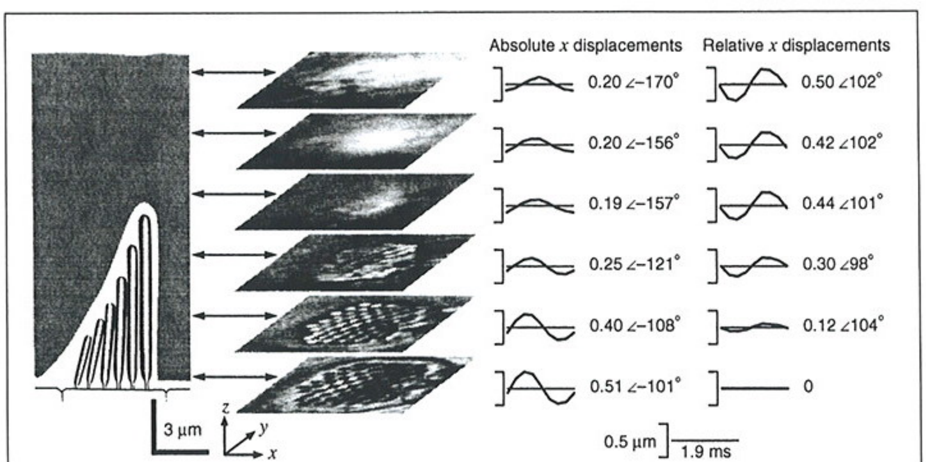
Massachusetts Eye and Ear Infirmary

The Massachusetts Eye and Ear Infirmary is a specialty hospital dedicated to excellence in the care of disorders that affect the eye, ear, nose, and throat, as well as the head and neck regions. The infirmary and its Department of Otolaryngology are committed to educating clinicians, researchers, and the public about prevention, diagnosis, treatment, and rehabilitation. MEEI offers a unique environment that combines research (basic and clinical) with patient care and teaching. The Department of Otolaryngology at MEEI has more basic researchers than many larger departments, and several faculty and students from RLE's Auditory Physiology group are actively involved in collaborations there. MEEI's scientists and clinicians teach undergraduates, graduate students, medical students, postdoctoral fellows, and resident surgeons. Students generally conduct research in laboratories headed by infirmary staff, and many students are affiliated with the Harvard-MIT Division of Health Sciences and Technology (see article on page 7).

Otolaryngology research at MEEI began in the early 1800s, but it wasn't until after World War II that research in this area emphasized the underlying physiological mechanisms of the auditory system. When Dr. John W. Irwin established the infirmary's Microcirculatory Laboratory, he realized that basic research scientists were needed. With otolaryngologist Dr. Francis Weille, he started discussions in the mid-1950s with then-MIT president Dr. James R. Killian, Jr. that resulted in the establishment of the Eaton-Peabody Laboratory at MEEI. (See article on page 15.) Today, more than forty years later, EPL remains a basic academic laboratory committed to auditory physiology research in a clinical setting. EPL effectively brings together faculty and students from both MIT and Harvard Medical School, along with clinical researchers from MEEI and Massachusetts General Hospital, to work on interdisciplinary research teams.

The Department of Otolaryngology now houses a broad range of research in areas related to the anatomy, physiology, and disorders of the ear, the vestibular (balance) system, and the head and neck. An effort is made to transfer basic research obtained in MEEI's laboratories and apply it to work being carried out in its other laboratories. One example is the transfer of basic information on cochlear implants that is acquired in EPL and applied in the infirmary's Cochlear Implant Research Laboratory (see related cover story sections on EPL and CIRL on pages 16 and 17).

The sensory receptor cells of the inner ear are stimulated by sound-induced motions of microscopic sensory hairs that protrude from the cell's surface. These sensory hairs and other structures in the inner ear comprise a complex hydromechanical system that not only contributes to ear's remarkable sensitivity, but also performs important signal-processing functions. Professor Dennis M. Freeman and his colleagues in RLE's Auditory Physiology group have developed a video system to measure the mechanical properties of inner-ear structures. Video images are recorded by computer and then analyzed so that the basic three-dimensional structure and its motion can be visualized.
(Photo by John F. Cook)



In order to simulate the motions of structures in the middle ear, the cochlea of an alligator lizard is stimulated by an underwater pressure transducer and observed with a microscope. Key structures, including hair bundles and the tectorial membrane, are directly imaged to determine relations between the motions of these structures during acoustic stimulation. These relations have not been measured previously. The schematic diagram (at left) shows planes of section containing six sensory hairs in the bundle of one cell and the overlying tectorial membrane (darker area). These planes are connected by arrows to a corresponding sequence of images with 3-micrometer spacing developed from the video microscopy imaging system used in RLE's Auditory Physiology group. The leftmost waveforms show average displacements of the stereocilia in the x direction during one cycle of the stimulus. The associated numbers are the peak-to-peak magnitude (measured in micrometers) and the angle (in degrees) of the fundamental component of the displacement. The rightmost waveforms show relative differences between the left waveforms and the bottom left waveform.

shape of objects displayed on a computer screen. Dr. Salisbury is also affiliated with MIT's Mechanical Engineering Department and the Artificial Intelligence Laboratory.

AUDITORY PHYSIOLOGY

Sensations in Sound

Communication signals must be both produced and perceived, and although RLE's research in speech perception and auditory psychophysics are focused on the perception of acoustical signals, these areas build on the basic understanding of auditory physiology. Investigators in RLE's Auditory Physiology group examine how the auditory system works and, in particular, seek to understand the mechanisms associated with the coding of acoustic stimuli. The aim of this work is to determine what "language" is used by our sensory nervous system to describe the outside acoustic environment. Such fundamental knowledge is a step toward understanding higher level cognitive behavior in humans.

By way of a bundle of microscopic hairs, sensory cells in the inner ear sense the sound-induced motions of inner-ear structures and trigger the neural messages that inform the brain about external sounds. RLE's Auditory Physiology group studies these auditory mechanisms and their effects on hearing. Theoretical and experimental studies are focused on how both the structures involved in auditory signal processing carry out their function and how they contribute to sound perception.

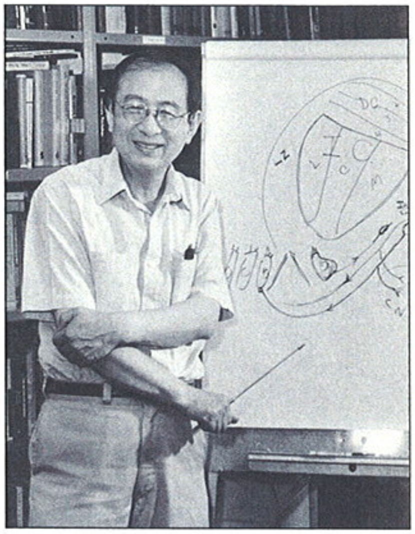
Professor Dennis M. Freeman has devised techniques to study the submicron motion of hair cells in the inner ear of the alligator lizard. He has shown how these hair cells move in response to the sound-produced vibrations in the inner ear. The hair cells have tufts of sensory hairs that, when displaced, produce electrical and chemical signals to the brain with information about a particular sound. These studies promise a better understanding of inner-ear (cochlear) mechanical processes in mammals. His group has also developed video methods to measure motions as small as nanometers. They are applying these methods to measure the mechanical properties and sound-induced motions of essential inner-ear structures. Using similar methods, they have begun studies of other microelectromechanical systems (MEMS), including microfabricated

Eaton Peabody Laboratory: From the Beginning

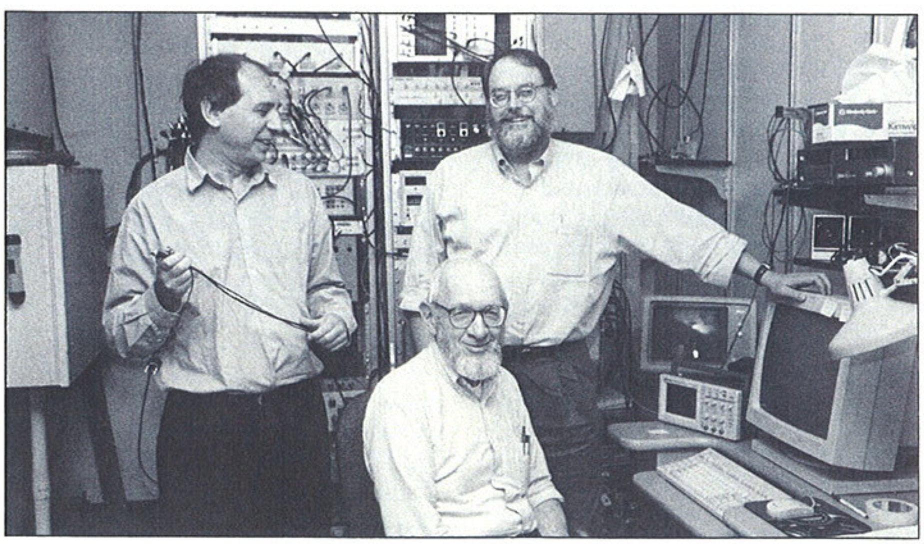
After graduating from the University of Chicago in 1955 with a doctorate in biophysics, Dr. Nelson Y.S. Kiang joined the research staff in RLE's Communications Biophysics group. The following year, he became the first appointment to the newly established Eaton-Peabody Laboratory at the Massachusetts Eye and Ear Infirmary, where he served as director from 1962 to 1996. He was appointed to MIT's faculty in 1983, and has held a faculty appointment in Harvard Medical School's Department of Otology and Laryngology. Professor Kiang has also held research appointments at MGH and the MEEI. Today, he is Eaton-Peabody Professor in the Harvard-MIT Division of Health Sciences and Technology, where he was instrumental in starting the Speech and Hearing Sciences Program in 1992. Professor Kiang recalled the impetus for establishing the Eaton-Peabody Laboratory at MEEI in a 1989 interview with ***RLE currents:***

"At the start, it was very fuzzy. The goal of the ear-nose-throat doctors was to get science started at the Massachusetts Eye and Ear Infirmary, so they sought advice from professional research people. This was almost thirty-five years ago, and very little research of a basic nature was going on at the Infirmary. As I understand the story, they were dedicating a building as the research component of the Eye and Ear Infirmary. At the dedication ceremony, Dr. Killian, who was then president of MIT, commented that it was too bad they didn't have any real science going on here. The doctors thought they were dedicating a building for scientific research, and here's someone telling them they didn't have any research going on! The surgeons were intrigued by his comments, so they decided to enlist his cooperation.

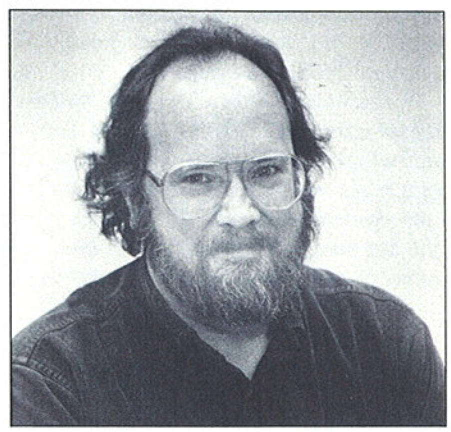
Dr. Killian found Walter Rosenblith doing auditory work at RLE, and asked him to help the Eye and Ear Infirmary set up a laboratory. Walter assigned three of us to look at the situation—Larry Frishkopf, Robert Brown, and myself—and we met with the people from the Eye and Ear Infirmary. That's how I met Dr. John Irwin, a close friend of Dr. Francis Weille, an otolaryngologist. Dr. Irwin was a microcirculation expert in the Mass General's allergy unit who had come to the Eye and Ear Infirmary to start basic research on otolaryngology. So, our group of three from MIT met with Dr. Irwin and Dr. Weille, and that's how things began."



