RLE currents

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The Research Laboratory of Electronics at the Massachusetts Institute of Technology

AUDITORY PHYSIOLOGY:
The Earmark of RLE Research

Working together, our eyes and ears are the two sensory organs that process most of our communication from the outside world. Few of us stop to consider the efficient processing of sensory stimuli by our auditory system. How can we discriminate between speech, music, and other sound stimuli so quickly? How do the various acoustic stimuli affect our auditory mechanisms? What enables both our auditory and nervous systems to transduce an acoustic signal into electromechanical activities that are understood by our brain? What is involved in our auditory nervous system that allow us to ignore background noise (such as our own heartbeat or the rumblings of an air conditioner) so that we can concentrate on meaningful sounds?

The aim of basic auditory physiology research in RLE is to discover what aspects of our acoustic environment our auditory mechanisms respond to, and how this information is processed by the brain. The understanding of such fundamental knowledge is a step towards the comprehension of higher level cognitive behavior in humans.

Sound Processing in the Human Ear

We hear sounds because they produce rapid changes in air pressure which, although small, are strong enough to vibrate our eardrum membrane, a delicate movable diaphragm attached to the three small bones or ossicles of the middle ear—the *malleus*, *incus*, and *stapes* (sometimes referred to as the hammer, anvil, and stirrup). These bones connect the eardrum membrane to the inner ear.

In a piston-like fashion, the stapes (the body's smallest bone) moves in and out of the inner ear, a fluid-filled structure that contains the vestibular and hearing organs. Pressure changes in the inner ear set the *basilar membrane* into motion. Attached to the basilar membrane is a complex collection

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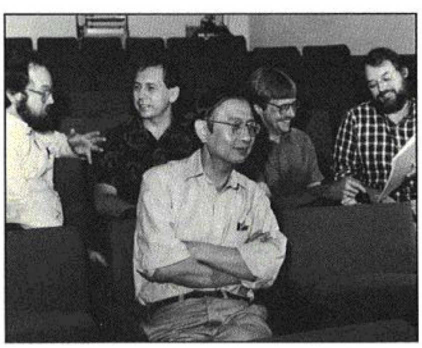
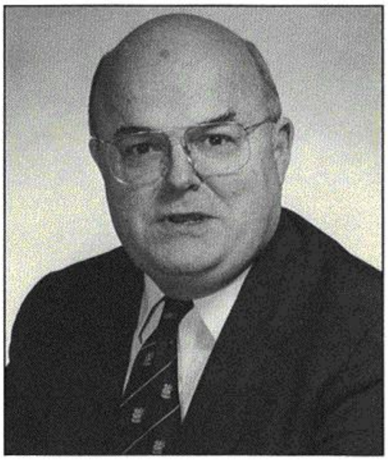


No matter how alert or responsive we are, there is a limit to the number of things to which we can focus our attention at any one time. For example, we cannot listen effectively to two simultaneous conversations. This difficulty in processing information from two different sources at the same time occurs even when no response is required from the listener. One aspect of Professor Nelson Y. S. Kiang's interests focuses on how the auditory system differs from a passive receiver, and how the brain and the ear work together to perform selective perception. Here, Professor Kiang is in the front row, attempting to eavesdrop on the conversations behind him. Providing the input stimuli are (from left): Research Associate Dr. John J. Rosowski, Research Scientist Dr. Bertrand Delgutte, Research Scientist Dr. Dennis M. Freeman, and Research Scientist Dr. Donald K. Eddington. (Photos by John F. Cook)

Director's Message



Professor Jonathan Allen, Director
Research Laboratory of Electronics

It may be surprising that a laboratory called the Research Laboratory of Electronics has such a large amount of research in language, speech, and hearing. In the beginning, the laboratory was concerned with the physical phenomena of electronic devices in systems such as radar. These concerns quickly expanded to include interests in coding and the representation of information, which led to a basic theoretical understanding of communication in man-made systems. Given this extensive and fundamental concern with the means for communication, it was natural for RLE researchers to expand their interests to include communication in animals and humans. Today, these interests include linguistics, speech communication, auditory psychophysics, auditory physiology, and sensory communication through all modalities. In fact, RLE has one of the world's greatest concentrations of research in these areas, and these investigations are especially good examples of the interdisciplinary research fostered in RLE.

Communication signals must be both produced and perceived, and although many RLE research areas such as speech perception and auditory psychophysics focus on the perception of acoustic signals, all these activities build on the basic understanding of auditory physiology. No fewer than five RLE faculty members concentrate on the various aspects of auditory physiology, together with an outstanding group of technical staff and students. The focus is on the detailed study of how auditory pressure perturbations are guided by the outer ear structures to the eardrum, translated through the middle ear's network of connected ossicles, and transduced in the inner ear to spike potentials on the auditory nerve to higher processing centers in the brain.

Over the years, incredible growth in understanding these processes has exploited state-of-the-art experimental techniques and sophisticated theoretical modelling. Exceedingly small motions must be carefully characterized, and intricate studies of cell physiology are needed to comprehend the overall transduction process. Great effort has gone into the coding of intensity, pitch, frequency spectra of sounds, and timing. In the early work, many studies used well-understood stimuli such as clicks and wideband noise. But, in recent years, as the knowledge of neural encoding has improved, there has been an increasing emphasis on the use of speech-like sounds. Progress in this field is hard won, and is based on the need for comprehensive experiments and their theoretical characterization. Much work still lies ahead in order to understand the overall physiology of the peripheral auditory system, including subtle details of speech coding.

Just as auditory physiology is the basis for other hearing-related disciplines, important applications have been built on the growing knowledge of hearing functions. Recently, models of the cochlear processing of speech sounds have been used as "front ends" for contemporary speech recognition systems, and have provided realistic spectral and timing discrimination that imitates human functions. Another application is the development of cochlear prostheses, where a string of electrodes is clinically introduced into the inner ear to directly stimulate cochlear hair cells and their connections to the auditory nerve. These applications are expected to grow in importance and impact, and lead to other uses.

RLE's research in auditory physiology has brought together a wide variety of strengths in biology, psychology, physiology, electrical engineering, and measurement technology. Auditory physiology is a wonderful illustration of RLE's long-term dedication to fundamental knowledge of human and animal communication. We take particular pleasure in both the scientific contributions and the service to society which this important work provides.

AUDITORY PHYSIOLOGY
(continued)

of cells, the *organ of Corti*, which generate impulses in nerve fibers attached to special receptor cells called *hair cells*. Vibrational displacements of subatomic dimensions can be sensed by these hair cells, which deliver chemical transmitters to the endings of the auditory *nerve fibers*. Approximately 40,000 nerve fibers transmit impulses to the brain. Recoding this neural activity into more usable forms occurs in the auditory pathways, including the *brainstem*, *thalamus*, and *cortex*.

Auditory Physiology Research

Research on hearing is wide ranging, and couples theoretical and experimental researchers from many professional disciplines. Auditory physiology seeks to examine how the auditory system works, and the mechanisms associated with the coding of acoustic stimulus. Investigators attempt to understand the language used by the sensory nervous system to describe the external acoustic world.

Technological advances in recent decades have made it possible to study and measure the auditory system and its components more precisely than ever before.

In many auditory physiology studies, controlled stimuli are needed to collect, measure, and analyze responses from experimental subjects. The electrical activity of specific nerve fibers can be measured either at a single-cell level, or from populations of neurons. By inserting electrodes connected to measuring devices and computational facilities, experimenters can record electrical responses of sounds. The development of extremely refined microelectrode tips (measuring about one-thousandth of a millimeter) has made possible the recording of nerve impulses from identified single neurons. The massed electrical discharges from populations of these single neurons can be measured also, and is useful in studying responses from humans.

Electron microscopy combined with classical anatomical methods have resulted in highly detailed descriptions of auditory cells, and the ability to accurately trace the neural pathways has become highly developed. Refined and specialized techniques in physiology have enabled the measurement of electrochemical changes in neurons. Advances in computer science have resulted in improved experimental control and data analyses. In addition, developments in microprocessors and miniature electronic components have made possible auditory prostheses such as cochlear implants, which are artificial devices that provide hearing for the deaf.

RLE Research in Auditory Physiology

In studying how the body responds to acoustic stimuli, researchers at RLE and the Eaton-Peabody Laboratory at the Massachusetts Eye and Ear Infirmary conduct a broad range of investigations:

Professor Nelson Y. S. Kiang, Director of the Eaton-Peabody Laboratory, has studied how single neurons contribute to electric responses recorded from the scalp, as well as stimulus coding in the nervous system. This research not only

