

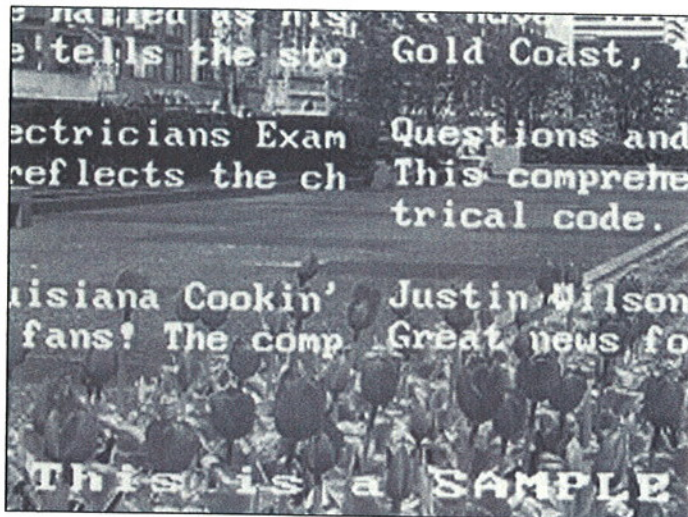


# RLE

# currents

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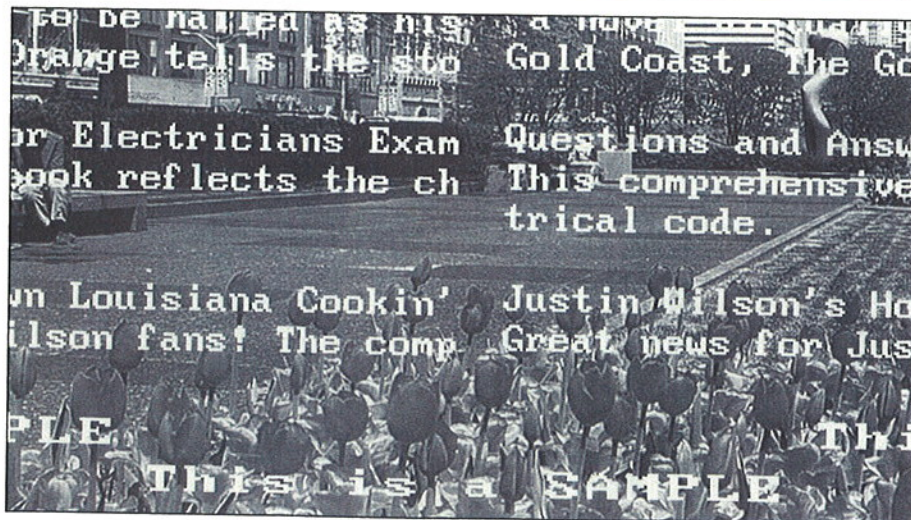
The Research Laboratory of Electronics at Massachusetts Institute of Technology



Although no single person or invention can be credited with the development of television, the so-called electronic hearth of today has its roots in the 1817 discovery of light-sensitive selenium by Swedish chemist Jöns Jakob Berzelius. By 1881, silhouettes were transmitted using selenium and a scanning phototelegraph device. However, there was a growing desire to transmit sound with *moving* images.

In 1884, German scientist Paul Gottlieb Nipkow patented the first mechanical television system. The Nipkow disk consisted of a rotating perforated disk placed between an image and the element selenium. The disk rotated before an image, effectively dividing the scene into lines, while the selenium behind the disk captured the moving image. Nipkow's design was the first to propose scanning a moving image. Unfortunately, a working system was never built by Nipkow himself because an amplified electric current was needed to drive a receiver. In 1906, American (continued on page 2)

## CHANGING THE IMAGE OF BROADCAST TECHNOLOGY: RLE's Advanced Television and Signal Processing Group



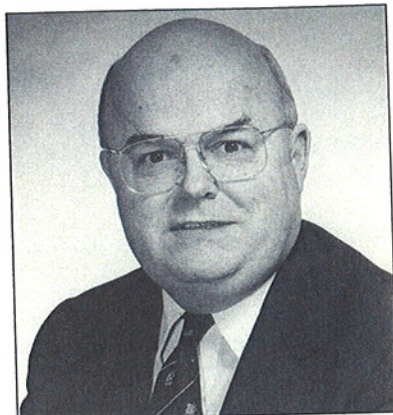
Corresponding portions of a National Television System Committee (NTSC) image (top) and a high-definition television (HDTV) image are shown. An HDTV image contains more than two million picture elements (pixels) and is approximately six times the spatial resolution of current NTSC images. HDTV employs a 16x9 aspect ratio, compared to NTSC's boxy 4x3 ratio, and provides a wide-screen effect that viewers are accustomed to in movie theaters. HDTV's digital image is free of all transmission impairments such as noise and ghosting, and is accompanied by CD-quality surround sound. The realization of HDTV and other advanced television systems has been made possible by developments in signal processing, telecommunications, digital compression and transmission, and very large-scale integration.