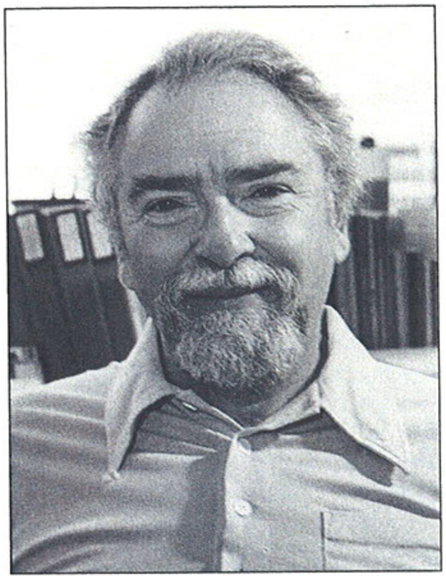
Dr. Nelson Y.S. Kiang, Eaton-Peabody Professor (Photo by John F. Cook)



Research Scientist Dr. Bertrand A.R. Delgutte (at left), Professor William T. Peake (seated), and Principal Research Scientist Dr. Donald K. Eddington discuss their work in an experimental facility at the Eaton-Peabody Laboratory of Auditory Physiology at the Massachusetts Eye and Ear Infirmary. Investigators use this facility to control stimuli and process recorded responses when studying the auditory system's responses to acoustic stimuli. It is also used to deliver electric stimuli to the ear for studies involving cochlear implant devices. (Photo by John F. Cook)



RLE Research Affiliate Dr. John J. Rosowski seeks to understand the role of the different middle-ear structures and how they are affected by disease. At the Eaton-Peabody Laboratory at the Massachusetts Eye and Ear Infirmary, he conducts several investigations in order to further this understanding, including comparative studies involving the variation of structure in vertebrate ears. (Photo by John F. Cook)



Dr. Thomas F. Weiss, Thomas and Gerd Perkins Professor of Electrical and Bioengineering, explores the cochlear mechanism by which sound stimuli are encoded into auditory nerve signals. His recent investigations in RLE's Auditory Physiology group have centered on the hydrodynamics underlying the motion of sensory hair cell bundles. This motion is transduced by the sensory cells to produce messages in nerve fibers.
(Photo by John F. Cook)

What's in a Name?

Our coverage of the Eaton-Peabody Laboratory at the Massachusetts Eye and Ear Infirmary raised two questions: Who was Eaton and who was Peabody?

In the early 1950s, Dr. Francis Weille, an otolaryngologist at MEEI, treated two distinguished patients: Miss Amelia Peabody of Dover, Massachusetts, and Dr. James R. Killian, Jr., then MIT's president. Dr. Weille discussed the possibility of a collaborative effort with Dr. Killian in which MEEI would house and support basic scientists from MIT. Miss Peabody, a renowned Boston sculptor and patron of the arts, provided the generous support needed to establish the Eaton-Peabody Laboratory in 1956. Dr. Killian provided the necessary brainpower to staff the facility, and Dr. Nelson Y.S. Kiang of RLE's Communications Biophysics group became the laboratory's first appointment.

EPL's namesake and benefactress, Amelia Peabody, was born in 1890. A proper Bostonian who described herself as "one of the Kidder Peabody Peabody's" (her father was banker Frank E. Peabody, MIT class of 1877), Miss Peabody was known for her wide range of civic activities. She served on the boards of many Boston organizations and contributing generously of her time and wealth to the different causes in which she believed. A farmer, huntress, horticulturist, and humanitarian, her interests and creativity were far reaching. In 1948, she also sponsored experiments for the first solar-heated house. The Amelia Peabody Charitable Fund of Boston has carried on her good works since her death in 1984.

William Storer Eaton, it was discovered, was her mother's second husband, and it was Miss Peabody's request to bestow the two prestigious names on the newly formed laboratory.

silicon structures that measure acceleration and angular velocity. (For a more in-depth look at Professor Freeman's research in auditory physiology, video microscopy, and MEMS, please see the "Faculty Profile" on page 20.)

Professor William T. Peake studies signal transmission in the normal and pathological auditory system with an emphasis on the acoustic, mechanical, and electrophysiological processes of the ear and on interspecies comparisons. In working toward a theory that would integrate our understanding of signal processing in the ear across vertebrate species, he and his colleagues are developing a description of the structure and acoustic function of the middle ear for all species of the cat family. This work, which is an integrated approach to comparative physiology and the anatomy of animal hearing, aims for general laws of sound transmission through ears by measuring the forces and motions in many different kinds of ears. These laws can then be applied to several problems, such as improving the techniques used in the surgical reconstruction of the ear and determining how the external and middle ears contribute to hearing in diseased ears or in ears with vastly different structures.

Dr. Thomas F. Weiss, Thomas and Gerd Perkins Professor of Electrical and Bioengineering, studies signal processing in the auditory system and, specifically, the inner ear's complex process of transduction, which involves the transduction of mechanical signals into a neural representation. His research in this area focuses on the microscopic motion of sensory hair cell bundles in the inner ear and how their motions transmit mechanical stimuli. The aim of this work is to understand the nature of the hydrodynamics that form the basis of hair bundle motion. His approach in attempting to comprehend the properties of the mechanical, electrical, and neural signals in the peripheral auditory system employs the use of several computer-assisted techniques. He and his colleagues recently built an interactive simulator that allows investigators to conduct an in-depth study of the generation of nerve spike potentials.

The Eaton-Peabody Laboratory at the Massachusetts Eye and Ear Infirmary

The Eaton-Peabody Laboratory (EPL) is an interdisciplinary laboratory dedicated to the understanding of acoustical stimulus reception and processing in the normal and pathological auditory system. The laboratory was established in 1956 at the Massachusetts Eye and Ear Infirmary as a joint operation of the infirmary, MIT (through RLE), and the Harvard Medical School. The staff consists of about 35 people, of whom 17 form a group of senior investigators whose backgrounds are quite diverse. For example, the investigators who study the neural processes of the central nervous system include scientists with degrees in physiology, electrical engineering, medicine, neuroanatomy, and biopsychology.

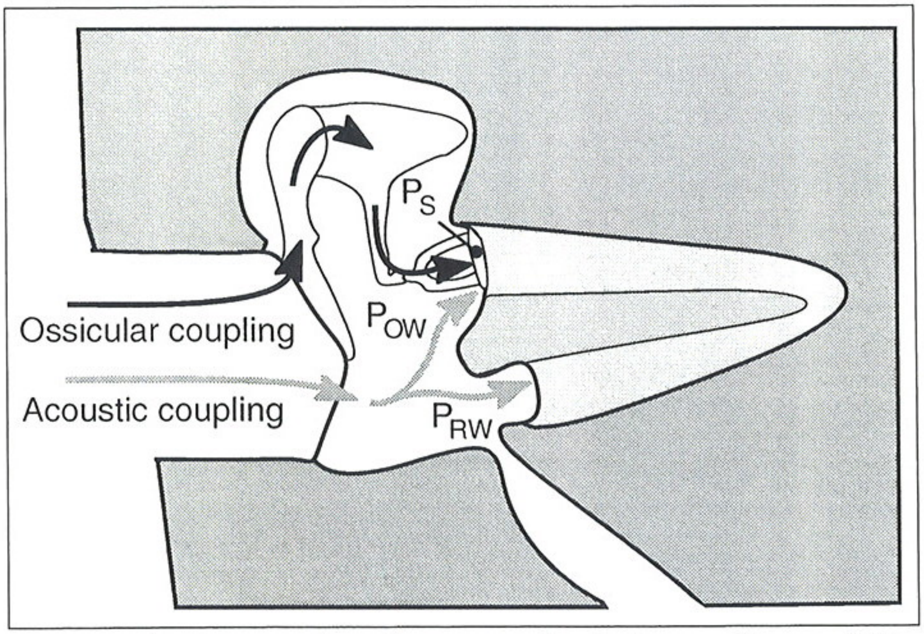
Projects range from basic science, such as the search for a chemical transmitter substance at the junction between the inner ear and the nervous system, to applied projects, such as the analysis of acoustic performance in reconstructed middle ears in humans. Investigators cooperate with Massachusetts General Hospital in the use of imaging methods to study auditory brain activity in humans.

Over the years, EPL has been a leader in advancing knowledge of the mechanisms involved in the mechanical processes of the middle ear, the transduction processes of the inner ear, the coding of acoustic stimuli in the neurons of the auditory nerve and cochlear nucleus, the effects of intense sound on the inner ear, feedback control signals from the brain to the ear, the analysis of evoked potentials from the auditory nervous system, speech coding in the nervous system, and neuroanatomical investigations.

The coding of sound in the auditory system is the focus of Research Scientist Dr. Bertrand A.R. Delgutte. Using recordings from auditory-nerve fibers, he has generated models that show a relationship between auditory nerve responses and acoustic stimuli. Recent work with colleagues at EPL has suggested that musical pitch may correspond to the most frequent interval between action potentials in the entire auditory nerve. This interpretation helps to explain the phenomenon known as the "missing fundamental," which describes the listener's experience of hearing a pitch at the fundamental frequency of a voice or instrument even when that frequency is not present. This phenomenon has long been studied by experimental psychologists, physiologists, and musicians.

Dr. Delgutte also seeks to develop an improved hearing-aid design by observing how inner-ear mechanics affect low-frequency sounds. In this area, he conducts studies with electric stimuli to determine auditory nerve activity produced by cochlear implant devices.

RLE Research Affiliate Dr. John J. Rosowski and his colleagues have recently worked on quantifying the changes in middle-ear mechanics that are produced by perforations of the human tympanic membrane. By evaluating the functional mechanisms for these losses, he has demonstrated that, in small perforations, the losses can be explained by a decrease in sound pressure difference across the tympanic membrane. Larger perforations appear to affect the coupling of tympanic-membrane and ossicular motions. Dr. Rosowski's findings are significant for the design and placement of tympanostomy tubes, which act as controlled perforations to alleviate middle-ear infections. Dr. Rosowski also collaborates with Professor William Peake to measure the mechanics and acoustics of the external and middle ears of normal and diseased human ears, as well as the ears of other terrestrial vertebrates.