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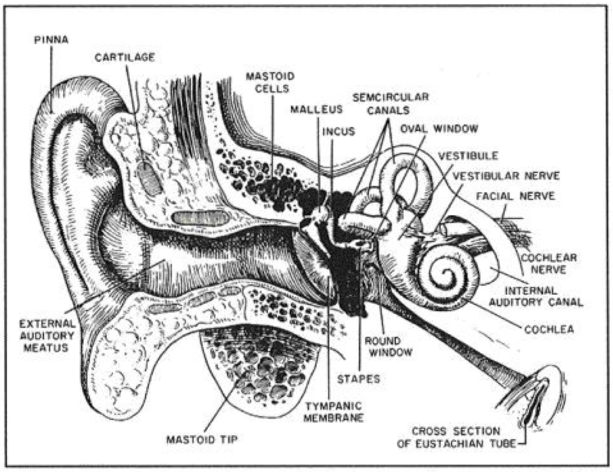
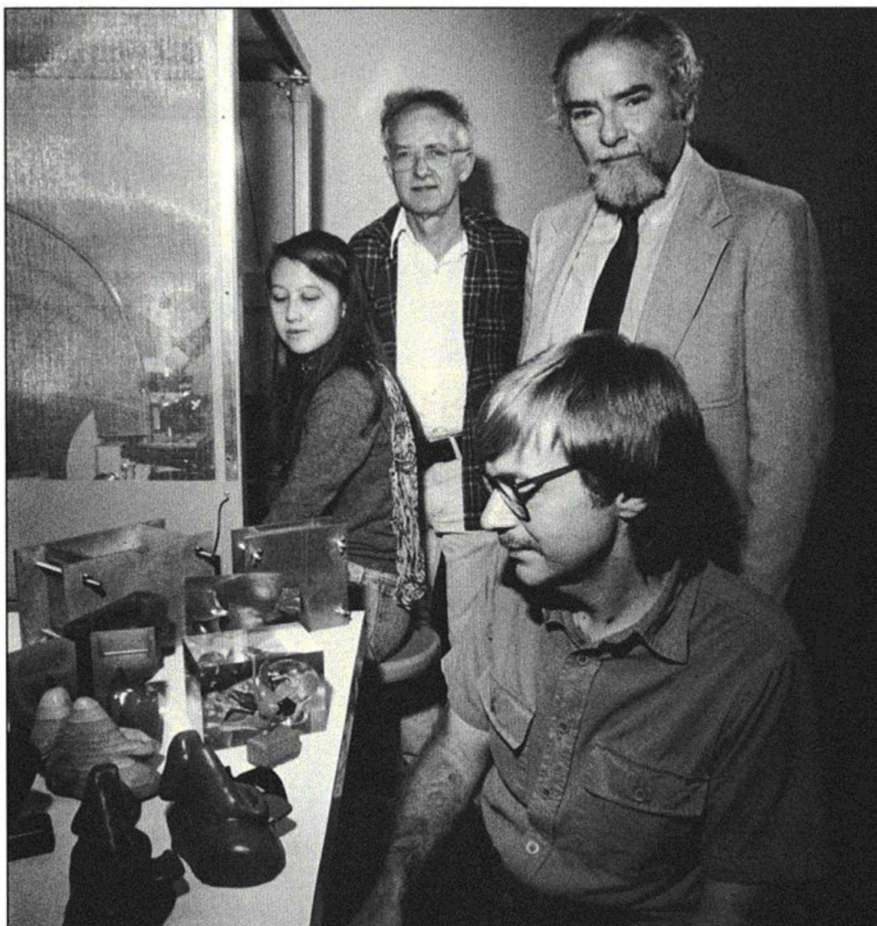


A cross section of the ear. This drawing shows the general structures and mechanisms of the human ear.



In all vertebrate ears, sound causes vibration of the middle and inner ear that ultimately stimulates the ear's transducer cells, or hair cells. These hair cells contain tufts of sensory hairs, whose displacement produces electrical events that result in nerve signals carrying information about the sound to the brain. Little is known about the microscopic mechanical events that displace the hair bundles, and techniques are being developed in RLE to investigate these properties in the inner ear of a lizard. To aid in visualizing the structure of the lizard's auditory receptor organ, an accurate plastic model of the ear (magnified 50 times) was constructed from anatomical sections. The investigators participating in this project display the model and molds used (from left): graduate student Donna K. Hendrix, Professor Lawrence S. Frishkopf, Professor Thomas F. Weiss, and Research Scientist Dr. Dennis M. Freeman. The results of this research will enable the measurement of hair bundle motions, as well as inner ear fluids and structures. (Photo by John F. Cook)

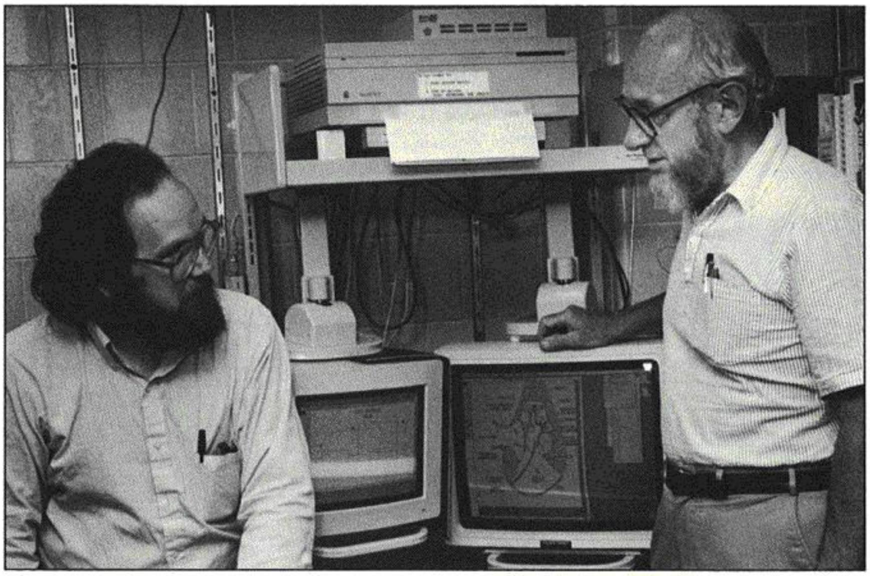
AUDITORY PHYSIOLOGY
(continued)

seeks to improve understanding of basic physiology, but also has clinical applications.

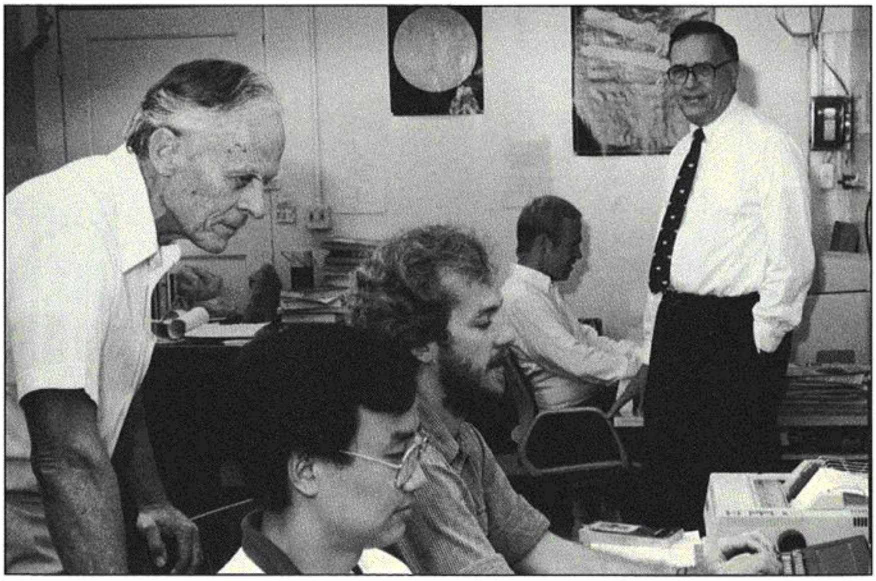
The cochlear mechanisms by which acoustic stimuli are encoded into auditory nerve signals have been investigated by ***Professor Thomas F. Weiss*** and ***Research Scientist Dr. Dennis M. Freeman.*** This work is focused on how the microscopic motion of sensory hair cell bundles in the inner ear convey mechanical stimulus. The aim of this research is to understand the hydrodynamics underlying hair cell bundle motion. Dr. Freeman has constructed a scaled physical model of the lizard ear, which is useful in visualizing the complex anatomy of the ear. In addition, Dr. Freeman has been involved with the design and development of motion detection devices to measure movements of inner ear structures.

Together with Professor Weiss and Dr. Freeman, ***Professor Lawrence S. Frishkopf*** has measured hair cell stereociliary tuft motions as they relate to frequency selectivity in the cochlea of the alligator lizard. These studies contribute to the understanding of acoustic analysis in more complex mammalian cochleas.

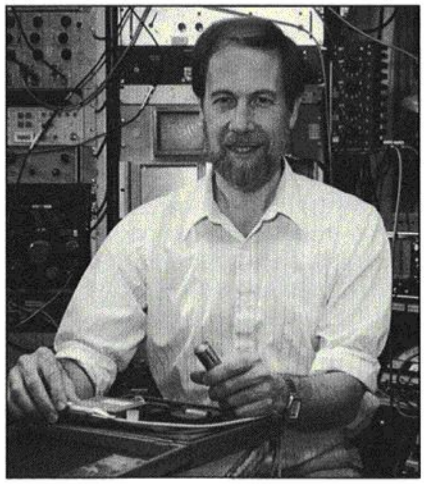
Principal Research Scientist Dr. John J. Guinan studies auditory reflexes, such as middle-ear muscle or inner-ear mechanical reflexes. Dr. Guinan has demonstrated that olivocochlear efferents alter cochlear mechanics, resulting in threshold shifts of auditory nerve fibers and adjustments in the effective range of the auditory system.