## Director's Message

Since the first broadcasts in the early 1940s, television has played a dominant role in our culture. Its potential to inform, entertain, and educate seems almost limitless. In light of the significant progress made over the last few decades in signal processing, technology, and the understanding of human perception, it is not surprising that television viewers demand improved broadcast reception, and that designers and manufacturers envision many possibilities to realize those improvements. The opportunity to develop high-definition television seems "ripe" for our time, and RLE's investigators have played a vital role in supplying both the basic research and prototype design needed to establish this radically new standard.

The design of a high-definition television system is a challenge that requires squeezing a 30-megahertz signal into a 6-megahertz channel. A veritable *tour de force* of signal processing techniques is used to eliminate channel degradation, including "ghosts" due to multipath reception and interference from neighboring channels. Our knowledge of human visual perception is applied to minimize the effects of noise and to increase spatial resolution in stationary areas where it is necessary. Of course, the algorithmic methods used to implement these techniques place a strong demand



Jonathan Allen, Director,  
Research Laboratory of Electronics

on the technology, and modern VLSI processes have permitted the use of multiple standards by exploiting fast logic and large amounts of memory.

Working closely with industrial partners, RLE's investigators have contributed to these outstanding new systems, which deliver both high-resolution images and CD-quality sound. University-based research in this area is unusual because of industrial sponsorship and direct competition with large, well-established manufacturing industries. This highly competitive experience has served as a unique real-world design test for our students. It is a fascinating example of innovative university research that has found an immediate application, and it will be a great benefit to us all.

second. The receiver displayed a tiny, uneven orange-and-black image. American Charles Francis Jenkins invented a similar device, consisting of an electric motor and prismatic rings, which displayed a cloudy 40-line image on a six-inch-square mirror.

Today's modern television system, however, would evolve not from these early mechanical ones, but from developments associated with electronic television. The fundamental component of electronic television is the cathode-ray tube, which is the picture tube found in all modern sets. Cathode rays were first identified in 1859 by German mathematician and physicist Julius Plucker, and British chemist William Crookes confirmed their existence in 1878 by building a tube to display them. English physicist Ambrose Fleming worked with Crookes' tube and found that cathode rays could be deflected and focused. In 1897, German physicist Karl Braun built an oscilloscope to demonstrate how cathode rays could be controlled by a magnetic field. By 1907, English inventor A.A. Campbell-Swinton and Russian scientist Boris Rosing independently

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### BROADCAST TECHNOLOGY

(continued)

engineer Lee De Forest invented the triode electron tube, making it possible to amplify video signals created by photoconductivity and photoemission.

The first commercially viable TV system, developed by Scottish inventor John Logie Baird of Great Britain, was a mechanical system based on Nipkow's disk. Adopted by the British Broadcasting Corporation in 1929, it produced an image of 30 lines at 12 frames per



RLE

**currents**

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suggested an electronic scanning system in which the cathode ray tube could produce an image on a phosphorus-coated screen. Campbell-Swinton later proposed a scanning system that used a charge-collecting screen and an electron gun to neutralize charge in order to create a varying current, thus replacing the mechanical Nipkow disk. These developments would soon be applied to the electronic scanning system used in today's televisions.

Another important development in electronic television was the arrival of vacuum tubes that could perform different functions. By modifying Thomas Edison's common household light bulb, various types of tubes were created to regulate current (the 1904 Fleming valve or diode), to amplify electronic signals (the 1906 De Forest triode), and to transmit radio waves (the 1912 Armstrong regenerative circuit). These became the glass building blocks of the

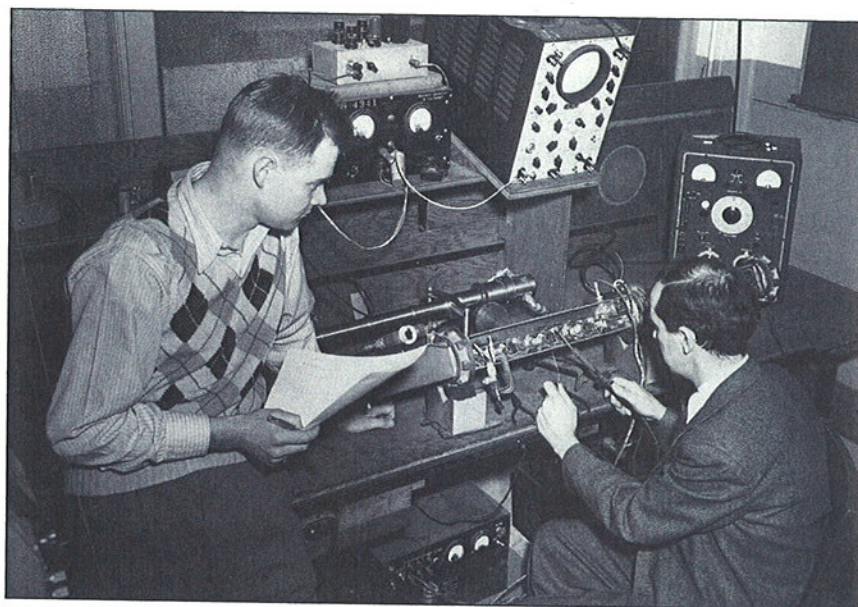
electronic television system.