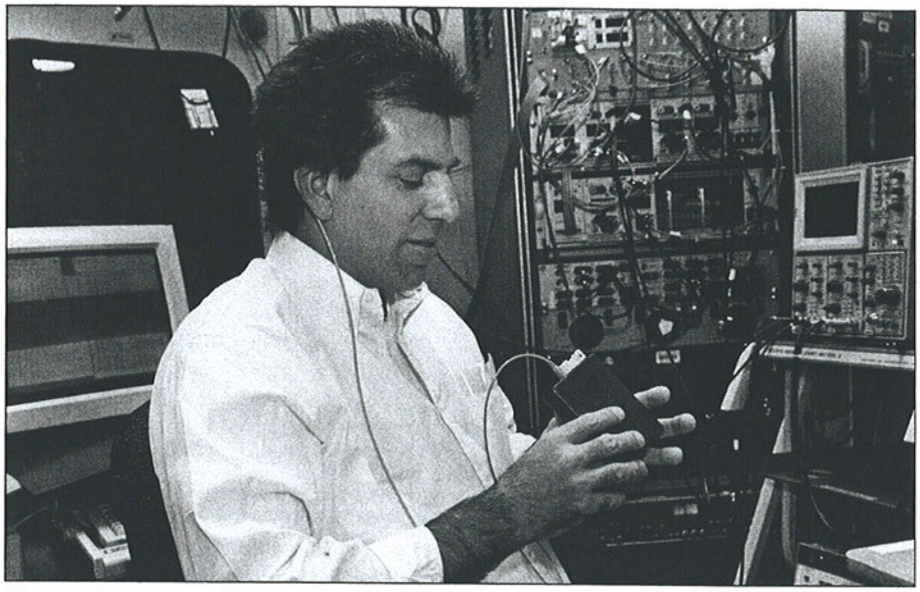


A schematic that shows ossicular and acoustic coupling. In the normal human middle ear, sound signals from the external auditory canal can be transmitted to the cochlea by two mechanisms: the tympano-ossicular system, which achieves ossicular coupling (P_S), *and the direct acoustic stimulation of the oval window* (P_{OW}) *and round window* (P_{RW}), *which results in acoustic coupling. Physiological and anatomical studies of middle-ear mechanisms have led to quantitative descriptions that relate properties of middle-ear structures to their acoustic and mechanical functions. These descriptions are developed by investigators in RLE's Auditory Physiology group in collaboration with colleagues at the Massachusetts Eye and Ear Infirmary and the Harvard Medical School. This work enables clinicians to understand the pathophysiology of conductive hearing loss caused by middle-ear lesions and to predict the results of reconstructive middle-ear surgery.*

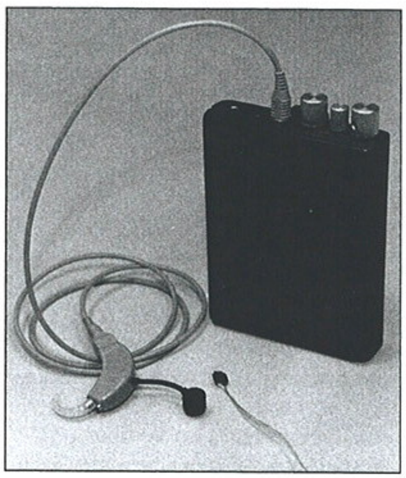
The Cochlear Implant Research Laboratory at the Massachusetts Eye and Ear Infirmary

Most people who suffer profound hearing impairment cannot translate the mechanical energy of sound into the nerve signals that the brain uses to hear. Cochlear implants are electronic devices comprised of a microphone connected to an externally worn sound processor that stimulates an array of electrodes implanted in the deaf patient's cochlea (inner ear). The processor translates sound into electric stimuli that are delivered to the implanted electrodes, where they elicit spike activity on the surrounding auditory nerve fibers. This action successfully provides a measure of sound sensation to the patient. In effect, cochlear implant devices have been described as providing a type of hearing aid that bypasses a malfunctioning ear to deliver electric signals directly to the brain.

The goal of these neuroprosthetic systems is to elicit patterns of nerve activity that mimic the activity in a normal ear for a wide range of sounds. Such a system may enable postlingually deafened individuals who have a sufficient number of remaining nerve fibers to recognize spontaneously all types of sound, including speech. While the sensations produced by today's devices enable most cochlear implant users to communicate fluently when combined with lipreading, only 15 percent are able



Since undergoing cochlear implantation more than ten years ago, Michael Pierschalla has served as a research subject in a joint program conducted by RLE and the Massachusetts Eye and Ear Infirmary (MEEI). Michael demonstrates the Geneva/MIT sound-processing system, which has been given to nineteen other subjects in the MIT/MEEI research program. Compared to the commercial devices worn by the subjects in this program, most of them have experienced significantly better speech reception with this experimental processing system. (Photo by John F. Cook)



The components of a cochlear implant system designed to restore a measure of hearing to profoundly deaf patients (clockwize from left): the earhook, the processor, and the implant. The programmable, Walkman-sized processor is an experimental device designed by a team of scientists and engineers from MIT, the Hospital Cantonal Universtaire and École d'Engineers in Geneva, Switzerland, and the Research Triangle Institute. A cable connects the sound processor to an earhook that contains a microphone and distributes the processor's six output leads to a pedestal connector. The implant consists of a bundle of six electrodes inserted into the cochlear and two ground electrodes. All eight electrodes terminate in a connector housed in a percutaneous pedestal that is anchored to the bone and protrudes through the skin. Software developed by investigators at MIT makes it possible for research subjects to field-test promising sound-processing strategies developed in MIT/MEEI laboratories. (Photo by John F. Cook)

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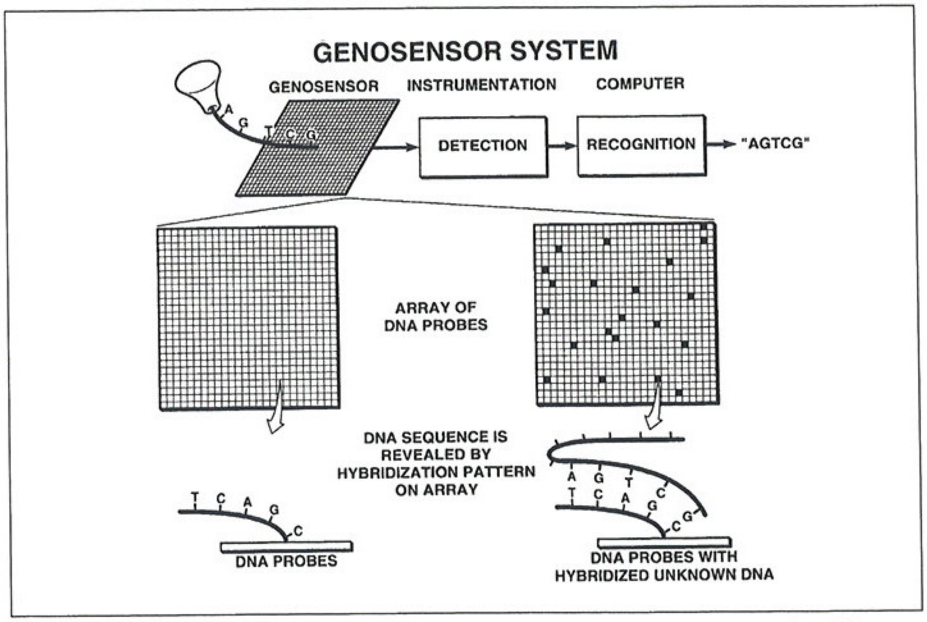
to carry on fluent conversations without lipreading. (In related research, RLE's Sensory Communication group found that, when used in conjunction with lipreading, cochlear implant devices provide substantial benefits to speech reception, thus enabling more reliable and comfortable communication. The Sensory Communication group continues to document the speech perception performance of individuals with cochlear implants, with an emphasis on the improved design and ongoing evaluation of processing schemes that may improve implant performance.)

Research carried out by the multidisciplinary group of clinicians and scientists at the Cochlear Implant Research Laboratory (CIRL) focuses on the fundamental mechanisms underlying the sound sensations produced by electric stimulation of the auditory nerve. For example, the results obtained from computer models of electric current in a cochlear implant and the results obtained from models of how these currents excite the nerve fibers are combined with results from various tests carried out with cochlear implant users. Based on these studies, new sound-processing techniques are being developed that may provide significant improvements in speech reception for some deaf individuals.

Principal Research Scientist Dr. Donald K. Eddington is director of CIRL and an associate professor in Harvard Medical School's Department of Otology and Laryngology. A pioneer in the field of auditory prostheses, he explores the basic mechanisms of hearing and develops the necessary technology (including software and electronics) to improve the performance of auditory neuroprostheses such as cochlear implants. His work involves the electric stimulation of the human auditory system that includes: the evaluation of physiological considerations and the development of models, conducting psychophysical studies of cochlear implant users, and the study of speech coding for electric stimulation and implantable hardware. By understanding how electric stimuli are transformed into sound perception, investigators can then design the next generation of cochlear implant devices.

In addition, Dr. Eddington was recently named director of the W.M. Keck Foundation Neural Prosthesis Research Center. This effort involves scientists, engineers, physicians, and students from four Boston area institutions working together on the development of neural prostheses that promise improved function for deaf, blind, mute, and balanced-impaired individuals. Investigators from MIT, the Charles Stark Draper Laboratory, the Massachusetts Eye and Ear Infirmary, and Harvard Medical School are now collaborating in a broad area of bioelectronics research in order to develop shared solutions to new neural prosthetic aids. Dr. Eddington serves as principal investigator for the Keck Center's Hearing Project, which seeks to develop a prosthesis that will enable profoundly deaf cochlear implant users to communicate fluently without lipreading. The goal of this project is to produce a wearable neural stimulator that will permit better communication for deaf patients who have been implanted with electrodes for auditory nerve stimulation.



This diagram illustrates a conceptual genosensor system that has been developed by Research Affiliate Mark A. Hollis and Visiting Scientist Dr. Daniel Ehrlich. This system involves working prototypes of microelectronic chips called genosensors, which are part of a new technology for DNA sequence determination. The prototypes being developed in RLE may provide a substantial increase in speed over conventional DNA sequencing methods now used in the biomedical, pharmaceutical, and agricultural industries.

A team of investigators from RLE, the MIT Whitehead Institute for Biomedical Research, (left), and the MIT Lincoln Laboratory are developing innovative genosensor technology at the Whitehead. Since 1982, scientists at the Whitehead in Cambridge, Massachusetts, have provided a new understanding of the genetic origins of human cancer, created novel vaccine therapies for cancer and AIDS, and have made fundamental contributions to gene therapy. RLE's group is carrying out research at the Whitehead to devise a microdetection technology for automated DNA sequencing and to develop microelectromechanical systems for biochemical analysis (bioMEMS).
(Photo by John F. Cook)

ELECTRONICS FOR BIOLOGICAL ANALYSIS

On the Frontier

The new field of microelectromechani cal systems (MEMS) extends integrated-circuit technology from purely electronic devices to micromachines that can sense and manipulate objects. The even newer field of bioMEMS uses miniaturized analytic instruments, such as sensors, that are made of discrete, integrated devices. BioMEMS devices are used to analyze biological molecules such as DNA. Their potential for massive parallelism matches the enormous amount of information needed to identify genes and organisms with the advantage of carrying out computations quickly and inexpensively. For example, as the Human Genome Project begins to identify many genes whose functions are unknown, a direct method that could determine their function would be to learn which proteins interact with these genes and where the genes are located.