Computer displays illustrate the anatomy and physics of how sounds are coupled from the external ear to the inner ear. Research Associate Dr. John J. Rosowski (left) and Professor William T. Peake study how structures such as the tympanic membrane, the ossicles, and air-filled cavities affect signals transmitted through the middle ear. (Photo by John F. Cook)



Professors Campbell L. Searle (standing, left) and William M. Siebert discuss the results derived from data acquired from the auditory system of the cat with graduate students (front to back) Richard Y. Kim, Hugh E. Secker-Walker, and Timothy A. Wilson. The group's overall interest is to identify the essential signal processing functions of the inner ear, and to examine the constraints that this processing places on perceptual tasks such as speech recognition. (Photo by John F. Cook)

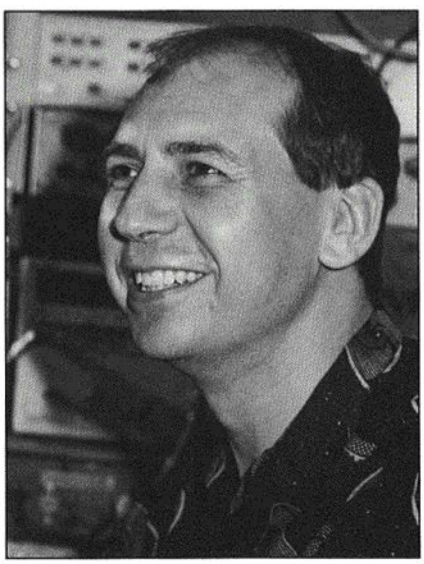


Principal Research Scientist Dr. John J. Guinan, Jr., works with an ultra-sensitive microphone that measures sounds in the ear canal generated by the ear itself during the hearing process. Mechanical amplifiers in the cochlea produce these sounds, and Dr. Guinan is studying how feedback nerves from the brain to the cochlea influence these amplifiers. The equipment shown in the background generates the sounds presented to the ear, and extracts the sound produced by the cochlea. (Photo by John F. Cook)

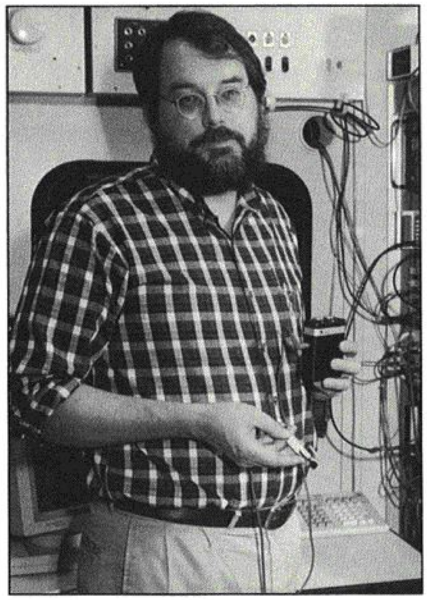
Professor William M. Siebert has developed mathematical models for physiological systems, particularly the peripheral mechanical and neural structures in the auditory system. This research is aimed at understanding how these structures contribute to an organism's functioning. In collaboration with ***Professor Campbell L. Searle***, he is also investigating the role of human auditory mechanisms in speech recognition.

Signal processing and mechanical transduction in the middle ear are the focus of ***Professor William T. Peake's*** research. He has studied acoustic transmissions in the ears of different species, and how structural components influence mechanical response properties. In collaboration with ***Research Associate Dr. John J. Rosowski***, he has examined how sounds are transmitted through the middle and inner ears.

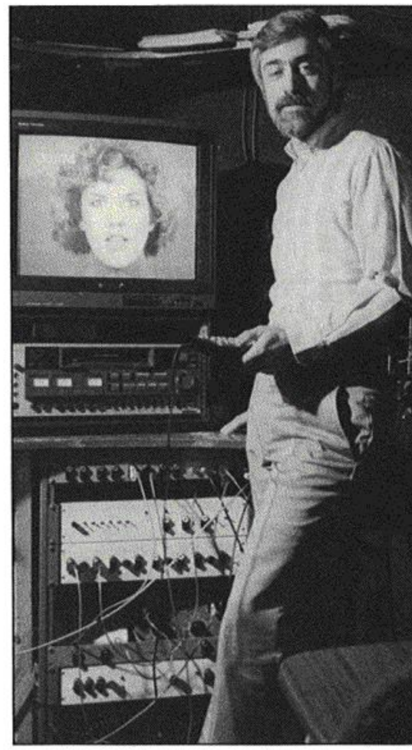
Research Scientist Dr. Bertrand Delgutte is interested in the coding of speech in the auditory system. He has demonstrated that nonlinear mechanical phenomena in the inner ear can play a larger role in auditory masking than had previously been thought, particularly for intense, low-frequency sounds. Continued experiments in this area may lead to improved hearing aid design. Dr. Delgutte has also conducted studies with electric stimuli to determine auditory nerve activity produced by cochlear implants.



Research Scientist Dr. Bertrand Delgutte's work involves recording from single auditory nerve fibers, and generating models that relate auditory nerve responses to acoustic stimuli. This research contributes to understanding how humans process speech signals and how communicative disorders may occur. (Photo by John F. Cook)



Research Scientist Dr. Donald K. Eddington shows the portable stimulation system worn by human subjects as part of the experimental cochlear implant project. The hearing aid case (in right hand) contains a microphone and an amplifier which send a signal to the sound processor (black box). The sound processor converts the signal to four channels of electrical stimuli that are delivered to four electrodes implanted in the subjects' inner ear. When the electrodes are stimulated with small electric currents, they activate otherwise inactive nerve fibers and produce sound sensations. Dr. Eddington's experiments are focused on developing a basic understanding on how the electric stimuli are transformed into sound perception. With this understanding, investigators can design the next generation of cochlear implants. (Photo by John F. Cook)



When used in conjunction with lipreading, cochlear implants provide substantial benefits to speech reception, enabling more reliable and comfortable communication. Principal Research Scientist Dr. William M. Rabinowitz works with Research Specialist Lorraine A. Delhorne of RLE's Sensory Communication Group to examine audiovisual stimuli used in patient evaluations. The sentence under examination, "How many of your brothers still live at home?," is part of a corpus available on laser video disc. This technology allows computer-controlled, high-speed access to high-quality audiovisual events. (Photo by John F. Cook)

Research Scientist Dr. Donald K. Eddington does fundamental research and experimentation on the development of auditory neuroprostheses with the Massachusetts Eye and Ear Infirmary's cochlear implant project. In patients with little or no functioning of hair cells, usable hearing can be provided by electrically stimulating the auditory nerve directly. (For further background on cochlear implant research at Eaton-Peabody Laboratory, see *Boston Globe*, July 10, 1989, page 27).

Principal Research Scientist Dr. William M. Rabinowitz seeks to develop increased understanding of normal auditory and speech perception processes, and to apply this understanding to the problems of hearing impairment and deafness. His current research is focused in three areas: multimicrophone processing, which addresses certain deficiencies in currently available hearing aids; the cochlear implant project at the Massachusetts Eye and Ear Infirmary; and tactile speech communication, which substitutes the sense of touch for the damaged ear.

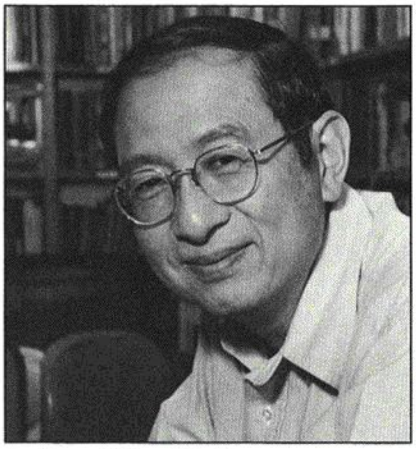
by Dorothy A. Fleischer

FACULTY PROFILE: Nelson Y. S. Kiang

Professor Nelson Yuan-sheng Kiang was born in Wuxi, China, in 1929. After immigrating to the United States with his family, he attended the University of Chicago, and received his Ph.B. in 1947, at the age of eighteen. He graduated with a Ph.D. in Biopsychology from the University of Chicago in 1955, and joined RLE's research staff in Professor Walter Rosenblith's Communications Biophysics Group.

In 1956, he was the first appointment to the newly established Eaton-Peabody Laboratory at the Massachusetts Eye and Ear Infirmary, where he is now Director. He is currently a professor in the Department of Brain and Cognitive Sciences at MIT's Whitaker College, and a professor of physiology in the Department of Otology and Laryngology at the Harvard Medical School. Professor Kiang also holds research appointments at the Massachusetts General Hospital and the Massachusetts Eye and Ear Infirmary. In 1968, he received the Beltone Award for Distinguished Accomplishment as a Research Investigator in the Field of Hearing, and was conferred an honorary M.D. in 1981 by the University of Geneva in Switzerland. He is a member of many professional societies.

*In July 1989, a scientific symposium, "Basic Research in a Clinical Environment," was held in honor of Professor Kiang's sixtieth birthday. In keeping with his reputation as an insomniac (*Boston Globe, *February 21, 1989, page 29), he participated in the following interview only twelve hours after his return from a trip to the Gobi Desert in Mongolia.*



Professor Nelson Y.S. Kiang

• How did you become interested in auditory physiology?

When I was at the University of Chicago, I had thought of studying the brain with Professor Ralph Gerard. But, when he moved to the University of Illinois, I had to find another mentor. Professor William Duwayne Neff was studying the auditory part of the brain, so I joined his laboratory and did my thesis on the auditory cortex. By the time I graduated from the University of Chicago in 1955, I had taken or audited a wide variety of courses, but there was no engineering school or engineering courses. At that time, the development of computers was just beginning, and it was obvious that both the brain and computers processed information. So, I came to work with Professor Walter Rosenblith at MIT, because the one major discipline that was missing from my training was engineering.

• Did you have a mentor?

Not one, but many. Dr. W. D. Neff taught me how to be a scientist. You can read how science is done, you can study the history of science, but you have to practice it in order to be a professional. In Neff's lab, I learned how to be a scientist. Walter Rosenblith taught me how to write. In science, not only do you have to find out things for yourself, but you have to communicate the results to others. Then, Dr. John Irwin taught me how to run a laboratory. Those individuals were my three major teachers.