In the early 1920s, Russian immigrant Vladimir K. Zworykin patented the all-electric camera tube (iconoscope), based on Campbell-Swinton's earlier work. American teenager Philo T. Farnsworth also invented a similar camera tube called the kinescope. These discoveries were based on observations made in 1888 by German physicist Wilhelm Hallwachs, who noted that certain substances emitted electrons

## Looking Back at Broadcast Research in RLE

**A**t RLE in the late 1940s, a new frequency modulation radio receiver was built by Professor Lawrence B. Arguimbau that could eliminate signal deterioration due to multipath interference. Transatlantic tests were conducted to demonstrate the effectiveness of this new receiver design, which handled signals that were too distorted for conventional FM equipment of that day. The receiver's design included high-quality limiters and wideband amplifiers that were able to capture the stronger of two co-channel signals with only a small amplitude differential.

Professor Arguimbau had joined the MIT faculty in 1939 and conducted research in both radio and television broadcasting. When the inventor of FM multipath radio, Dr. Edwin H. Armstrong, came to RLE as a visiting scientist in the early 1950s, Professor Arguimbau had the opportunity to collaborate with him. Unfortunately, Professor Arguimbau resigned from MIT in 1954, a year before he was convicted of contempt for refusing to answer questions before the House Committee on Un-American Activities. In 1975, he died at his home in Onset, Massachusetts, at the age of 69.



Graduate student John Granlund (SB '44, SM '47, ScD '50) watches Professor Lawrence B. Arguimbau make adjustments to the frequency modulation radio receiver designed in RLE. (Photo courtesy MIT Museum)

In the postscript to the 1948 edition of his book *Vacuum-Tube Circuits*, Professor Arguimbau wrote:

*The whole field of radio communications is still undergoing rapid changes. Textbooks and preconceived notions become obsolete in a short time. Some books published as recently as the early twenties devote hundreds of pages to transmitters and receivers that do not use vacuum tubes and in one or two concluding chapters talk about triode circuits that are now museum pieces.*

*Conservative organizations have already made proposals which at the present writing sound a little fantastic. One example is worth noting. It has been suggested (C.E. Nobles, "Television Programs from the Stratosphere," Westinghouse Engineer, November 1945) that a network of airplanes flying at 40,000 feet be used for microwave broadcasting and relaying. Planes spaced at 400-mile intervals could cover a given region. On this basis about 1000 planes might cover the entire land area of the globe with a sound and television network. For less than the cost of World War II it would be possible to equip every home in the entire world with a projection-type television receiver of the highest quality. At the moment this is a fantasy, but it is a technically realizable fantasy. This writer does not care to predict that it will never happen.*



**I**t may have been described as something less than spectacular: a man taking his glasses off, putting them on again, and then blowing a smoke ring. What is considered the world's first television broadcast in 1928, engineered by Ernst F.W. Alexanderson of General Electric, was viewed in three homes in Schenectady, New York.

*Life Magazine* has selected this, and the revolution that followed, as number fourteen in its list of

## **"Top 100 Events of the Millenium."**



*At home in Schenectady, New York, with radio and television broadcast engineer Ernest F.W. Alexanderson, circa 1928. As Dr. Alexanderson and his family view his newly designed television projection system, they portray one of television's first audiences. (Photo courtesy Schenectady Museum)*

when exposed to light. He demonstrated the possible use of photoelectric cells in cameras; a property called photoemission, which was applied to the image orthicon tubes in electronic television cameras.

Coupled with the application of the cathode ray tube for the receiver, electronic television cameras quickly demonstrated electronic television's superiority over mechanical systems. Zworykin, a former student of Boris Rosing, continued to develop his electronic television system. It initially scanned at 50 lines per second. Mechanical cameras used in experimental

broadcasts in 1930 transmitted 120 lines, and by 1933, Zworykin's system was employed with a resolution of 240 lines. EMI and Marconi, two British electronic companies, also created all-electronic television systems. Using the highly sensitive orthicon camera tube developed by RCA, this system was adopted by the BBC in 1936. It transmitted 405 lines at 25 frames per second.

### **Defining the Standards**

Television broadcasts began in the United States in 1939 with the National Broadcasting Company (NBC) transmitting to 400 sets in the New York City

area. Initial broadcasts used a scanning system of 340 lines at 30 frames per second. The Federal Communications Authority (FCA), the forerunner of today's FCC, set the first American standards for broadcast television in 1941, calling for 525 lines at 30 frames per second.

During World War II, television production was suspended in the United States. Research and development resumed after the war and a two-year delay, during which the FCA scrutinized possible schemes for color television, ultimately rejecting all proposals. Meanwhile, the sale of black-and-white sets climbed—from an estimated 10,000 in 1945 to 10 million by 1950.