Research Affiliate Mark A. Hollis and Visiting Scientist Daniel Ehrlich have devised a new technology for DNA sequence determination that offers the potential for lower cost and higher throughput than conventional techniques based on gel electrophoresis. DNA sequencing is the process used to determine the order of the 3 billion DNA letters that characterize each human being. Drs. Hollis and Ehrlich use an approach that exploits the natural base-pairing property of DNA by attaching short, single-stranded DNA fragments (or probes) of known DNA sequences to specific sites on a microelectronic chip. Single-stranded fragments of DNA, or targets, are then washed across the chip. The target DNA hybridizes, or binds, strongly to the probes that contain its Watson-Crick complement, and binds much weaker to the other probes. Specialized circuitry on the chip detects and reports the sites that contain hybridized DNA, thus enabling the base sequence of the target DNA to be determined by using an algorithm.

The hybridization and detection techniques were further demonstrated in working prototypes of the microchips, which are called genosensors. In these devices, electrodes at each biosite can sense the local change in the electrical permittivity induced by target-probe hybridization. Larger genosensors have been constructed and tested, and their complexity is sufficient to introduce the possibility of diagnosing genetic diseases, such as cystic fibrosis, using simple, inexpensive tests. In addition to detecting and sequencing unknown target strands of DNA, the same techniques could be used to analyze and identify other unknown biopolymers and biostructures such as polynucleotides, RNA, antibodies, and cells.

by Dorothy A. Fleischer

Web Cites

For more information on the projects and investigators mentioned in this issue, please visit the following World Wide Web sites on the Internet:

Retinal Implant Project
http://rleweb.mit.edu/firstpage.html

RLE Speech Communication group
http://web.mit.edu/speech/

(continued on page 29)

FACULTY PROFILE:

Dennis M. Freeman

Pennsylvania native Professor Dennis M. Freeman (SMEE '76, PhD '86) attended Pennsylvania State University (BSEE '73), and came to MIT to pursue his graduate education. In 1974, he joined RLE's Communications Biophysics group. Under the supervision of Professor Campbell L. Searle, he completed his master's thesis on auditory signal processing and auditory psychophysics. He then joined Professor Louis D. Braida's group, where he developed hardware and software systems to study auditory and tactile psychophysics. Working with Professor Thomas F. Weiss, he completed doctoral work on cochlear hydrodynamics at the level of single sensory cells. In 1986, he was appointed as a research scientist in RLE's Auditory Physiology group, where he and Professor Weiss have established a laboratory to experimentally measure sound-induced motions of inner-ear structures. Dr. Freeman joined MIT's faculty in the Department of Electrical Engineering and Computer Science as an assistant professor in 1995, and was appointed to the W.M. Keck Foundation Career Development Professorship in July 1997 (see "Circuit Breakers," *page 26). Since 1987, he has also been a research affiliate with the Eaton-Peabody Laboratory at the Massachusetts Eye and Ear Infirmary.*

Professor Freeman's investigations into the physiology of the inner ear seek to characterize the signal-processing properties of the peripheral auditory system. He and his colleagues in RLE have introduced novel microscopic photodetection methods and high-resolution image-processing techniques to measure the motions and physical properties of inner-ear structures. The focus of these studies includes sensory receptor cells and other structures in the inner ear that comprise a complex hydromechanical system. Professor Freeman has successfully demonstrated a video system that was developed in his group to measure the mechanical properties of these inner-ear structures. A computer records and analyzes video images so that basic three-dimensional structures and their submicron motions can be visualized and measured. These video methods have shown for the first time how the microscopic hairs in the inner ear move in relation to its other structures. Professor Freeman has recently begun to apply the same experimental methods to characterize motions of synthetic microelectromechanical systems (MEMS). These systems are fabricated with methods similar to those used to fabricate microelectronic systems. Thus, they promise to revolutionize the design of sensors and actuators, much in the same way that microfabrication has revolutionized electronic design.

Professor Dennis M. Freeman
(Photo by John F. Cook)

• *Did you always want to be an engineer?*

When I was a kid, I didn't even know what an engineer was, but I always wanted to build things. My father was into carpentry and building different kinds of things. I liked to do that too and, in fact, I still do a lot of that today. I enjoy getting an idea about something that doesn't exist, making it, seeing it work, and then trying to make it better. But the ability to make things with electronics is quite different. It's a different type of building, but with the same puzzles. How do you put together something that *does* something?

My first experience with computers was in high school. We had a Teletype linked to a computer 20 miles away. That computer had as much power as one of today's hand-held calculators, but it did things I couldn't understand and I wanted to know how to build one. That became a particular fascination for me as an engineering undergrad at Penn State. They were going to teach me what I needed to know to build a computer, and I *really* wanted to know how. When I learned to make devices out of transistors, that was great, and when I learned to make them out of logic elements, that was even better.

• *Did you have a mentor?*

One person who sticks in my mind is a professor of computer graphics at Penn State named Buchanan. As a freshman, I saw a film on the use of computers that had been made at MIT by Ivan Sutherland (PhD '63), but I didn't know that at the time. It was the most amazing thing I had ever seen. I asked myself, "Could I make computers do graphics?" I worked with Buchanan my entire time at Penn State, and I wrote a computer graphics language. My most important mentors at Penn State, though, were my fellow students. Bruce Hill was a computer science major, and we both wanted to know what the other knew. I spent almost every other night in the computer science building writing the graphics program, and Bruce taught me how to do it. Students often learn more from their peers than from their professors, and that was true for me. Certainly, the professors were wonderful, but I spent more time with students, and I learned more from them.

I've also had many mentors here at MIT. My first was Cam Searle. I met him at an open house where he was demonstrating his psychophysics research. He wanted to understand how we hear, and his approach was to explore how we determined direction in hearing. This was a new application domain for me—building devices to study hearing. I liked building things, but until that time, I hadn't thought about what they'd be used for. Cam was making things for a purpose, and it was a purpose I could identify with. My family has a history of hearing problems, and I have a slight hearing problem myself. Many of us had worked in a noisy brick factory, and I worked there one summer. It was a terrific experience, but I didn't understand why I had headaches and ringing in my ears. It was probably because of that noisy environment, but nobody really knows; we all could have lost our hearing anyway because hearing loss is generally so common.

• ***What was the focus of your work with Lou Braida?***

Lou was applying signal-processing theory, particularly *digital* signal-processing theory, to make a better hearing aid. It was an exciting application and I spent a lot of time there. We were making wonderful signal processing devices with great ideas behind them—manipulating sounds with signal processing to make them easier to hear. But when we tested them on people who were losing their hearing, they didn't help. It was frustrating to conceive the idea for a device, figure out how to make it, build it, test it on a person who was losing their hearing, and then learn the device didn't help. I wanted to know more about how ears worked because maybe I didn't understand hearing well enough to know what parts of the signal were important. I planned to take a month to learn how ears worked. Once I understood that, I planned to return to Lou's group and make a better hearing aid. That's what I thought I was going to do.

• ***Why did you shift your focus to physiological modeling and hydrodynamics?***

There was a huge gap between what we knew and what we needed to know to make a better hearing aid and how the ear processed sound. I wanted to work on figuring out how the ear processed sound, with the goal of providing information that would help engineer better hearing aids. It turned out that the answers to my questions were hard to find, and it became a career in itself to understand the physiology. It's been exciting, but the reason I became involved in the first place was my desire to make sensory aids.

As I became interested in physiological modeling, attention began to focus on the individual cells. Many properties of the ear, such as the traveling waves of motion in the cochlea, were well understood, but several things weren't. For example, it *seemed* like the waves were too big, and that viscous properties of the surrounding water should attenuate the wave sooner. I thought this was an interesting and doable problem since viscosity had been well understood for over a hundred years. It was just a matter of working out the theory. That's when I started work on fluid dynamics.

• ***How have the various theoretical and experimental studies in the Auditory Physiology group evolved?***

As a result of my thesis, I had predictions about how the mechanically sensitive parts of the sensory hair cells should move, but there were no data available. It seemed like there were useful things to learn from developing theories, but the theories rapidly went beyond the existing data to test the theories with. For example, we had always been interested in determining the basic processes by which sounds are encoded into neural signals. Researchers had made remarkable progress to understand neural responses, but the code at that level became so complicated that it was hard to make quantitative predictions. It wasn't clear that we understood the code, but we did understand many *properties* of the code. We could make lists of properties, but we didn't know if there was some unifying theory to tell us why the code was that way.

We decided to get closer to the periphery to understand how information about sound was coded in motion. That was a necessary step before going to the neural level and, presumably, it was also simpler. If we understood that transformation, it might help us make the bigger step between sounds and the neural signals.

Our first step in trying to understand the mechanics was theoretical. The second step was to work out new ways to do experiments, because it would have been pointless to work out a theory in vast detail before we checked out its premises. So, over the next seven years, Tom Weiss and I worked on setting up our lab here in RLE.

• ***Could you describe some of the unique methods that your group has developed?***

The technology didn't exist to help us understand how sound was coded in motion. There were proven physiology methods to solve many problems, but this wasn't one of them. It's also important to remember that when we measure the motions of the ear, they're smaller than microns. Motions of the most intense sounds can be measured in microns. But we hear sounds over a 100-decibel range, which is 10^5. If the biggest motions in the ear are the size of microns, the smallest motion may be as small as a micron divided by 10^5. If we took a high-quality picture of an ear as it moves in response to sound, we'd barely be able to detect its motion as a blur.

However, several technologies emerged that offered us new opportunities, and one was the charge-coupled device (CCD) camera. Previously, high quality and video didn't go together. High-quality pictures meant photographs, not video. Suddenly, in the early '80s, high-grade scientific video imagers became a new resource. But just because there are new video cameras on the market doesn't mean they can be applied to measuring the motions due to sound in the ear. In fact,

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no one was using video in auditory research then. The motions we were studying were much smaller than the pixels on the camera, and there's no way that a structure could actually move from one pixel to the next.

Fortunately, the artificial intelligence (AI) people were working on clever algorithms to determine motion from video images. Their purpose was to give moving robots the ability to tell the motion of a scene. If you could determine the motion of a scene, you could figure out the direction in which the robot was moving.

The key was that these algorithms had the ability to average scenes across lots of pixels. Another key was that they could take advantage of the fact that, although a camera doesn't have good spatial resolution, it can have good brightness resolution. Even with a small motion, the camera still modulates brightness in all pixels of an image. If an object moves, certain pixels get dimmer while others get brighter. Overall, there's a small change in many pixels. The AI people worked out these algorithms to combine that information across many pixels in order to determine small motions in an image. In one time instant, we know what the scene looks like because we have a picture of it, so we can detect any change. In the next instant, there may be many little brightness changes—brighter or dimmer. Then we ask how could this structure have moved to give that pattern. We deduce that it would have had to move, say, .01 pixel in one direction and .005 pixel in another direction. Our techniques combined high-grade scientific imaging and the algorithms that could use the information contained in those images, plus the realization that we could apply these technologies to hearing. We brought together ideas from different disciplines that had nothing to do with what was then considered to be hearing sciences.