• How would you describe your interaction with RLE's Communications Biophysics Group?

In 1955, I joined the group as one of the few biologically trained people. Most were engineers or psychologists, but there was a niche for me, since I knew anatomy and how to do surgery. Because I also knew some mathematics and physics, I quickly picked up engineering ways of thinking. Walter's graduate students and I worked together on many experiments, and we taught each other different ways to think about signals in the brain.

• What was the impetus behind the Eaton-Peabody Laboratory (EPL)?

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 (I don't know it first-hand because I wasn't there), 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.

It quickly became clear to Brown and Frishkopf that they couldn't communicate with the clinicians. There was a big cultural difference between science and medicine then, which remains to this day. The duty of medicine is to care for sick people, and that of science is to find out how the universe works. My MIT colleagues saw little future in this effort to establish a laboratory, because the concept of research was so different to clinicians and researchers. I, however, had done my thesis work in a laboratory active in both otolaryngology and physiological psychology. I knew otolaryngologists well, and could speak their language. I had some training in medicine as well as the basic sciences, so it was easy for me to move from one group of people to another. You might say that I'm a linguist in science, because I find it easy to communicate with clinicians, engineers, biologists, and psychologists. Even though science and medicine don't have the same mission, they do overlap somewhat.

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• *How would you contrast the research environments at EPL and RLE?*

RLE was established by the physics and engineering departments as their research component. Physics is a basic science, and engineering is an applied science. In some sense, engineering and medicine have a closer intellectual tie because both are applied fields. Physics, biology, and psychology are basic areas where the fundamental drive is to *understand* something, regardless of the application. Engineering and medicine use the principles of science to benefit mankind.

RLE was a mixed culture of physics and engineering. Some people were interested in fundamental ideas, others were interested in the application of those ideas. The genius of RLE was to couple those two activities; to realize that applications can depend upon fundamental knowledge to such a degree that sometimes engineers have to do fundamental research, or that physicists may want to work on practical applications. RLE's success formula, and the secret of success in all research, is to bring different cultures together. For students, the great educational value of RLE is that it brings the basic sciences and engineering into one research entity.

• *What is the nature of the interaction between the doctors and researchers at the Eye and Ear Infirmary?*

Socially, it's very amicable. In the beginning, the otolaryngologists were extremely sympathetic to EPL. They wanted something to happen, they knew something good would come from this interaction, but they couldn't predict exactly what. It's clear that most advances in medicine have come about through an interaction with basic sciences, and some of that has happened here. I don't think you need to convince any doctor that basic science is a driving force in medicine today.

Medicine itself is not a monolithic entity. There are people ranging from academicians who do research in universities and hospitals, to community practitioners who concentrate on delivering health care. Few people can do both the business and scientific sides of medicine well at the same time. Each requires such dedication and background that it is difficult to be good at both. So, it is important to have people who can cross-link the major groups of professionals, people who can move intellectually or physically between the various groups at will.

To this end, we must become more flexible in how we educate people. We should allow people to create their own combination of activities to suit their own personalities, interests, and training. Some people want all engineers trained a certain way, all doctors trained a certain way, all physicists trained a certain way. I believe these activities shouldn't be so rigidly defined, and I would much rather see more flexible education. People should be taught to think, evaluate, and make decisions. In running a multidisciplinary laboratory, I've learned that the best people tend to have broad interests.

This is why I believe in a liberal education. My concept of a university is that it plays with ideas. The fundamental job of a university is to *think*, and to teach how to think. But, to *apply* those thoughts, one goes to the various professional schools such as engineering, medicine, law, business, or theology. Of all the professional schools, engineering is the only one I can think of that doesn't require its practitioners to attend college first. In medicine and law, one generally goes to college to sample the range of intellectual work. Then, one specializes and learns how to practice a profession. To have engineering conform to the standards of other professions would require considerable change because there is that built-in inertia to resist change.

There's also a noticeable difference between most Harvard and MIT students. Many Harvard students have had a liberal undergraduate education before they come to EPL as graduate students. MIT engineering students, on the other hand, are trained to be terrific problem solvers. One can give them a problem, and if they know how to think about it, they will solve it. But, Harvard students are generally better equipped to ask questions. They might not know how to solve a particular problem or deal with it quantitatively, but they have inquiring minds, and they ask broader questions.

For our students, part of the value in working at the EPL is that they get to meet other kinds of students. By getting to know each other, they learn the different cultures first-hand. Although the differences can be great, after spending four or five years together in the laboratory, these students gain a deeper understanding of many fields, and some of them cross over. Some Harvard students eventually end up doing engineering-like work, and some engineering students end up doing basic science work. To me, EPL is not so much a unit that cranks out research, but rather a place where students are educated.

• *What is your approach to investigating the human auditory system?*

Our philosophy is to take the auditory system apart like a watch, figure out how all the pieces work independently, then put it together as a system to see how it functions as an integrated whole. From psychology, we know what people can do in response to sounds. For example, we can conduct a conversation. The physiological question is: What is happening in the brain in order for you to understand what I'm saying, and for you to frame a response by generating a sound sequence with your speech production system? This chain of events is the foundation of human social interaction, and the communications industry is based on this process.

We've also applied the ideas about complicated systems, previously developed by physical scientists and engineers, to study the auditory system. In other words, we regard the auditory system as a machine that processes information, and we systematically trace signals through its various components. Because I am at both MIT and the Harvard Medical School, I take two different views. At MIT, we tend to think of the brain as an information processing machine. At Harvard, we think of the brain as a wet organ full of active chemicals. Both views are correct, and by understanding both, one gains a more complete perspective.

• *How was the ability to measure signals directly from single auditory nerve fibers developed?*

When I came to MIT, the radar people were using signal processing to average signals embedded in noise. We took those techniques and applied them to the detection of signals from the ear and the brain. That approach worked well. In the late '50s, digital computers with random access memories were being developed by Group 51 at Lincoln Laboratories. (Part of that group later started the Digital Equipment Corporation.) I believe their first hard-wired special-purpose digital computer, which I named the Average Response Computer (ARC-1), was used by us in RLE's Communications Biophysics Group to examine gross evoked responses in the auditory system. At the time, general-purpose computers were beginning to evolve, and the ability to record from single neurons was developing in the field of neurophysiology. We simply combined these techniques to describe the information carried in the spike discharge patterns of single neurons. The summed waveforms of the single neuron activity make up much of the fast components in the gross evoked responses.

• *How dependent is your work on the development of new technology?*

In a narrow sense, every technical advance changes how we do things, and enables us to answer different kinds of questions. Certainly, computers have a tremendous impact, as well as new materials and equipment. Monitoring the activity of huge numbers of neural elements simultaneously is the one step that's needed for the next big push in understanding complex systems. Right now, we can record from single units, or a few units in many situations. But, if we ask how a large collection of units interact, we would need to record their signals simultaneously, and there isn't a good way to do that right now. There are only the beginnings of new techniques which enable us to examine what's happening in large ensembles of neurons.

EPL is not a technologically driven laboratory, in the sense of being dominated by a single approach. We're interested in studying the auditory system, and we'll use whatever tools are available. So, technologically, we try to keep up with all the developments, whatever they are. If a method will help us to answer a question, we'll go out and learn it. So, we use electron microscopy, single-unit recordings, immunological markers, computer modelling, etc.

> Our philosophy is to take the auditory system apart like a watch, figure out how all the pieces work independently, then put it together as a system to see how it functions as an integrated whole.

• *What are your plans for developing a graduate teaching program in speech and hearing?*

Bill Peake, Ken Stevens, and Lou Braida are the key RLE people in planning this program. We want to start a graduate teaching program for researchers in the speech and hearing sciences that will take students well trained in the hard sciences, and offer them fairly rigorous courses in acoustics, signal processing, and systems theory, together with the biology of speech production and hearing.

There are over 250 graduate departments of speech and hearing in this country. Most are devoted to training paramedical or para-educational professionals such as speech therapists, audiologists, and pathologists who work in clinics or schools. There are many jobs in these areas, and speech and hearing departments cannot train enough people to staff these jobs. As a result, hardly any of these graduate departments train researchers. So, the speech and hearing field has this anomaly of lots of jobs, lots of schools that train professionals to fill these jobs, but no base of research from which new ideas can flow. It's like medicine was before World War II—lots of practitioners, lots of medical schools to train the practitioners, but very little in the way of training programs for researchers. Our program will not compete with the existing programs, because we're not going to train practitioners; we want to train researchers.

• *Do models for man-made devices help you in modelling the human auditory system?*

Yes, certainly. Strangely enough, fewer and fewer students in the medical sciences are trained to think at a systems level. Modern medicine is driven by molecular biology, which has been so successful that it has crowded out some of the other intellectual threads essential to medicine. For example, systems theory—how complicated systems work—isn't taught in many medical schools anymore. When I was in school, it was taught as part of physiology. But, that's no longer true. It survives by a hair's thread. Systems theory is an endangered species in the biological academic world.

In a sense, EPL is preserving systems theory as an important way to think about how the body works. Our proposed speech and hearing graduate program will have systems theory as its philosophical backbone. By keeping systems theory alive in this special field of auditory research, it may someday reenter the main body of medicine, and become a major force again. It has to, because all bodily systems, such as the immune and metabolic systems, have their own signals and control mechanisms.