The National Television System Committee (NTSC) set the standard for color television broadcasts in the United States. In 1951, the color system developed by Hungarian-American engineer Peter Goldmark was tried, but it was incompatible with the 525-line broadcast standard established in 1941. The color system selected by the NTSC in 1953 was compatible with existing black-and-white sets, and it inserted the color signal information inside the black-and-white signal. In 1960, Japan also adopted the NTSC system. The former Soviet Union and France adopted the SECAM system (*système électronique couleur avec mémoire*) in 1967, which transmits 625 lines at 25 frames per second with less color distortion than the NTSC system. Today, there are no less than fifteen broadcast standards around the world.

### **How High and How Advanced: Defining Definition**

Since the establishment of broadcast standards in 1941, American television signals have been transmitted in an interlaced format. In other words, the 525-line image on the television screen is generated by first displaying the odd-numbered lines and then, 1/60th of a second later, displaying the even-numbered lines. The television's electron tube generates a half-resolution image 60 times per second. Unfortunately, these alternating scan fields can produce serrated edges on moving objects and an annoying interline flicker that is visible to the human eye. To overcome this, deinterlacing techniques are used to realize the progressive scan format. In progressive scan, all lines in a television image are transmitted in their numerical order at twice the speed of the inter-



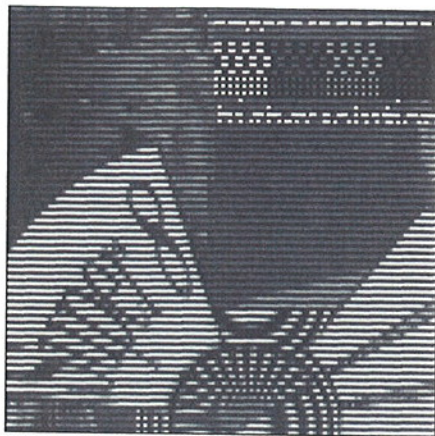


Figure A

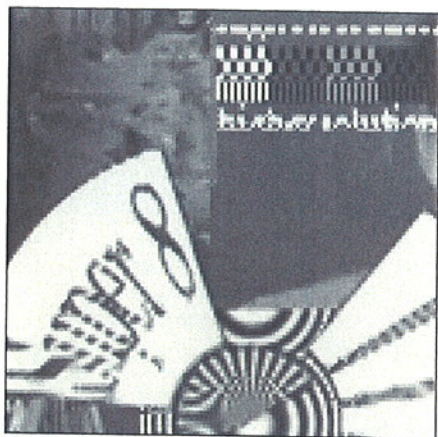


Figure B



Figure C

*In order to display an interlaced image on a progressive scan display, an operation called deinterlacing is needed. Figure A is an interlaced image that has only odd-numbered lines. Figure B shows the results of deinterlacing using a spatial method. Figure C demonstrates the results using a spatio-temporal method that was developed in RLE's Advanced Television and Signal Processing group.*

laced format. This produces a higher-quality image at twice the resolution of current television displays. However, an intelligent or smart receiver that is capable of frame-store memory is required to process the transmitted data while simultaneously displaying the processed image.

The development of innovative techniques, such as progressive scan, raised the issue of upgrading standards for terrestrial television broadcasts in the United States. The advent of very large-scale integration technologies and innovative signal processing theories have made it possible to incorporate new developments, such as frame-store memory and sophisticated signal processing capabilities, into television receivers at a reasonable cost.

Japan and Europe were first to establish large government-funded laboratories and industry-supported consortia to develop future television systems using these new technologies. In these countries, HDTV was anticipated as the next wave in the high-tech consumer electronics revolution, and it was expected to generate tens of billions of dollars in annual revenues. These developments would not only affect consumer products, such as television, VCRs, and other video equipment, but also direct-satellite systems and the semiconductor industry.

Beginning in 1968, HDTV research was conducted by Japan's public broadcast network, NHK, in collaboration with several Japanese electronics companies. Working prototypes were demonstrated in the early 1980s, followed by commercially produced systems in the mid-1980s. Viewers were astounded by the breathtaking quality of the images displayed by HDTV, which provided increased resolution and a wider aspect ratio. Digital technology, which was driven by advances in the solid-state field, produced a new television format with a much higher resolution, larger and sharper images with less visible line structures, and high-fidelity sound. Japan's original interlaced 1125-line system (called MUSE) is still the main system used there today. Although it is analog, MUSE uses digital compression techniques and is broadcast on a satellite system not compatible with Japan's NTSC terrestrial broadcast system.

As worldwide interest in HDTV grew in the late 1980s and early 1990s, battle lines were being drawn in the

United States over the development and adoption of a broadcast standard for this new technology. The computer industry, for example, would not support any standard that allowed nonsquare pixels or an interlaced scan format.

### **RLE's Advanced Television Research Program**

Although the United States had been a leader in the early development of television, its role was diminished in part because countries such as Japan and Great Britain had government-funded television research laboratories that contributed to their industrial leadership. Television was also no longer perceived by American engineering students as exciting or significant; thus, it became difficult to attract high-quality students to the field.