• *What are the other methods that you've developed to characterize the performance of optical systems?*

Cameras couldn't help us if we weren't able to use a microscope because the structures we're looking at are so tiny, so we've done a lot of work in microscopy. Microscopes are wonderful signal-processing devices that turn optical targets into images. The perfect microscope would be one where the image was so many times bigger than the target, but it's not that simple. Microscopes have their own distortions, and the ear is not particularly cooperative. Cells in the ear, like most cells, are nearly transparent. The tectorial membrane, an important structure in the inner ear, is almost entirely transparent. Even if the microscope were relatively perfect, it would still have difficulty imaging those structures. So we've tried to understand how microscopy works and then adapt it to make high-quality pictures of ears. This continues in our work on microelectromechanical systems (MEMS), where we're developing new optical methods. Another important element in our measurement techniques is a strobe system. We need to watch motions at audio rates. We're interested in watching motions in the range of tens of kilohertz, which far exceeds the speed of any camera. We just couldn't take pictures without strobe illumination, so we're doing work in that area also.

• *You've described the ear as "a naturally occurring biological micromechanical system."*

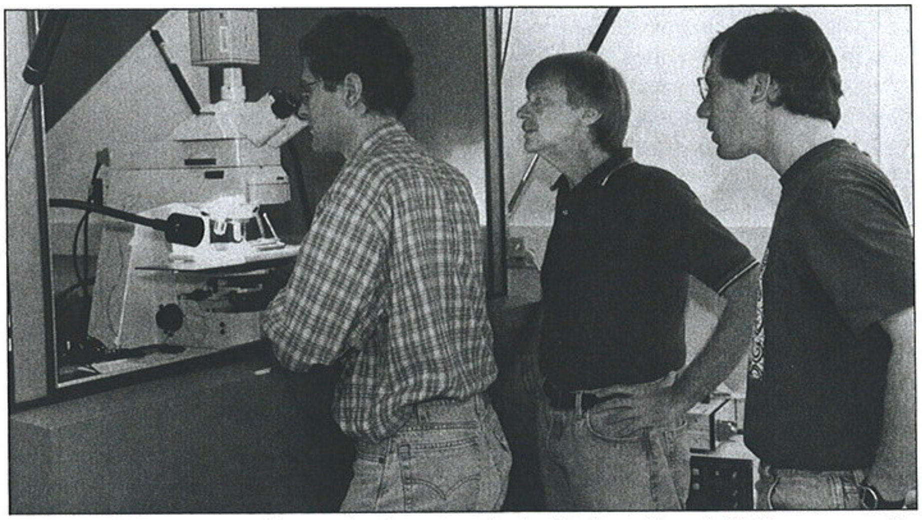
That's an observation due to neuroscientist James Hudspeth that sticks in my mind, and it's a nice way of looking at it. The ear is a machine with more than a million moving parts. From that perspective, it's an incredibly complicated machine. In the ear, there are approximately 15 thousand sensory hair cells connected in a system that works as a unit. One way to think about their organization is that they are many cells cooperating in one big machine, but each cell itself has hundreds of parts as well. Each hair cell is made of 60 to 100 microscopic sensory hairs, and those are all connected by tiny proteinaceous filaments. We also know the mechanism by which the motions in the ear are converted into electrical signals is located in those sensory hair cells. The mechanism involves ion channels, which are macromolecules that are an integral part of the cell's membrane. These channels open and close to allow ionic currents to go into the cell. We believe that the direct stimulus to them is mechanical stress. Somehow, one hair cell, with hundreds of microscopic sensory hairs tugging on little filaments, is tugging on hundreds of ion channels. It's a machine that we believe to be entirely mechanical with hundreds of parts in each cell, but then the cells are part of this bigger entity: the inner ear.

• *What are the implications of your work with MEMS?*

About fifteen years ago, MEMS were a scientific curiosity. People figured out that they could take methods similar to those used for microfabricated electronics and make microfabricated machines. Decades earlier, it was a big deal when people learned how to make transistors. When we realized we could make electronics with transistors instead of tubes, it had enormous implications for the kinds of systems that could be made. They could be bigger, more complex, and more compact. That was a big step, but the next step was even bigger—to put not one, not tens, not even hundreds, but thousands and tens of thousands of electronic parts on one chip. The fact that they can make novel devices with MEMS today is historically similar to the transistor. What if we could make a machine with a million moving parts? Is there a new and enabling technology with mechanics like there was with electronics? I don't know, and I don't think anyone knows.

I'm excited about the intellectually fascinating projects we could do if we could put together a million moving parts, because we know that the ear does some pretty amazing signal processing by linking together a million of its parts. People already know that if we put multiple mechanical parts on the same chip and fabricate sophisticated electronics to connect them, we can make reliable devices that don't rely on a single mechanical part. It's like the space shuttle, where every switch is triply redundant. With three independent contacts on every switch, they have several computers that do the same computation and compare answers. The information is not considered reliable unless they all get the same answer.

Who would have thought that airbag deployment systems would be one of MEMS' biggest applications? Multiple sensors allow us to be much more confident when we deploy an



(From left): Graduate student Michael A. Mermelstein, Professor Dennis M. Freeman, and graduate student Alexander J. Aranyosi observe the motions of a microfabricated test structure using a light microscope that is part of a computer microvision system. The test structure is driven to move with a 25-kHz electrical signal, and slow-motion video images are taken with stroboscopic illumination. The light microscope sits on an actively destabilized vibration isolation table inside an acoustic chamber. In this environment, measurements can be isolated from floor vibrations and airborne sounds. (Photo by John F. Cook)

airbag system because we know there's a good reason for it. Another application is projection video. Texas Instruments uses an array of a million mirrors to steer light. Each mirror generates one dot on a projection screen, and we get a beautiful picture. Those have been two big commercial successes for MEMS. Also, one of the widest dynamic-range accelerometers is made by Analog Devices. Since the range of a single mechanical part may not be that great, they have combined multiple parts with overlapping ranges, so the performance surpasses that of a single part. As you can see, several curious opportunities have already been realized, but I don't think we've come close to understanding the implications of putting millions of mechanical parts on one chip.

• ***What is the nature of your work to model the effects of hydrodynamic forces on MEMS?***

With my background in fluid dynamics, it was natural to take MEMS, measure their motions, and deduce the effects of fluids, especially gases. One performance limitation in MEMS devices is that they have to work against viscosity, just like the ear. Some high-performance devices, like Draper Laboratory's gyroscope, can only work in a vacuum. A vacuum is fine if we have a high-performance device, but if we can better understand the limitations, maybe we can engineer around them. One of the things I'm interested in with MEMS is making versatile instruments to measure their motions, because those don't exist today. In that case, video would be both an inexpensive technology and a flexible tool that could bring us a broader application, and we're interested in developing that.

• ***I understand that your group was first to quantify MEMS devices in all three dimensions.***

Other people have measured the motions of MEMS before us, and one standard method is laser-Doppler interference. There, we shoot a laser beam at a structure, bounce it back, and use the Doppler shift. Normally, we get one dimension—the axial motion. What's interesting about our system is its ability to measure all three directions for all structures simultaneously. Existing laser-Doppler interference methods tell you one component of the motion of one point, but our application can tell you all three components of the motion at all points. When Draper made a microfabricated gyroscope, they got insights into how to do the engineering by looking at it under a microscope with strobe illumination. But they couldn't see its three-dimensional motion. Our approach helped them see all the modes of motion. That was something people hadn't done with MEMS before.

• ***Does your MEMS work influence your hearing research?***

It has in a couple of senses. In biological specimens, we see multiple structures moving in potentially different ways with potential interference between our measurements. There might be interaction between the motions we measure in one spot and the motions we measure elsewhere. However, MEMS structures are much simpler, and we have strong notions about how they should be moving. This lets us test our device and improve its sensitivity by being able to measure targets whose motions we understand better. There's also been technical feedback to the hearing projects because they share instrumentation with MEMS as well. When an instrument is improved in our MEMS work, it instantly feeds back into our work on hearing.

• ***What are the prospects for building signal-processing systems that use components similar to those in nature?***

It's inevitable that we'll learn to use biological structures more like the parts in biological machines. Just like MEMS were fifteen years ago, biological transducers are now a scientific curiosity. Today, molecular biologists can determine the structure of an ion channel and its exact sequence of amino acids. Then they can manipulate and change its structure. By changing it, they can figure out the relation between a molecule's structure and function. Change one amino acid, and we can alter the kind of ion that is passed by the ion channel. We could change a calcium channel into a sodium channel. As soon as we understand this relation between structure and function, then we can start engineering. We can select a function, then manipulate the structure to get that function. It isn't too far into the future because molecular biology today is at least on par with MEMS fifteen years ago.

• ***What is the most challenging aspect of your research?***

Our group is driven by scientific questions, as opposed to being driven by a methodology. We're interested in how the ear works, and we're focused now on how it works mechanically. However, the technology isn't available commercially to investigate that, so we have to build our own instruments. With our video microscopy system, we ended up making a new technology to study a scientific problem, but it also has applications other than hearing. So, there's this tension between instrument development and the application of the instrument itself. After we develop a new instrument, there's a desire to improve it and keep developing it, but we're also interested in the scientific problem. What should we do next? Should we take the current system and study a problem in hearing, or do we improve the current system to make it ten times more sensitive? Ultimately, that would also make it more useful for hearing.

Another challenge involves our group's interdisciplinary nature, since we work in many different domains. I want our focus to continue to be in micromechanics and not to move too far off into developing microscopes or algorithms or doing something else. So there's a tension between how much effort we put into developing a new microscope versus how much effort we put into using a current microscope to solve scientific questions. I don't necessarily regard this tension as an obstacle. In fact, I like to think of it as an opportunity. Many current technologies are lying around that could possibly be co-opted to study hearing. I like to be more positive and say there are many opportunities out there to use these new technologies to study problems in hearing.

• ***What do you consider your most significant achievement?***

The demonstration of what we could do with video was surprising. I think people in both the hearing sciences and MEMS were surprised that we could get such a sensitive measurement from a light microscope. I'm also pleased to see how powerful an instrument this new video technology has proven to be. We're getting so many insights into so many problems by using these new imaging methods. Our group is unique in the way we have shown that video microscopy can be used quantitatively. We've demonstrated much better precision in our measurements than most people thought was possible.

We must provide opportunities that allow students to learn outside their own disciplines, to learn to appreciate that what other people know can also be useful, and to learn to explain their ideas at a more primitive level.

• ***How would you describe the balance between theory and experiment in your group?***

There's kind of a back and forth. Initially, I was driven by the experiments to work out the theories in my thesis. When I finished my doctorate in 1986, the theory was well in hand and we cranked out papers on theory. That stimulated questions that could only be answered experimentally, so we wanted to ramp up the experiments. Now, many of our experimental methods are mature enough that they're providing answers to fuel the theory. We're at a point where it makes sense to start work again on theoretical issues because we have new insights from our experiments. We have enough results to incorporate into the theories to make them better and to continue our work.

This evolving process can be traced to my interest in Tom Weiss' approach to combining theory and experiment, which has been highly productive. By doing both, he can decide which experiments to do and which theories to work out. He can make them cooperate with each other. If a theoretical issue was important for interpreting the experiments, he could work it out. If an experiment was crucial to deciding between two theories, he could do that too.

Our group has a focused scientific goal in that we *really* want to understand the mechanics of hearing, but we need to combine theory and experiment. It doesn't make sense to work only on a particular theory, and theories that don't connect to experiments aren't interesting. We're unique because we try to get every student to do both theory and experiment. Even for the people who are theoretical by nature, we try to get them to understand the experiments so that they can incorporate that knowledge into their theories.