• *Part of your research focuses on prosthetic devices for the hearing impaired, specifically, cochlear implants. What is the goal of this research?*

The cochlear implant is an electrode system inserted into the ear to stimulate the auditory nerve. Basically, it's a hearing aid that bypasses a malfunctioning ear to deliver electric signals directly to the brain. The cochlear implant device used here at Massachusetts Eye and Ear Infirmary was developed, in part, by Donald Eddington. Don is a member of EPL, but the cochlear implant work is done by a special group formed for that purpose.

• *What are your views on people who advocate deaf rights?*

There is a deaf population that has formed functional communities, and cochlear implants present some problems to these communities. Let me make an analogy: Many Chinese immigrants who come to this country don't know English. They form communities in which facility with English is not necessary. Then, their children go to American schools and learn English. No matter how strong the family ties, there is now a force that tends to pull these generations apart, because the parents are socially limited to the Chinese-speaking community, but the children are now free to enter the English-speaking community. That puts children and parents in two different worlds, and produces strains within the family, that can, in some cases, compromise the family structure.

In a similar manner, within a tightly knit deaf community, there will be social forces that tend to pull that social unit apart if the children can co-exist in a hearing world. The parents' decision to permit an implant is a difficult one, because you can't wait until a child is twenty-one to make his own decision. Similarly, one can't keep a child in an exclusively Chinese-speaking community until he's twenty-one, and then have the child decide if he wants to learn English. For the deaf parents of a deaf child, the option of a cochlear implant and having the child move into the hearing world is a hard decision for the parents to make. This problem will be exacerbated when implants become practical for infants.

Many people have learned to live with deafness, and they've adjusted perfectly well. To put a cochlear implant in these people could be very disruptive to their lifestyle. It might be more helpful for people who were recently deafened, and who miss the hearing world. That's why it's a matter of individual choice. Nobody should push cochlear implants for people who don't want them. But, it is important that the information be made available on what can be done with cochlear implants and what their limitations are.

• *How do you see your work as providing a direct benefit to society?*

In the short-term, there are direct applications to medicine. But overall, simply by our presence, we interact with the clinicians, and force them to question what they do, even in areas unrelated to hearing.

Medicine is organized like the military. Both these institutions can't afford to debate endlessly. They must decide what course is most likely to prove useful, and take action. So, these organizations have an authoritarian structure with a system of ranks and authority. In a scholarly field, if a beginning student can construct a valid argument that overturns the thoughts of the most distinguished professor, we must go along with the student. Ideally, rank has nothing to do with it. It's the cogency of the argument that's important, not who's making the argument. You can't do that in medicine. If there's a question of how to treat a particular patient, the person with the most experience has the authority to prevail.

By our presence, we can provide an attitude of questioning towards medical procedures that have not been well validated. They're usually done because of theory or inertia, or perhaps for business considerations. Sometimes, patients are harmed by treatments in the armamentaria of the clinician. We can often sharpen these issues for our clinical colleagues. The scholar's job is to question everything. The practitioner's job makes it impossible for him to question dogmas, simply because he doesn't have time.

By our presence, we can provide an attitude of questioning towards medical procedures that have not been well validated. . . . The scholar's job is to question everything. The practitioner's job makes it impossible for him to question dogmas, simply because he doesn't have time.

If we researchers came from the outside and asked difficult questions, we would be perceived as attacking the clinicians. But, because some of us have "grown up" with each other, we're friends, and our clinical colleagues know our motivations are good. When we question them, they know there's some valid reason behind it. There are direct ways in which our research has had an impact, like the cochlear implants or electric response testing, but there are also much more indirect and long-range benefits which are probably more important. By putting a basic research laboratory in a clinical environment, and having young clinicians and researchers "grow up" with each other, we build connections, the exact outcomes of which are unpredictable, but must surely be beneficial.

• What is the most important issue facing EPL today?

EPL exists in a very fragile environment. Hospitals care for the sick as their primary function. Teaching hospitals, as an additional mission, try to improve health care and teach new ways of thinking to people coming up in the system. All of medicine is in crisis at the present time, and most hospital priorities are being driven by economic factors. The academic hospitals, in particular, are in difficult shape because they cannot write off the difficult cases and treat just the profitable ones. Economic considerations are now growing in educational institutions as well. So, a laboratory that exists at the interface of education, basic research, and health care will be affected by adversities in any of these entities. At the moment, they're all under pressure, and the status of EPL is not at all certain. One note of hope is that we have a very strong cadre of young people who believe in the original idea, and somehow, they will carry it into the next generation. I have a lot of faith in the young people we train but, it will not be easy. On the other hand, it never was easy.

• What has been your greatest success?

Our philosophy of tracing signals through the auditory system is a very general idea which depends on finding examples where it is useful. We knew it had to be successful at some level, because that has to be one way to think about the system. Being able to demonstrate that this idea can help us understand how we process auditory information in specific cases is gratifying. We've shown how the auditory nerve describes the acoustic environment. It is the difference between *believing* this is going to be a good way to think, and *showing* that it is useful in generating new insights. We need no longer debate the issue of whether or not this is a good way to do things. Intellectually, it's satisfying to see our intuition confirmed by demonstration. At a different level, the continued existence of EPL is satisfying, because there have been times when it was not clear whether the laboratory would continue to exist.

• What is the biggest obstacle you've had to overcome?

One can be correct philosophically and still become extinct, because insufficient attention is paid to metabolic needs. Financial support of EPL has largely been through the National Institutes of Health, with private support being key at critical times. I've always disliked publicity. Many young people feel this attitude has constrained us. They see other places that "advertise" getting support from private donors who are attracted by hyperbole. But, organizations can be endangered also when they reach the attention of their "predators." So, in the early days of EPL, it was extremely important for us to have low visibility. Being a four-institution laboratory, it's very fragile, and it can be harmed in so many ways. We were always low-key, and paid attention mainly to our science, and did not get involved in academic politics.

My preference has always been to do science and make that strong until we were unassailable at that level. If we had tried to start a teaching program earlier, we wouldn't have gotten anywhere. In order to start programs like that you need the help of other people, you need to go to the faculty councils of both institutions, and you need to develop political support. In politics, people respect power and size. So, as the first head of EPL, I had to make certain that we were strong enough to play in other arenas. I think we're at a stage now where we're strong enough to try other things, such as the teaching program. But, I still think it's important not to be too ambitious; not to have the desire for power, control, influence, fame, and money—all of which intrudes into the academic process. I think we should always keep our eye on the ball—the intellectual work. We seek to understand, and that's what EPL is all about. I don't know if this philosophy will persist into the next generation, but I hope it will.

I don't think being remembered is as nearly important as imparting to students the values that one holds dear—intellectual integrity, dedication to scholarship, and a sense of quality in one's work.

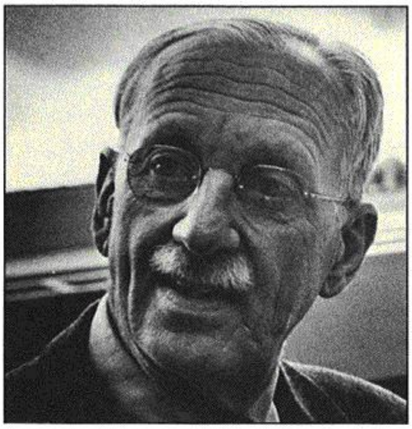
• Is there something you're working on that you're excited about?

I'm trying to extract myself from the day-to-day running of EPL, because I believe that the next generation must know how to do that, and the only way they can learn to do it is *to do it*. At the same time, I'm turning more towards other activities of broader interest. The laboratory is embedded in a social framework, and as it matures, it must interact with many other entities. It's important for EPL to have strong connections with other units at MIT and Harvard, and to regularize the laboratory's relationships with its parent institutions—getting our young people appointed to proper positions, and showing them how these institutions work. They need to know that they can't live in the laboratory as a isolated ivory tower. The MIT people have to learn how MIT works, the Harvard people have to learn how Harvard works, and they have to start taking control of the reins. That's hard, because most scientists want to work on their science.

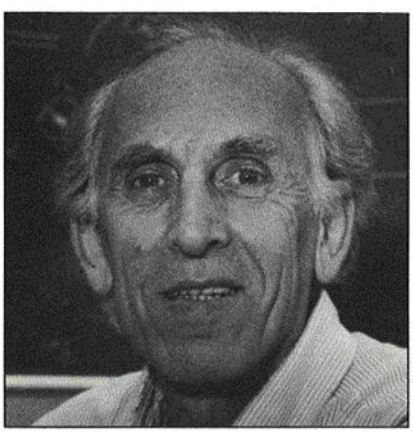
• How would you like to be remembered?

It's not so important for anyone to remember me, as it is for them to support the ideas that I stand for. I've been a member of RLE since January of 1955, and although people at RLE may not see me around all the time, I'm very much of an RLEer. I believe in the laboratory's values, and I think they need to be constantly reaffirmed. I don't think being remembered is as nearly important as imparting to students the values that one holds dear—intellectual integrity, dedication to scholarship, and a sense of quality in one's work. I think that's the best legacy to leave them, and they should pass it on—like a virus that becomes part of our genetic heritage.