By 1983, television broadcasters and manufacturers in the United States believed it was time to address this lack of progress. The Center for Advanced Television Studies (CATS), a consortium of ten companies that broadly represented the American television industry, sponsored the Advanced Television Research Program (ATRP) in RLE to develop the basic science and technology essential to advanced television systems. ATRP investigated designs for advanced television systems, encouraged its students to work in the television industry, and provided a common place for its sponsors to address issues of mutual interest without violating antitrust laws. Focusing on basic three-dimensional signal processing research, no commercial products were to be manufactured at ATRP.

Initial audience research studies conducted by ATRP showed that transmission impairments in over-the-air (terrestrial) television channels were the main limitation to television picture quality. By designing an entirely new system, ATRP researchers found it was possible to overcome major signal impairments such as ghosts, noise, and interference. This was achieved by modifying the transmitted signal in anticipation of channel degradation, decoding the received signal, and accounting for the channel degradation. With this system, it was possible to increase the signal's robustness while providing better picture and sound quality in the same 6-megahertz channel. In addition, more stations could be accommodated within a given spectral band because of the greater spectrum efficiency. Similar

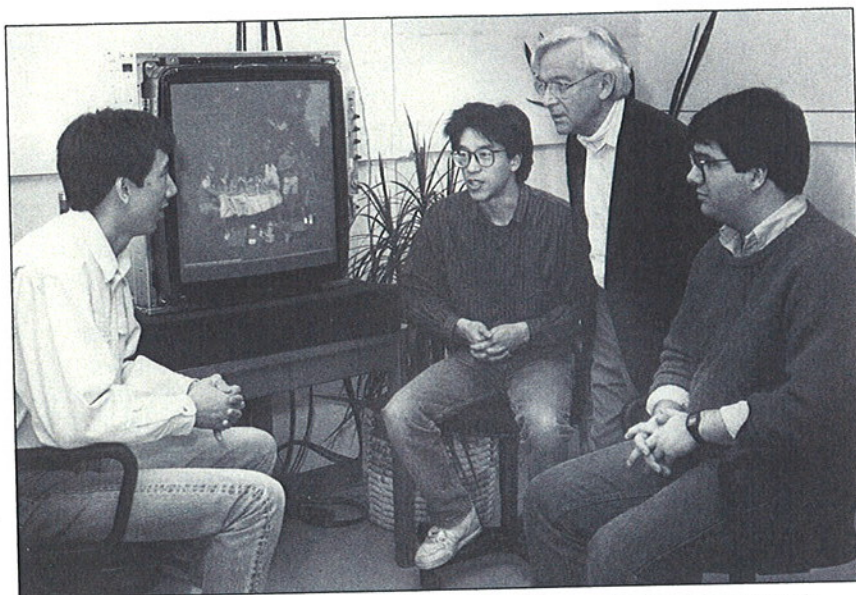


# The Advanced Television Research Program at RLE

In 1983, the Advanced Television Research Program (ATRP) was established in RLE to develop the science and technology for advanced television systems. The program's first head, Professor William F. Schreiber, had pioneered many developments in the field of image processing and transmission coding. Although there had been no research on advanced television in RLE until ATRP, Professor Schreiber's students had worked on various television coding problems in RLE's Cognitive Information Processing group. Thus, they were able to apply what they had discovered about image processing to advanced television research (see related cover story section on ATRP on page 5).

Professor Schreiber's earlier innovations had included a digital system for the Associated Press Wirephoto Service called Laserphoto. With Professor Donald E. Troxel, he also developed the Electronic Darkroom, an interactive multiprocessing computer system for Wirephoto manipulation and transmission. The combination of the Laserphoto and Electronic Darkroom systems gave picture editors the freedom to manipulate Wirephotos entirely by computer, and this method was adopted by the Associated Press in the late 1970s. Professor Schreiber's other contributions have included a computer-based prepress system for color printing and an electronic process camera.

At the [Edwin] Armstrong Centennial Conference held at Columbia University in 1990, Professor Schreiber explained:



In this 1990 photograph, graduate students of the Advanced Television Research Program and Professor William F. Schreiber discuss the fruits of their labor: an advanced television image displayed on the monitor. From left: graduate students David Kuo (SM '87, PhD '90) and Adam S. Tom (SM '86, PhD '90), Professor Schreiber, and graduate student Peter A. Monta (PhD '95). (Photo by John F. Cook)

*Image processing is not an abstract science (although abstract science may be useful in getting the work done) and it is not a mere academic exercise. We try to develop devices and systems that not only exhibit some principle, but that successfully perform some service that is needed and for which there is a market. I have found that academic work of this kind can make important contributions to the education of scientists and engineers. They learn to seek solutions to problems, rather than finding problems that can be solved with the specialized knowledge that they may already possess. Goal-oriented research also motivates students to seek careers on the economic front lines, where our country needs them. The best people do the best work, and so I am very proud that many of my former students, as good as any in the world, are helping to design the best American products.*

From 1985 to 1988, the Advanced Television Research Program was briefly housed at MIT's Media Laboratory. The program returned to RLE in 1989 and its research continues in RLE's Advanced Television and Signal Processing group headed by Professor Jae S. Lim.

techniques are used in cable, satellite, and fiberoptic transmission systems.