• ***Have other scientific disciplines influenced your research?***

We've profited enormously by learning from other groups. For example, our video work started with my reading a paper by Carver Mead at Caltech, who used ideas that Berthold Horn came up with here at MIT to make a vision chip. Carver had made an artificial eye that was able to sense motion. It was an imaging chip, but the output wasn't a picture, it was a motion. Through Carver's work, I learned about the work in the artificial intelligence labs, and that's been important for our video work.

• ***What is your hope in terms of your research providing a practical benefit to society?***

I'm still interested in the work that Lou Braida and the people in RLE's Sensory Communication group are doing. My hope is that our two fields will get to the point where they can take advantage of each other's knowledge. Even when I worked with Lou, we knew many things about hearing that we could incorporate into hearing aids. We knew that ears did a frequency analysis and we could put some of that information into the aids, but the level of detail wasn't great. Today, we know about the many features of physiological responses, but we don't understand their implications with regard to hearing. I'd like to understand what those implications are. My original goal for getting into physiology was to help bridge the gap between the knowledge of how the ear works and how hearing aids work. That's really a long-term goal, and I hope our group can contribute towards it.

• ***Are you excited about a project currently underway?***
I'm excited about MEMS because it's new to our lab and it's great fun, but we've also just finished work on a magnetic-bead method to measure properties of the tectorial membrane. We fasten a tiny magnetizable bead to the tectorial membrane that we pull around with electromagnets to measure its mechanical properties. That's exciting because it's an experimental method that we've been testing for a long time and it's just started to work. Our different projects are at different levels of maturity, and each level has its own excitement. There's the ancient stuff and the brand-new stuff, but they're all interesting for different reasons and they attract different kinds of students. Some of the experimental methods that we've been developing are reaching the point where they can now be used to study hearing, and that's exciting. Some of the theories have been around forever, but we're now getting new data to put into them, and that will make them more interesting.

• ***What's been the impact of the Harvard-MIT Division of Health Sciences and Technology?***
The bringing together of the two different institutions has been important. The HST program enriches our campus with more interesting projects for our graduate students. Our engineering students, for example, can work in hospitals on exciting problems that are important to health science or health technology. Reciprocally, we provide a somewhat more technical environment for Harvard's medical students. They're training a class of physicians who'll be more savvy in terms of technical issues. In fact, a HST MD student is working in my lab on his scientific project.

What if we could make a machine with a million moving parts? Is there a new and enabling technology with mechanics like there was with electronics?

• ***You've said that as scientific application areas become more specialized, there's a need for more interdisciplinary training and improved communication skills. How do you see your role in this?***
It's often the case that our graduates don't go into a room filled with electrical engineers. They might be on a team where they *are* the electrical engineer. They might be working with a physicist or a biologist to develop a product or to accomplish some research. More likely, they'll be working with someone from outside their field and they can't rely on their jargon. They'll have to express their ideas more fundamentally. That's something they can learn, just as they can learn a focused discipline like engineering. They can learn how to interact effectively, but that only comes with practice. I'm trying to provide that practice while giving students exposure to other disciplines.

Our research group in RLE is interdisciplinary. We have students from HST, mechanical engineering, electrical engineering, and computer science. So there are many different perspectives. Our group meetings are exciting because someone working on microscopy might have a microscopy solution to any given problem. Someone else who's working on computers might have a new way to use computers to solve that same problem. We have all these different people bringing their expertise to solve our problems. That's wonderful because we can choose among the approaches that look most fruitful and then pursue it because there's someone here with knowledge about it.

The class I teach, Quantitative Physiology: Cells and Tissues (6.021), is also a place to focus on interdisciplinary teamwork. This term, there are about 65 students in the class from ten different departments. The students team up in pairs to do two projects where they have to write a proposal, get it approved, do their experiment, and write it up like a scientific paper. I make a big deal out of the fact that this is their opportunity to team up with someone from outside their department and to learn how someone else thinks about the same problem. Some of our most exciting teams have been a chemical engineer paired with an electrical engineer, because they do things differently and, if they work together, they can take advantage of their differences.

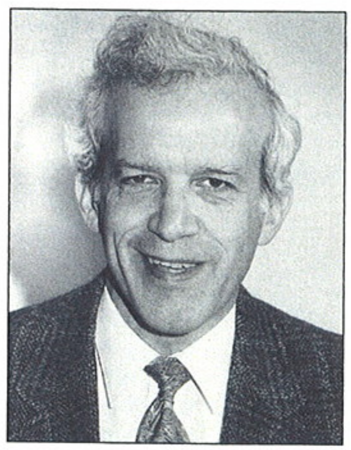
We must provide opportunities that allow students to learn outside their own disciplines, to learn to appreciate that what other people know can also be useful, and to learn to explain their ideas at a more primitive level. When you have to explain ideas more simply, you must think about them more simply. Once you've learned the jargon, you can even fool yourself. You may think you understand things better than you do. By forcing yourself to communicate on a more fundamental level where you'd expect everybody else will understand, you might reveal to yourself that you don't understand things as well as you thought you did.

• ***What is the most rewarding aspect of your work?***
Teaching is fun. It's the same as when I work with someone outside my field, because I have to use a simpler language to explain ideas. When I teach, I keep refreshing the basics in my own head. As we discussed earlier, as our research gets more focused, it also gets narrower, and we develop a specialized knowledge. That can be good, but it's also good to step back and look at the more fundamental ideas. What are the fundamental ideas in electrical engineering? What are the fundamental ideas in computer science? What I like about teaching is that I keep relearning the fundamentals, which are the things that actually have lasting value.

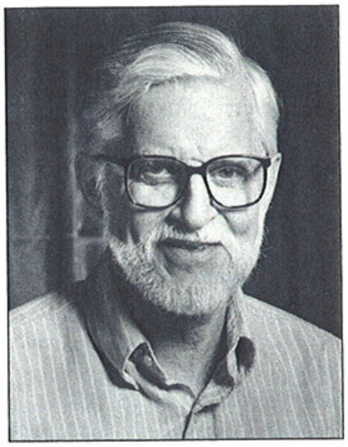
Ms. Lorraine A. Delhorne, a research specialist in RLE's Sensory Communication group, was promoted to research scientist, effective October 1, 1997. Since coming to RLE in 1982, Ms. Delhorne has carried out psychophysical experiments in the areas of auditory and tactile perception. Ms. Delhorne will continue to not only design but also to analyze the data collected from these experiments, which involve human subjects. As part of the group's research program on natural methods of tactual communication, she also investigates the tactual reception of fingerspelling, a communication method used by deaf-blind individuals. A graduate of Ashland College (BA'74) and Washington University's Central Institute for the Deaf (MS'82), Ms. Delhorne is a member of the American Speech-Hearing-Language Association, the Acoustical Society of America, the Alexander Graham Bell Association, and the National Cued Speech Association. *(Photo by John F. Cook)*

Dr. Dennis M. Freeman (SM'76, PhD'86), Assistant Professor of Electrical Engineering, was appointed to the W.M. Keck Foundation Career Development Professorship in July 1997. The Keck professorship was established in 1983 to support promising junior faculty in the field of biomedical engineering. Professor Freeman, a principal investigator in RLE's Auditory Physiology group, is involved in developing instrumentation that visualizes the microscopic motion of biological and synthetic structures. He has developed a video-based technique that measures sound-induced motions of inner-ear structures, and is now extending this method to other biomedical and engineering applications. Professor Freeman was also selected as a John F. and Virginia B. Taplin Fellow in Health Sciences and Technology. This is the first year for Taplin Awards Program, which is administered by the Harvard-MIT Division of Health Science and Technology. The Taplin fellowships seek to recognize and support the work of faculty and students who are building HST programs in the fields of biomedical engineering, physics, and chemistry. Professor Freeman is one of four Taplin fellows selected from Harvard and MIT for the 1997-1998 year. *(Photo by John F. Cook)*

Institute Professor Hermann A. Haus received the 1997 Ludwig Wittgenstein Prize awarded by the Austrian Research Foundation. Professor Haus, a principal investigator in RLE's Optics and Devices group, was cited for his pioneering work in the field of electrical and optical communications. In an announcement from the award presentation on June 6, 1997, in Vienna, Austria, the foundation praised Professor Haus: "His contributions to quantum optics and lasers are of outstanding importance to the rapid transmission of high data rates in optical communication systems. His investigations of noise in electrical systems have, at the same time, established the fundamental boundaries of communications. In his work, Hermann A. Haus understands how to connect his deep theoretical insight to problems of practical application and thereby sets an excellent example of the engineering art at its best. This constructive effort and logical clarity of his scientific thought process binds him to the heritage of Ludwig Wittgenstein." *(Photo by John F. Cook)*



Dr. Daniel Kleppner, Lester Wolfe Professor of Physics and RLE's associate director, was awarded the 1997 Oersted Medal of the American Association of Physics Teachers. The Oersted Medal is the association's highest honor, which is awarded annually for notable contributions to the teaching of physics. The association cited Professor Kleppner for "his contributions to physics and the teaching of physics, for the ways in which he challenges his students, at both graduate and undergraduate levels, [and] for his highly regarded efforts to entice the larger community to form a connection with physics." The award was presented at the meeting of the American Association of Physics Teachers in Phoenix, Arizona, on January 7, 1997. Professor Kleppner's wide range of work in RLE's Atomic, Molecular, and Optical Physics group focuses on atom interactions with static electricity, magnetic fields, and radiation. His related research interests include quantum optics and ultraprecise laser spectroscopy. A prominent member of the physics community, Professor Kleppner is a fellow of the American Academy of Arts and Sciences, the American Association for the Advancement of Science, and the Optical Society of America; and a member of the National Academy of Sciences. *(Photo by John F. Cook)*



Dr. Kenneth N. Stevens (ScD'52), Clarence J. LeBel Professor of Electrical Engineering, was named corecipient of the Frank E. Perkins Award during MIT commencement ceremonies on June 6, 1997. The Perkins Award is presented annually to an MIT professor who has served as an excellent advisor and mentor for graduate students. It is named in honor of Frank E. Perkins, Dean of MIT's Graduate School from 1983 to 1995. Professor Stevens, a principal investigator in RLE's Speech Communication group, shared the award with Professor George C. Verghese of the Department of Electrical Engineering and Computer Science. Since joining the MIT faculty in 1958, Professor Stevens has been a central figure in the development of speech communication research at RLE, conducting fundamental research in speech synthesis and the analysis of speech production processes. *(Photo by John F. Cook)*

alumni notes

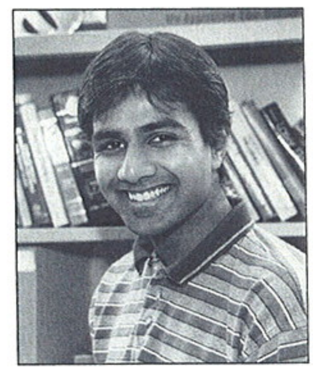
Dr. William D. Phillips (PhD'76), a fellow with the National Institute of Standards and Technology, was named co-recipient of the 1997 Nobel Prize in Physics. The Royal Swedish Academy of Sciences announced the award in October 1997, with Dr. Phillips sharing the prize with Dr. Steven Chu of Stanford University and Dr. Claude Cohen-Tannoudji of the École Normale in Paris. The three physicists were cited for developing methods to cool and trap atoms using laser light. Dr. Phillips had conducted seminal experiments to slow atoms with laser light and discovered that atoms could be cooled below the so-called Doppler limit to temperatures of a millionth degree above absolute zero.