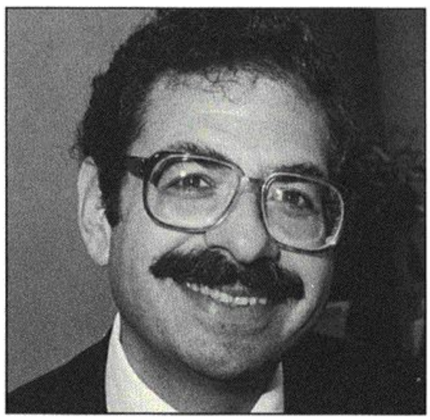
circuit breakers



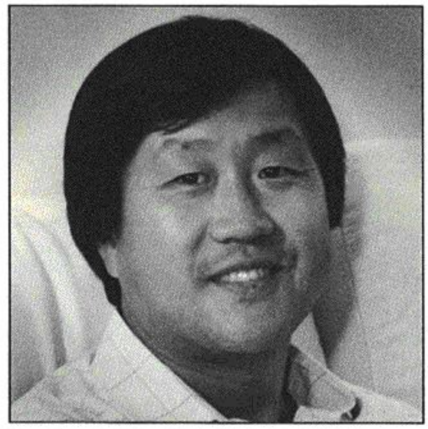
The American Physical Society has established the Will Allis Prize in Gaseous Electronics in honor of Physics ***Professor Emeritus William P. Allis*** (B.S. '23, M.S. '24). The biennial prize will recognize outstanding research on microscopic or macroscopic behavior of partially ionized gases, and will be endowed with contributions from Professor Allis' colleagues, GTE, GE, Xerox, IBM, and AT&T. In addition to his longstanding service with RLE, Professor Allis was chairman of the Gaseous Electronics Conference for thirteen years, and recipient of numerous awards in the field of plasma physics. *(Photo by John F. Cook)*



Dr. George Bekefi, Professor of Physics, received the IEEE Plasma Science and Applications Award on May 22, 1989, at the IEEE International Conference on Plasma Science in Buffalo, New York. The award cited his contributions to the understanding of electromagnetic radiation processes in electron beam devices and plasmas, including experimental and theoretical investigations into the generation of high-power electromagnetic radiation by free-electron lasers and relativistic beams. As a member of RLE's Plasma Physics Group, Professor Bekefi has pioneered research in the understanding of cyclotron emissions from plasmas and magnetic insulation. His research has yielded new radiation diagnostic methods for beams and plasmas, fundamental observations of electron beam quality, advances in microwave generation, and new free-electron laser techniques. *(Photo by John F. Cook)*

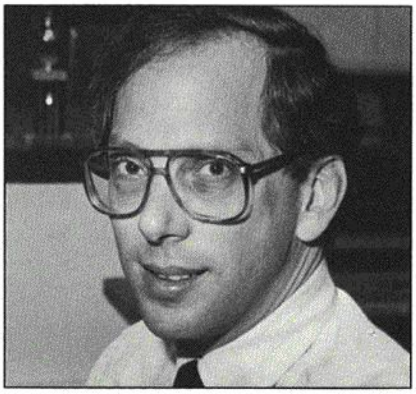


Dr. Marc A. Kastner received the Donner Professorship of Science in September 1989. Professor Kastner joined the MIT faculty in 1973, and served as Head of the Division of Atomic, Condensed Matter and Plasma Physics in the MIT Physics Department from 1983-1987. As a faculty member in RLE's Surfaces and Interfaces Group, Professor Kastner has made important contributions to the understanding of the electronic structure of amorphous semiconductors. Recently, his research has focused on the study of electronic conduction in small devices, and understanding the relationship between antiferromagnetism and superconductivity in high T_c superconductors. Professor Kastner is a graduate of the University of Chicago (B.S. '67, M.S. '69, Ph.D. '72). *(Photo by John F. Cook)*

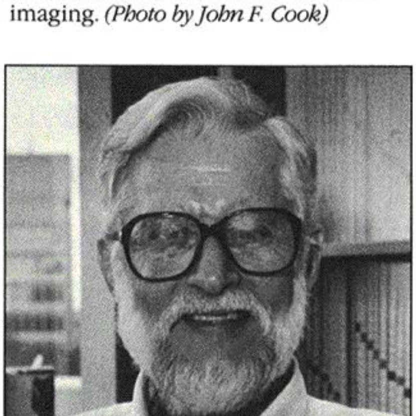


Dr. Jae S. Lim (S.B. '74, S.M. '75, E.E. '78, Sc.D. '78) was promoted from Associate Professor to Professor in the Department of Electrical Engineering and Computer Science, effective July 1989. Professor Lim, whose research interests include digital signal processing and its applications to image and speech processing, joined the MIT faculty in 1978. As the author of more than 90 articles, Professor Lim has received three prize paper awards, one from the Boston Chapter of the Acoustical Society of America in 1976, and two from the IEEE ASSP Society in 1979 and 1985. He was co-recipient of the 1984 Harold E. Edgerton Faculty Achievement Award. *(Photo by John F. Cook)*

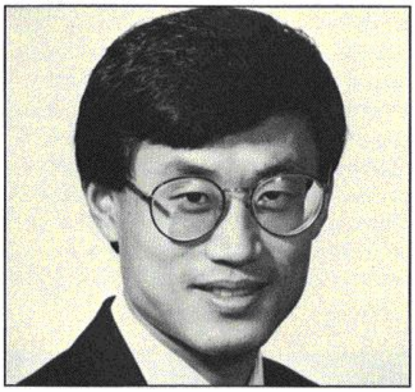
Dr. William F. Schreiber, Professor of Electrical Engineering and Director of the Advanced Television Research Program, was honored with two distinguished awards in 1989. In October, at the Technical Conference of the Society of Motion Picture and Television Engineers in Los Angeles, Professor Schreiber received the 1989 Journal Award for his article entitled "Improvements to NTSC by Multidimensional Filtering." This was the third time that Professor Schreiber has received the Journal Award from the Society. In addition, he recently received the Albert Rose Electronic Imager of the Year Award from the Institute for Graphic Communication. The Institute cited his contribution to the advancement of the technical state-of-the-art in electronic imaging. *(Photo by John F. Cook)*



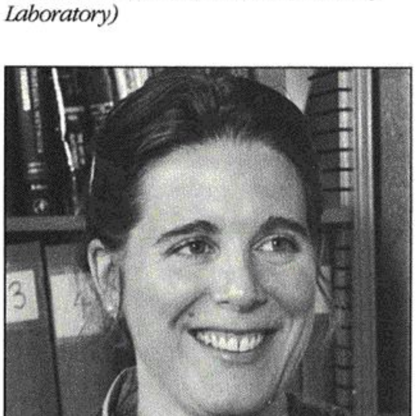
Dr. Jeffrey H. Shapiro (Ph.D. '70), Professor of Electrical Engineering and Computer Science, was appointed Associate Department Head of that department. After receiving his doctorate degree, Professor Shapiro was appointed as Assistant Professor at Case Western University. He returned to MIT in 1973 as an Associate Professor, and was promoted to Professor in 1985. As a principal investigator in RLE's Communications Group, Professor Shapiro's research focuses on signal analysis and communications theory in optical propagation, communications, and imaging. *(Photo by John F. Cook)*



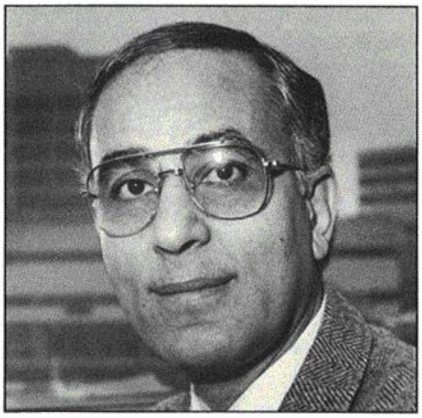
Dr. Kenneth N. Stevens (Sc.D. '52), Clarence J. LeBel Professor of Electrical Engineering, was recently elected Fellow of the American Academy of Arts and Sciences. As the senior member of RLE's Speech Communication Group, Professor Stevens has conducted fundamental research in speech synthesis and the analysis of speech production processes. Professor Stevens is a Fellow of the Acoustical Society of America and the IEEE, and a member of the National Academy of Engineering. He was awarded the Silver Medal in Speech Communication by the Acoustical Society in 1983. *(Photo by John F. Cook)*



Dr. Qing Hu was recently appointed Assistant Professor of Electrical Engineering, and will join the RLE faculty in January 1990. As a postdoctoral research assistant at the University of California/Berkeley, Dr. Qu invented a novel high T_c superconducting infrared detector. His work on the RLE faculty will include physics and the applications of superconducting devices at high frequency, far-infrared spectroscopy of quantum devices, and nonlinear dynamics. Dr. Hu is a graduate of Harvard University (M.A. '82 and Ph.D. '87) and China's Lanzhow University (B.A. '82). *(Photo courtesy Lawrence Berkeley Laboratory)*



Dr. Jacqueline N. Hewitt (Ph.D. '86) was recently appointed Assistant Professor of Physics, and has joined RLE's Radio Astronomy Group. Professor Hewitt's research interests include the application of high-resolution radio interferometry techniques to problems in astrophysics. Currently, she is working on several gravitational lenses (which were discovered as a result of her doctoral work in RLE), and is measuring the properties of nearby cool dwarf stars that show evidence of surface activity. Professor Hewitt holds a degree in economics from Bryn Mawr College, and worked at the Arecibo Observatory in Puerto Rico prior to completing her graduate studies at MIT. Before joining the RLE faculty, she worked with the Very Long Baseline Interferometry group at MIT's Haystack Observatory, and at Princeton University's Department of Astrophysical Sciences. *(Photo by John F. Cook)*