The most significant problem with the introduction of HDTV was the same problem faced by the introduction of color in 1954. Should HDTV be compatible with existing television standards, replace those standards, or be simultaneously broadcast with the existing

standards? Previously, the United States chose compatibility when developing its color standard. Although there were minor interference problems due to the additional chrominance signal, both monochrome and color sets could receive the same signal.

ATRP proposed simultaneous transmission (or simulcasting) of the same

program in both the old and new transmission formats via separate channels. It was also suggested that channels currently not used because of interference (taboo channels) could be used to accommodate the channels needed to transmit new formats. The FCC ruled that a completely new HDTV system design (that had yet to be developed)



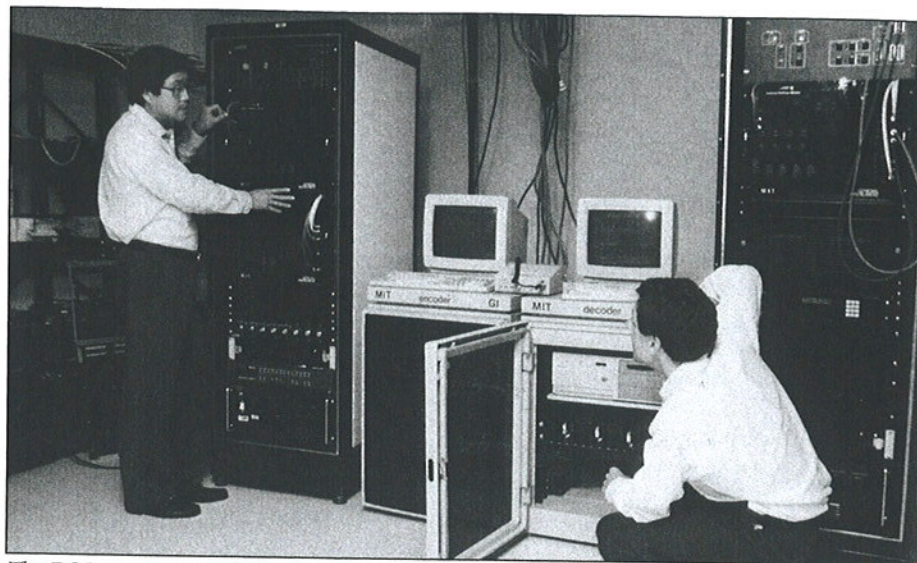
should be the basis for the new American standard. Simulcasting of the same program in both the old and new formats using separate channels met with great resistance in the broadcast industry, where a receiver-compatible signal format was preferred. Consequently, ATRP also demonstrated a receiver-compatible version of its proposed system that provided improved picture quality within one of today's channels. However, it did not have the improved resistance to channel impairments or the higher spectrum frequency.

Another obstacle in the United States was that HDTV would require a bandwidth larger than the NTSC's standard 6 megahertz for terrestrial broadcasts. Several options were considered, including a change in the channel allocation system from 6 megahertz to 20 megahertz, compressing the signal to fit inside the existing 6-megahertz bandwidths, and allocating multiple channels to accommodate the HDTV signal. Signal compression techniques eventually overcame this problem and, when the FCC decided to transmit digital instead of analog signals, it enabled several broadcast services to be sent within a single transmission. Compressed digital signals provide increased channel capacity, since they use only one-quarter the space of today's analog television signals.