As a graduate student with Professor Daniel Kleppner in RLE's Atomic Resonance and Scattering group from 1970 to 1976, he carried out a precision measurement of the proton's magnetic moment and studied the scattering of laser-excited

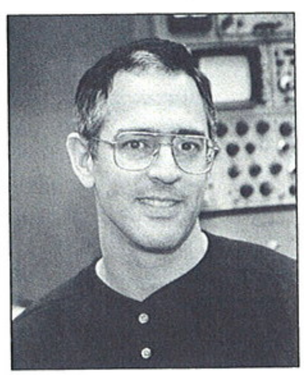
(continued on page 28)

RLE's New Research Staff

Dr. Jianyao Chen was appointed as a postdoctoral associate in RLE's Optics and Devices group, effective April 1, 1997. Dr. Chen will work with Professor Rajeev J. Ram on the quantum optics of microcavity lasers and electron dynamics in quantum structures. A graduate of the University of Science and Technology of China (BEng'82/MEng'85), McGill University (MEng'91), and École Polytechnique of Montreal (PhD'97), he has worked in the fields of microwave technology, fiber optics, and integrated optics. He recently completed doctoral work on the research and development of gain-coupled distributed feedback semiconductor lasers.



Dr. Chandra S. Raman was appointed as a postdoctoral fellow in RLE's Atomic, Molecular and Optics Physics group, effective August 1, 1997. A graduate of Caltech (BSEE'90) and the University of Michigan at Ann Arbor (MSEE'91, PhD'97), Dr. Raman has carried out studies on the fundamental interaction between atoms and light. In collaboration with Professor Wolfgang Ketterle's research group, he will investigate the properties of a dilute Bose condensate of sodium atoms in the group's continuing experiments on Bose-Einstein condensation.



Dr. Michael J. Schwartz (PhD'97) was appointed as a research scientist in RLE's Radio Astronomy group, effective October 21, 1997. Dr. Schwartz joined RLE in 1991 as a graduate student with Professor David H. Staelin's remote sensing group. Dr. Schwartz served as principal field scientist for the MIT Microwave Temperature Sounder project during five atmospheric studies conducted from the ER-2 high-altitude aircraft. A graduate of Carleton College (BA'85), he will continue to work with Professor Staelin in efforts to build a new passive microwave spectrometer for the ER-2 aircraft.

(Photos by John F. Cook)

IN MEMORIAM

Ms. Dorothea C. Scanlon, 72, of Quincy, Massachusetts, died on October 24, 1997.

Ms. Scanlon began her long-term affiliation with MIT in 1943 as an administrative assistant in the Property Accountability Group (Group 18) of MIT's Radiation Laboratory. She joined RLE when it was established in 1946 as secretary to Professors Robert M. Fano and Lan Jen Chu.

When Project MAC was formed in 1963, Ms. Scanlon joined Professor Fano in the director's office there. In 1976, Project MAC officially became MIT's Laboratory for Computer Science (LCS) and Ms. Scanlon was appointed the laboratory's administrative officer. A member of MIT's Quarter Century Club, she was affiliated with LCS until her retirement from MIT in 1989.

She is survived by a sister, Eva A. Greeley, of Milton; and many nieces, nephews, grandnieces and grandnephews. Remembrances may be sent to the American Lung Association, 1505 Commonwealth Avenue, Brighton, MA 02135-3605. *(Photo courtesy Eva A. Greeley)*

Dr. Helen (Lewis) Thomas, 91, died of cancer on August 6, 1997, at the Emerson Convalescent Home in Watertown, Massachusetts. Dr. Thomas served as director of RLE's publications office from 1955 to 1971.

Dr. Thomas graduated from Radcliffe College in 1948. She held the distinction of being the first woman in the United States and the second American to receive a doctorate in the history of science. Before coming to RLE, she was employed by the Harvard Observatory, the Harvard University radiation research laboratory, and the Raytheon Company. During her seventeen years at RLE, Dr. Thomas was highly respected for her work on several RLE publications, including the *Quarterly Progress Reports,* the *RLE Technical Report* series, and student theses. Her impeccable attention to detail and commanding editorial skills produced a solid and attractive archive of RLE's achievements. She retired from the publications office in 1971.

She leaves a son, Roger M. Thomas of Weston, Massachusetts; a brother, Harold B. Lewis of Salem, Connecticut; and two grandchildren. A memorial service was held on August 21, 1997, at Christ Church in Cambridge, Massachusetts. *(Photo courtesy Roger M. Thomas)*

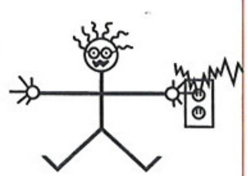
alumni notes *(continued from page 27)*

atoms. He continued the latter work as a postdoctoral associate with Professor Kleppner and Professor David Pritchard in RLE. In 1978, Dr. Phillips joined NIST, then the National Bureau of Standards. He began investigations on the effect of light forces on atoms in the early 1980s and, by the mid-1980s, he demonstrated the possibility of slowing and trapping atoms using laser light.

The scientific opportunities made possible by the atom cooling research include studies of ultraslow collisions, the formation of new types of molecules, and new investigations into atom-light interactions. Perhaps the most dramatic applications of these methods was the observation of Bose-Einstein condensation in 1995 by RLE graduates Eric A. Cornell (PhD'90) and Carl E. Wiemann (SB'73) at NIST and the University of Colorado, and to the demonstration of an atom laser in 1997 by Professor Wolfgang Ketterle in RLE's Atomic, Molecular, and Optical Physics group (see ***RLE currents,*** Spring 1997).

Dr. Phillips continues to study ultracold trapped atoms with applications to new types of atomic clocks and to the fabrication of nanostructure electronic circuits. *(Photo courtesy NIST)*

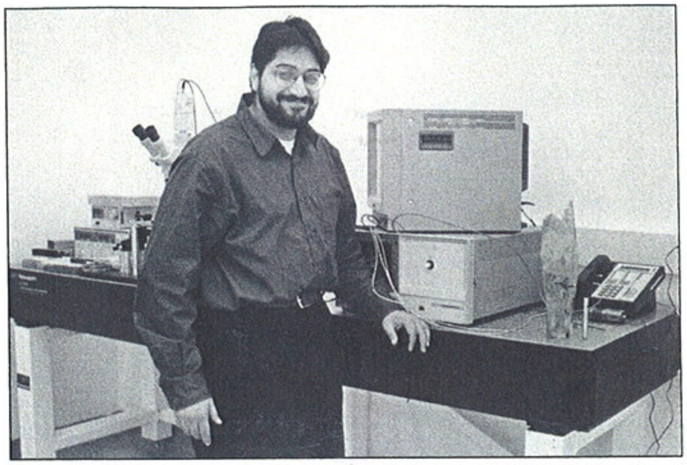
SHORT CIRCUITS



The staff of ***RLE currents*** would like to note the following correction to the Spring 1994 issue.

The caption for the "1958" photograph that appears on page 25 mistakenly identifies graduate student Richard K. Steinberg (PhD'49) as Robert M. Steinberg. The photograph depicts him and Professor Wayne B. Nottingham inspecting experimental cesium-vapor tubes, not high-vacuum tubes as reported, and was actually taken in 1949. Thanks to Dr. Richard K. Richards, formerly known as Richard K. Steinberg, for writing us with the correct information.

RLE LAB SCOPE



Professor Rajeev J. Ram in his group's new laboratory in Building 26. (Photo by John F. Cook)

With this issue, ***RLE currents*** introduces "RLE Labscope," a column designed to bring you up-to-date on RLE's latest research, announcements of upcoming conferences and presentations hosted by the laboratory, and other news items related to the laboratory and its investigators.

RLE hosted the semiannual meeting of the Consortium on Numerical Analysis of Wave Loads on Offshore Structures from September 24-26, 1997. The consortium supports research on the design of ships and structures used in subsea petroleum fields with a focus on the long-term development of computational tools. For example, WAMIT (Wave Analysis MIT) and TiMIT (Time Domain MIT) are industry-standard computer programs developed under the consortium's sponsorship. These programs are frequency- and time-domain hydrodynamic analysis tools that use a boundary-element approach to solve potential problems.

Research is carried out collaboratively in RLE's Circuits and Systems group and in MIT's Department of Ocean Engineering. The investigators are: Professor J. Nicholas Newman, Research Engineer Dr. Chang Ho Lee, Postdoctoral Associates Dr. Hiren D. Maniar and Dr. Leandro Farina, and graduate student Donald G. Danmeier of the Department of Ocean Engineering; and Professor Jacob K. White, Research Engineer Dr. F. Thomas Korsmeyer, Postdoctoral Associate Dr. Ali Beskok, and Visiting Scientist Bjarne Buchmann of RLE.

Consortium sponsors include: Chevron, Veritas Software, Exxon Production Research, Mobil, Norsk Hydro, Saga Petroleum, Shell, Statoil, the U.S. Naval Surface Warfare Center, and the Offshore Technology Research Center.

The September 1997 meeting included two days of technical presentations, plus a tutorial session on the third day that featured HIPAN: a higher-order element radiation/diffraction code designed to replace the WAMIT program. HIPAN, unlike lower-order boundary element approaches, uses the exact CAD representation of the structure geometry and a B-spline basis for the unknown potential. The result is a gain in computational efficiency (in terms of WAMIT) which can be as high as two orders of magnitude when high-accuracy solutions are required.

For information on the consortium's next meeting scheduled for March 1998 at MIT, please contact Dr. F.T. Korsmeyer, 617-253-5059, xmeyer@mit.edu, http://chf.mit.edu.

Professor Rajeev J. Ram's semiconductor laser research team in RLE's Optics and Devices group is establishing new laboratory facilities in Building 26. These facilities will enable students, faculty, and staff to carry out diode laser fabrication and high-speed testing of edge-emitting and surface-emitting laser diodes. Additional equipment will be used to characterize analog and digital optical fiber systems using direct modulation diode laser sources. Initially, studies will measure distortion and dynamic range in subcarrier multiplexed optical links. The new laboratory will also house spectroscopy facilities with high-temporal and high-spectral resolution. This equipment will be used to investigate the transport and relaxation of electrons in semiconductor devices in order to develop high-speed diode lasers. Fundamental research will be conducted on carrier dynamics in quantum dot systems and on the dynamics of excitons that are strongly coupled to an electromagnetic vacuum.