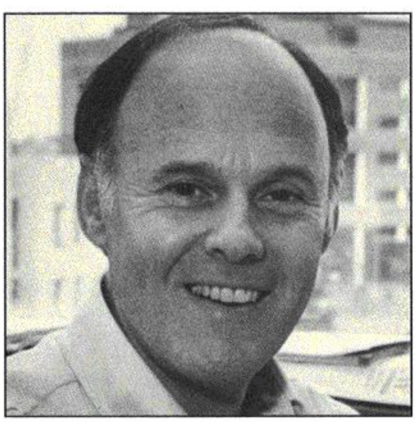


Dr. Sami M. Ali was appointed Research Scientist in RLE's Center for Electromagnetic Theory and Applications, effective September 1, 1989. Dr. Ali has been a Visiting Scientist with RLE intermittently since 1981, and was previously Assistant Professor of Electrical Engineering at Military Technical College in Cairo, Egypt. He holds degrees from Military Technical College (B.S. '65), VAAZ (M.S. '69), and the Technical University of Prague (Ph.D. '75), both colleges in Czechoslovakia. At RLE, he has theoretically modeled layered media and interactions with electromagnetic waves. Dr. Ali's current research involves microelectronic integrated circuits, microstrip antennas, pulse propagation and coupling in microstrip lines with nonlinear loads, and numerical frequency and time domain methods applied to electromagnetic problems.
(Photo by John F. Cook)

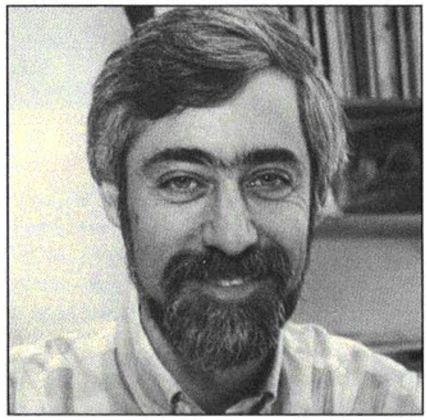
Dr. Mark A. Randolph (S.M. '83, Ph.D. '89) joined the RLE Speech Communication Group as a Research Scientist, effective September 1, 1989. Dr. Randolph will collect acoustic data on speech sounds in various contexts, extract acoustic properties, and identify spoken words from this acoustic data. Before completing his graduate study in RLE's Speech Communication Group, Dr. Randolph received a B.S. in Electrical Engineering from the Georgia Institute of Technology in 1983. His research interests include automatic speech recognition and synthesis, statistical pattern recognition, and computational linguistics. Dr. Randolph is a member of the IEEE, the Acoustical Society of America. *(Photo by John F. Cook)*

STAFF PROMOTIONS

Congratulations to five RLE Sponsored Research Staff members who received promotions in 1989:

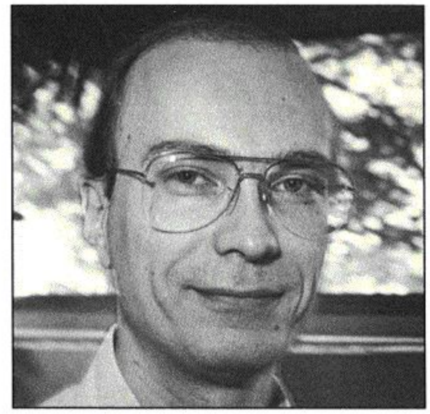


Dr. Joseph S. Perkell (S.B. '62, Ph.D. '74) was promoted from Principal Research Scientist to Senior Research Scientist in the Speech Communication Group. Since his affiliation with RLE in 1964, Dr. Perkell has conducted research in speech physiology and articulation. Recently, he completed an advanced system to track the movements of the speech articulators (see ***currents***, no. 1, vol. 1). Dr. Perkell is also a Lecturer in Oral Diagnosis and Radiology at the Harvard School of Dental Medicine (D.M.D. '67). *(Photo by John F. Cook)*

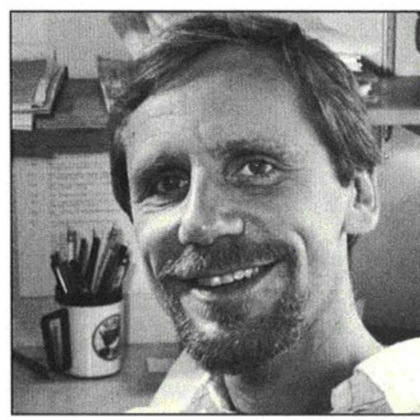


Dr. William M. Rabinowitz (S.M. '70, E.E. '71, Ph.D. '77) was promoted to Principal Research Scientist in the Sensory Communication Group. Dr. Rabinowitz's research interests include auditory physiology and acoustics. As a Research Scientist in RLE since 1979, he has served as principal investigator on projects involving tactile communication and cochlear implants for the hearing impaired. *(Photo by John F. Cook)*

Dr. Charlotte M. Reed was promoted to Principal Research Scientist in the Sensory Communication Group. With a background in speech therapy and bioacoustics, Dr. Reed is a world-renowned authority in psychophysics, speech communication, and tactile communication among the deaf and deaf-blind. A Research Associate since 1977, Dr. Reed received her B.S. in Education from Carlow College ('69), and a Ph.D. from the University of Pittsburgh ('73). *(Photo by John F. Cook)*

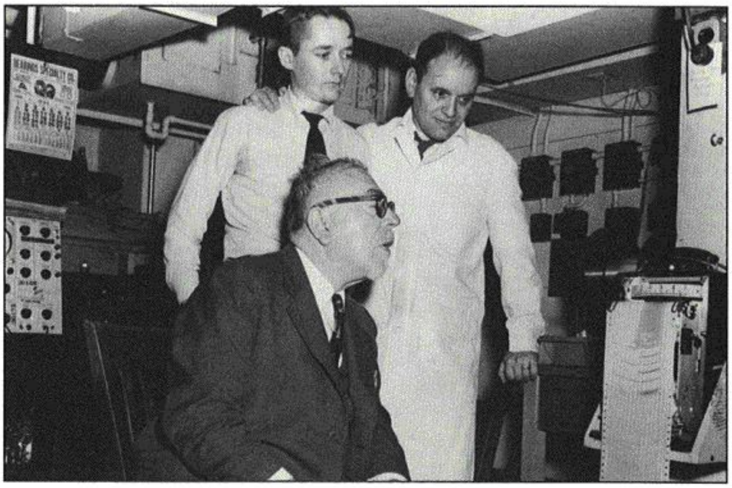


Dr. Philip W. Rosenkranz (S.B. '67, S.M. '68, Ph.D. '71), a Research Associate in the Radio Astronomy Group since 1973, was promoted to Principal Research Scientist. Dr. Rosenkranz's research includes remote sensing of the earth using microwaves, microwave propagation in the atmosphere, and planetary radio astronomy. He has also served as co-investigator on a project that involved microwave spectrometers on Nimbus 5 and Nimbus 6. *(Photo by John F. Cook)*



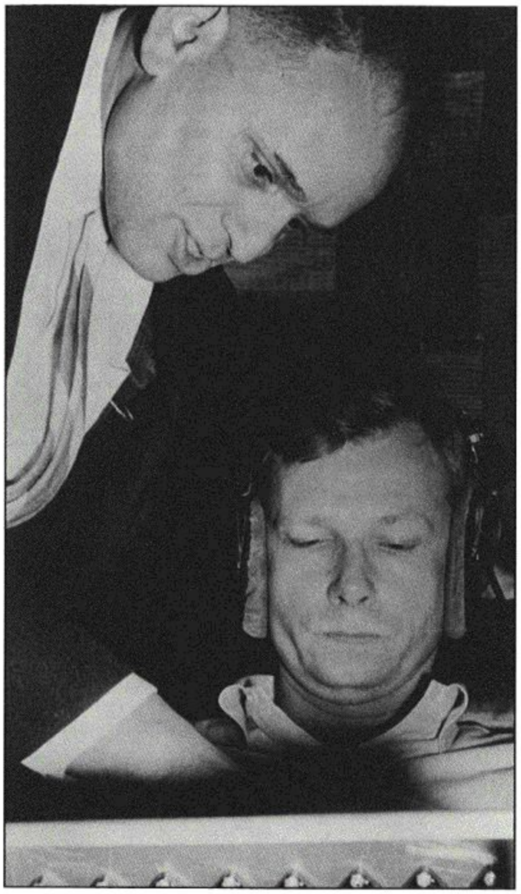
Dr. Patrick M. Zurek was promoted to Principal Research Scientist in the Sensory Communication Group. A graduate of Purdue University (B.S. in Psychology, '71) and Arizona State University (M.S. and Ph.D. in Psychology, '74 and '76), Dr. Zurek has been a Research Scientist with RLE since 1982. He is an expert in audition, and has served as principal investigator on projects involving hearing aids, binaural hearing, oto-acoustic emissions, and perception. *(Photo by John F. Cook)*

History of Auditory Physiology at RLE



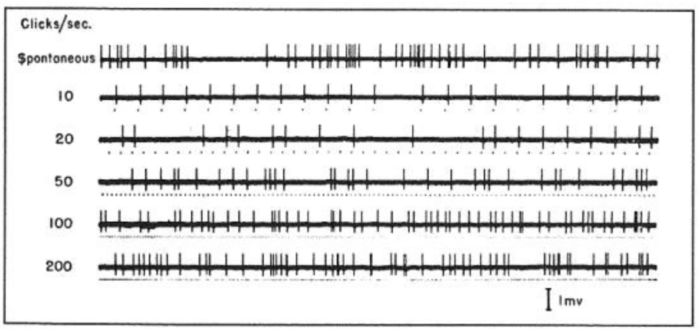
1955

Professor Norbert Wiener (seated) observes the autocorrelation function of brain waves, enabling the application of statistical communication techniques to communication biophysics. Professor Wiener is photographed with Research Assistant John S. Barlow (left) and Professor Walter A. Rosenblith. (RLE file photo)