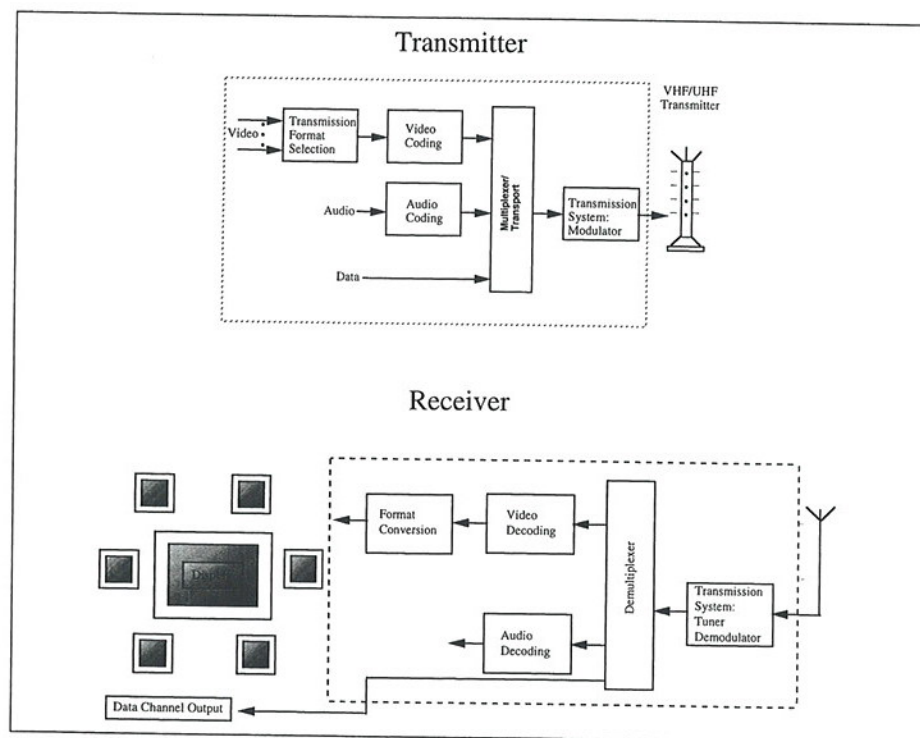
### The Grand Alliance and MIT

In 1987, the FCC ruled that HDTV standards must be compatible with existing NTSC service, and its transmission must be confined to the existing VHF and UHF frequency bands. The agency also established the Advisory Committee on Advanced Television Service (ACATS). The goal of ACATS was to assist the FCC in establishing an advanced television service in the United States, with the principal task of recommending an HDTV system for the FCC's transmission standard. By the end of 1988, twenty-three proposals were submitted, most of which were based on analog signal transmission. Professor Jae S. Lim and his students in the ATRP represented MIT in this competition, and they were the only university group to participate in the FCC's trials. (For more details on the FCC HDTV trials, see the *Faculty Profile* on page 14).

By 1990, the FCC announced that HDTV should be simultaneously broadcast and that it would prefer a full HDTV standard, rather than an extended-defini-



The FCC's testing of four digital advanced television systems took place from 1991 through 1992 at the Advanced Television Test Center in Alexandria, Virginia. Here, Professor Jae S. Lim (left) and Research Assistant Julien J. Nicolas (SM'82, ScD'94) adjust the MIT-General Instrument system. The four competing digital system proponents would later combine forces to design the Grand Alliance HDTV system. (Photo courtesy Jae S. Lim)



A schematic of the Grand Alliance's HDTV system, which allows different video source formats by using multiple-transmission (or scanning) formats. The different formats can include various film standards, magnetic and optical media, and synthetic imagery. Both video and audio sources are compressed by video and audio encoders. The output of the encoders is a bit stream that represents the audio and video sources. The transport system multiplexes the stream of bits from different sources. The transmission subsystem modulates the bit stream so that it can be transmitted over a channel. The subsystem can also compensate for noise that may be introduced by the channel. The signal is demodulated at the receiver and reconverted to a bit stream. The bits are then demultiplexed into streams of video, audio, and other accompanying data. From these streams, the decoders (or processors) reconstruct the image, sound, and digital data.



# Emmy Heralds the Digital TV Revolution

The Digital High-Definition Television Grand Alliance was formed in May 1993 at the request of the FCC's Advisory Committee on Advanced Television Service (ACATS). By successfully combining the best features of four competing digital approaches to high-definition television, the Grand Alliance system distinguished itself during laboratory and field tests conducted in 1995. In November 1995, ACATS recommended that the Grand Alliance system form the basis for the new digital television standard, which was adopted by the FCC one year later.

In addition to delivering remarkably clear HDTV images and five-channel CD-quality sound, the new technology will allow broadcasters to transmit an almost unlimited combination of video, audio, and data to the home via digital transmission. This will create a multitude of interactive and other information-age services such as access to the latest stock quotes and sports statistics. The technology provided by the Grand Alliance will also be capable of simultaneously transmitting full digital HDTV and a range of data services. It will also be able to provide a mix of both HDTV and digital SDTV (standard-definition television) programming.



*The statuette of a winged woman holding an atom symbolizes the Academy of Television Arts and Science's goal to support and uplift the arts and science of television. The wings represent the muse of art and the atom represents the electron of science. (Photo by John F. Cook)*

In recognition of its pioneering role in the digital television revolution, the Digital High-Definition Television Grand Alliance received the 1997 Primetime Engineering Emmy Award

for developing the technology upon which the new American standard for over-the-air digital television broadcasting is based. The Academy of Television Arts and Science (ATAS) recognized each participating member of the Grand Alliance research consortium: General Instrument Corporation, Lucent Technologies, Philips Electronics North America Corporation, Sarnoff Corporation, Thomson Consumer Electronics, Zenith Electronics Corporation, and MIT. MIT was represented by RLE's Advanced Television and Signal Processing group, headed by Professor Jae S. Lim.

The ATAS Engineering Emmy Award honors developments in engineering that are either so extensive an improvement on existing methods or so innovative in nature that they materially affect the transmission, recording, or reception of television. ATAS cited the Grand Alliance for being primarily responsible for developing and standardizing the transmission and technology for the upcoming digital television revolution by establishing a system that delivers a flexible mix of high-resolution television, multiple standard-resolution programs, multiple-channel digital audio, and data for advanced applications.

tion television standard. In May 1990, General Instrument Corporation submitted the first proposal for an all-digital HDTV system. By December 1990, ATRC (comprised of Philips Laboratories, Thomson Consumer Electronics, and the David Sarnoff Research Center) announced its digital entry. This was followed quickly by entries from Zenith Electronics Corporation, and AT&T, and then MIT. Thus, there were four contenders for the digital HDTV system, a modified "narrow" MUSE system, and an extended-definition system. Over the next two years, these systems would be tested at the Advanced Television Test

Center in Alexandria, Virginia.