Web Cites *(continued from page 19)*

RLE Sensory Communication group:

Aids for Sensory Communication
http://web7.mit.edu/ASC/

Virtual Environments and Teleoperation
http://mimsy.mit.edu

Touch Lab
http://touchlab.mit.edu/

RLE Auditory Physiology group's micromechanics page
http://umech.mit.edu/

Massachusetts Eye and Ear Infirmary
http://epl.harvard.edu/meei.html

MEEI's Department of Otolaryngology
http://www.meei-ent.harvard.edu/

MEEI's Eaton-Peabody Laboratory
http://epl.meei.harvard.edu

Massachusetts General Hospital
http://www.mgh.harvard.edu/

Harvard Medical School
http://www.med.harvard.edu/

Harvard-MIT Division of Health Sciences and Technology
http://www.hvd.mit.hst.med.harvard.edu/

HST's Speech and Hearing Sciences Program
http://web7.mit.edu/HSTSHS/www

MIT's Department of Electrical Engineering and Computer Science
Bioelectrical Engineering (Area VII)
http://web7.mit.edu/AreaVII/www/

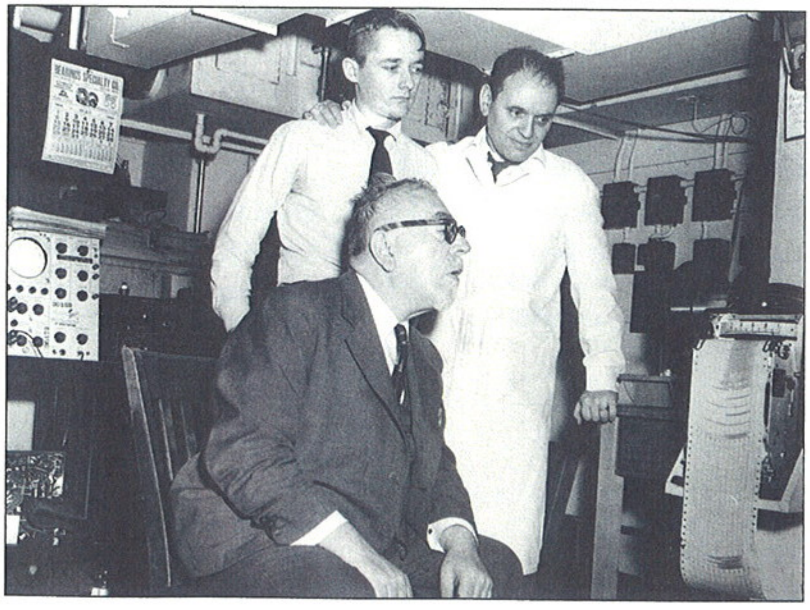
History of Biomedical and Bioengineering Research at RLE

1950

Professor Norbert Wiener conducts experiments to convert speech signals into a sequence of tactilely perceptible patterns that a deaf person might learn to understand. The original experimental device, called Felix, used several band-pass filters to subdivide the range of the spoken voice.
(Photo by Alfred Eisenstaedt)

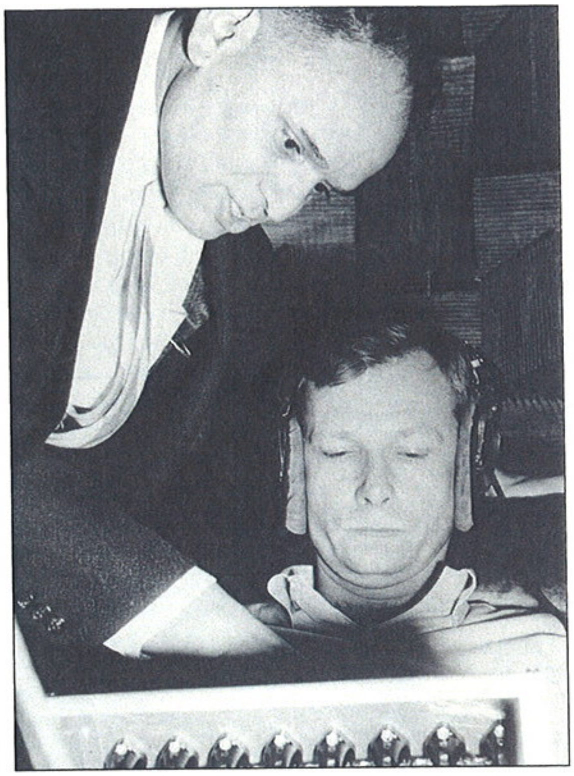
1955

Research staff members Lamar Washington, Jr. (left) and Dr. Clifford M. Witcher work on the experimental Vocatac device for RLE's Sensory Aids Project. Their device was based on earlier research by Professor Norbert Wiener to convert speech signals into tactile patterns.
(Photo by Benjamin Diver)



1955

Professor Norbert Wiener (seated) observes the autocorrelation function of brainwaves, enabling the application of statistical communication techniques to communications biophysics. Professor Wiener is joined by Research Assistant Dr. John S. Barlow (left) of Massachusetts General Hospital and Professor Walter A. Rosenblith of RLE's Communications Biophysics group.
(RLE file photo)

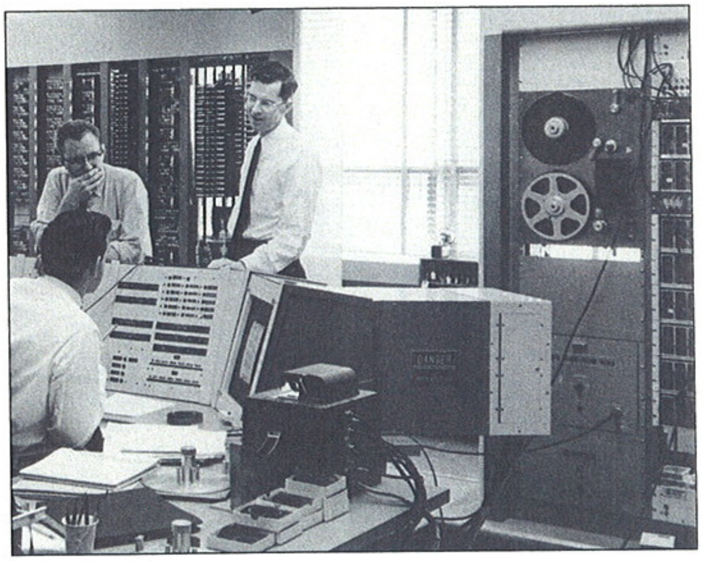


1956

Professor Walter A. Rosenblith (left) uses RLE staff member Dr. Thomas T. Sandel as an experimental subject in RLE's anechoic chamber. Professor Rosenblith was an essential figure in the development of RLE's Communications Biophysics group, and used computers extensively to explore the electrical nature of the central nervous system. *(Photo courtesy MIT Museum)*

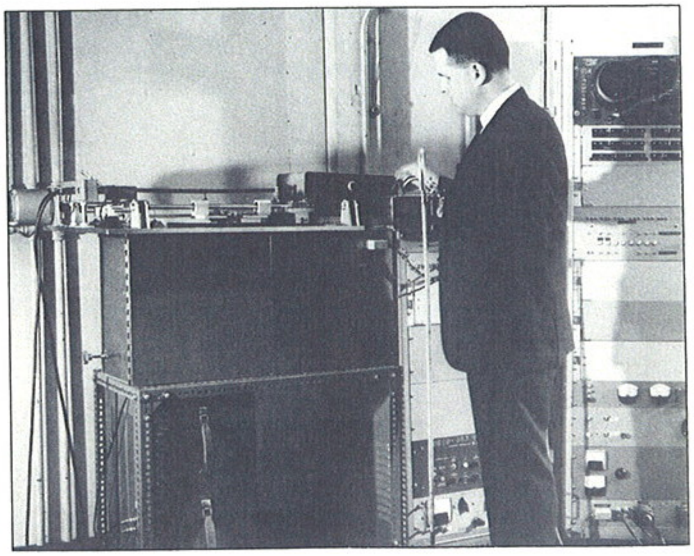
1958

Professor Jerome Y. Lettvin (left) and research staff member Walter H. Pitts of RLE's Neurophysiology group observe a subject from their landmark research published in "What the Frog's Eye Tells the Frog's Brain." *(RLE file photo)*



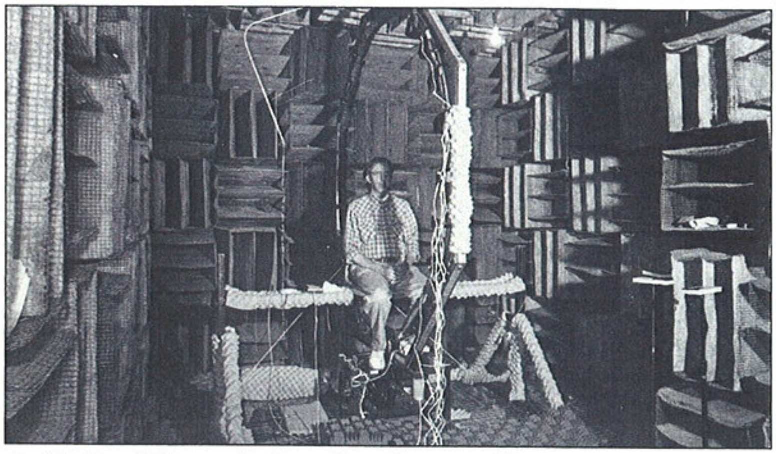
1960

Staff members Paul T. Brady, Jr. (seated) and Chester G. Bell (left) work with Professor Kenneth N. Stevens on the TX-0 computer to analyze speech sounds in RLE's Speech Communication group. *(Photo courtesy MIT Museum)*



1967

Research Associate Dr. Kenneth R. Ingham carries out an experiment with RLE's first reading machine for the blind in the Cognitive Information Processing group. It was the first affordable optical character reader and, in combination with the PDP-1 computer, it comprised the first computer system that could scan text and read it aloud. The system was also capable of outputting spelled speech and braille. *(Photo by Richard Geraigery)*



Archival and Manuscript Specialist Jeffrey A. Mifflin sits in one of two RLE anechoic chambers located in Building 20 that will be demolished along with the building in spring 1998. He is part of a team from MIT Archives working to document the research materials in the building. Over the years, countless experiments have been conducted in this unique echo-free research facility, which was designed to eliminate mechanical vibrations as well as acoustic and electrical interference. (Photo by John F. Cook)

Farewell to Building 20

After fifty years as an integral part of the MIT campus, Building 20 will soon be a memory. It will be torn down during the summer of 1998 to make way for a new structure that will house the computer, information, and intelligence sciences activities of MIT's Department of Electrical Engineering and Computer Science (EECS). The new Building 20 will be adjacent to RLE's Building 36, and will bring the computer scientists currently residing in Technology Square closer to campus.

Considered by many to be MIT's "ugly duckling" and affectionately known as the "plywood palace," Building 20's undeniable charm and magic is known to everyone who has worked in it. It would be unthinkable to have it disappear without saying goodbye to the legendary building that provided "temporary" housing for MIT's Radiation Laboratory and then became RLE's first home.

EECS is planning a celebration and reunion that will be held on Thursday and Friday, March 26 and 27, 1998. There will be talks, visits, displays, and an opportunity to see former colleagues and relive a moment from the past. If you ever had the opportunity to work in Building 20, you will certainly want to attend this farewell celebration. Please mark the date on your calendar. To ensure that you receive an invitation, please write to: Ms. Vera Sayzew, EECS Department, MIT, 77 Massachusetts Avenue, Room 38-401, Cambridge, MA 02139-4307; or send email to: vsayzew@mit.edu.

MIT's Building 20, the wooden barracks-type structure on Vassar Street, is slated for demolition in 1998. The building was originally constructed as temporary quarters for MIT's World War II Radiation Laboratory in 1943. (Photo by John F. Cook)

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