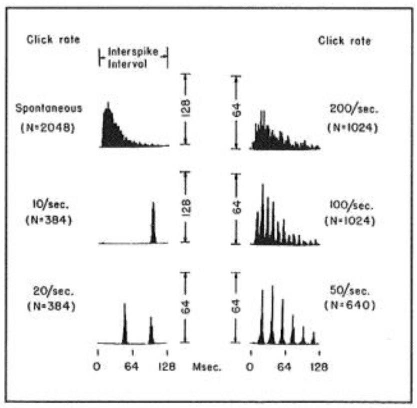
1956

Professor Walter A. Rosenblith (left) came to MIT in 1951 from Harvard's Psycho-Acoustic Laboratory, and was a key figure in the development of RLE's Communications Biophysics Group. His research in communications biophysics coupled mathematical modelling of brain activity and man-made communication processes. Professor Rosenblith used computers extensively to explore the electrical nature of the central nervous system. Here, he works with subject Dr. Thomas T. Sandel in RLE's anechoic chamber. (Photo courtesy MIT Historical Collections)



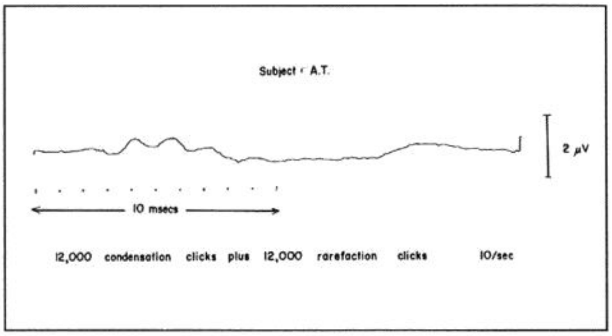
ca. 1960

(Figure 1) Electrical recordings from a single nerve cell in the cochlear nucleus. Time is represented on the horizontal scale; each vertical "spike" represents a nerve impulse for this cell. The stimuli are clicks presented at the indicated repetition rate.



ca. 1960

(Figure 2) Interspike interval histograms of single neuron data illustrated in Figure 1. These were the first histograms computed by a digital computer (the TX-0). The histograms revealed that neuronal activity is synchronized with the clicks, but does not respond to every click representation. Such histograms are now used to analyze single unit response to all parts of the nervous system.

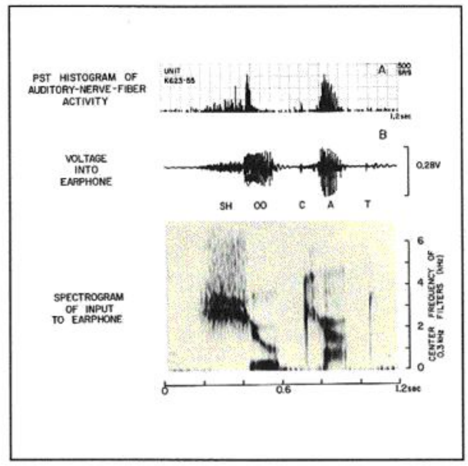


ca. 1960

First recording of human auditory brainstem potentials from the scalp. The responses to 1200 clicks were averaged using the ARC-1 computer. Today, brainstem potential responses are routinely used in diagnostic clinics throughout the world.

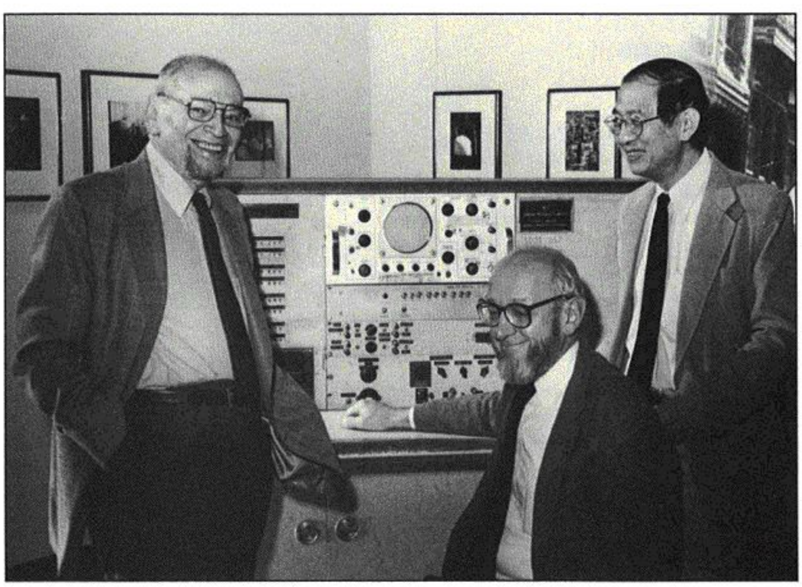
1971

In temporary quarters on Carleton Street, (from left) Professor Thomas F. Weiss, Professor William T. Peake, and Dr. Mark Mulroy conduct research during the refurbishing of the Eaton-Peabody Laboratory at the Massachusetts Eye and Ear Infirmary. (Photo by John F. Cook)



ca. 1972

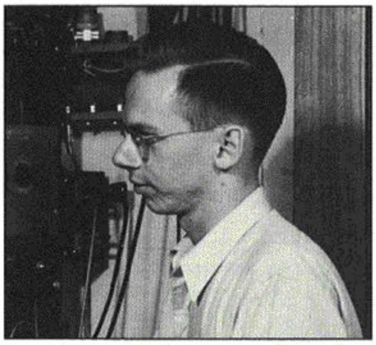
The top picture shows histograms of activity from a single auditory-nerve fiber in response to the spoken utterance "shoo cat." This fiber is "tuned" to approximately 2 kHz, and the response pattern can be predicted to a large extent by examining the speech spectrogram (bottom trace). The middle trace shows the time waveform of "shoo cat." The stimulus coding rules for the auditory nerve can be elucidated by this type of data.



1989

Professors Walter A. Rosenblith, William T. Peake, and Nelson Y. S. Kiang are reunited with the historic Average Response Computer (ARC-1) computer. The ARC-1 was a high-speed, transistorized, special-purpose, digital computer with a magnetic core memory. It was used in the late '50s and early '60s to record the averages of evoked electrical responses of the brain to a given stimulus. Designed in 1958 by Wesley A. Clark at Lincoln Laboratory, the ARC-1's most important aspect was its ability to operate on line, thus enabling experimenters to observe and modify results while the experiment was still in progress. Currently, the ARC-1 is housed at the MIT Museum. (Photo by John F. Cook)

IN MEMORIAM



The late Mr. Brown is shown in this photo from the 1950s.

Robert M. Brown, 62, died September 12, 1989, at his home in Marblehead, Massachusetts. Mr. Brown served as Chief Engineer in the Eaton-Peabody Laboratory of Auditory Physiology at the Massachusetts Eye and Ear Infirmary at the time of his death. He joined the RLE Communications Biophysics Group as an engineer in 1953, and from 1979, maintained his relationship with RLE as a Research Affiliate. Mr. Brown received a B.S. in Social Relations from Harvard University in 1950.

(Photo by Benjamin Diver)

UPDATE: RLE Collegium

RLE is pleased to welcome Grumman Corporation of Bethpage, New York, as our newest member in the Collegium. On October 24, 1989, RLE Collegium members from Grumman visited the Laboratory for a one-day research briefing tailored to meet the company's interests in materials and devices, and information and signal processing. Grumman Corporation has broad interests in the area of avionics, including novel materials and high-speed devices, the generation and detection of radiation, signal processing and signal processing architectures, and high-performance circuits for complex tasks.

The RLE Collegium was established in 1987 to promote innovative relationships between the Laboratory and business organizations. The goal of RLE's Collegium is to increase communication between RLE researchers and industrial professionals in electronics and related fields.

Collegium members have the opportunity to develop close affiliations with the Laboratory's research staff, and can quickly access emerging results and scientific directions. Collegium benefits include access to a wide range of publications, educational video programs, RLE patent disclosures, seminars, and laboratory visits.

The RLE Collegium membership fee is $20,000 annually. Members of MIT's Industrial Liaison Program can elect to transfer 25% of their ILP membership fee to the RLE Collegium. Membership benefits are supported by the Collegium fee. In addition, these funds will encourage new research initiatives and build new laboratory facilities within RLE.

For more information on the RLE Collegium, please contact RLE Headquarters or the Industrial Liaison Program at MIT.

UPDATE:

Publications

RLE has recently published the following technical reports:

Moving-Object Reconstruction from Camera-Blurred Sequences Using Interframe and Interregion Constraints, by Stephen C. Hsu. RLE TR No. 542. April 1989. 170 pp. $11.50.

Modeling and Simulation of VLSI Interconnections with Moments, by Steven P. McCormick. RLE TR No. 543. May 1989. 182 pp. $8.00.

Effects of Stapedius-Muscle Contractions on Masking of Tone Responses in the Auditory Nerve, by Xiao Dong Pang. RLE TR No. 544. May 1989. 241 pp. $17.00.

Iterative Maximum Likelihood Time Delay and Doppler Estimation Using Stationary Signals, by Bruce R. Musicus and Ehud Weinstein. RLE TR No. 545. September 1989. 160 pp. $12.00.

Efficient Verification of VLSI Circuits Based on Syntax and Denotational Semantics, by Filip Van Aelten. RLE TR No. 546. July 1989. 142 pp. $11.00.

Graph-based Representations and Coupled Verification of VLSI Schematics and Layouts, by Cyrus S. Bamji. RLE TR No. 547. October 1989. 202 pp. $14.00.

The Research Laboratory of Electronics welcomes inquiries regarding our research and publications. Please contact:

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