In February 1993, the FCC made the important decision of selecting an all-digital technology, but it did not select a system from one of the four contenders. After much deliberation, a recommendation was made to form a "Grand Alliance" of MIT, AT&T, Zenith Electronics Corporation, General Instrument Corporation, the David Sarnoff Research Center, Philips Laboratories, and Thomson Consumer Electronics. The Grand Alliance would take the best features of the four systems and develop them into an HDTV standard. The remainder of 1993 was devoted

to establishing the features of this new standard, and the system was constructed in 1994.

Ultimately, the Grand Alliance's design was submitted and its performance was verified in 1995. In 1996, the Grand Alliance system was formally adopted by the FCC as the basis for the new United States all-digital HDTV standard. Professor Lim and his students contributed to the design of the Grand Alliance system in several areas, including video compression, audio compression, and digital communications.

The Grand Alliance standard differs from existing NTSC television standards



in several significant areas: it is an all-digital standard that is broadcast with a packet transmission, it supports multiple transmission formats, and it is designed to be compatible with computers rather than existing NTSC television receivers. Using square pixels, it has a 16x9 aspect ratio and a 4x2x0 chrominance sampling.

Features of the Grand Alliance system include:

- Digital transmission, which allows for considerable flexibility in terms of several different scanning and frame rates. The multiple formats are all progressive scan (with the exception of the 1920x1080 format at 60 fields per second).
- Compression algorithms that use both a motion-compensated and a discrete cosine transform (DCT) algorithm. The motion compensation algorithm exploits temporal redundancy, while the DCT exploits spatial redundancy. A five-channel audio transmission system is supported by Dolby AC-3 digital audio compression and offers full surround sound.
- Each data packet in the switched-packet system contains a 4-byte header or descriptor and a 184-byte data word or payload to transmit video, audio, or auxiliary information. A decoder deciphers data from the header and determines how the picture should be displayed. For synchronization, the program clock reference in the transport bit stream contains a common time base. For lip synchronization between audio and video signals, the bit streams carry presentation time stamps that instruct the decoder when the information occurs relative to the program clock.
- A terrestrial transmission system that uses an eight-level vestigial sideband (VSB) technique. The eight-level signal is derived from a four-level amplitude modulation VSB. Cable transmission is realized by a sixteen-level VSB technique without trellis coding. A small pilot carrier is added (rather than the totally suppressed carrier that is typical in VSB). This pilot carrier is positioned to minimize interference with existing NTSC service.

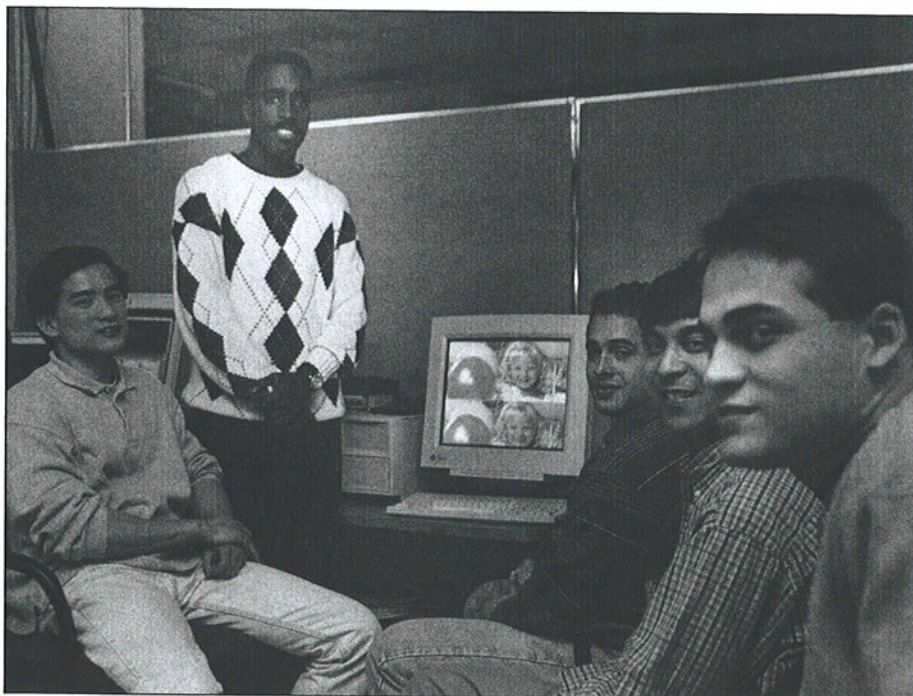
## Redefining the Broadcasting Industry

One reason the FCC looked into advanced television was to permit terrestrial (over-the-air) broadcasters the ability to broadcast HDTV programs, thus they would be able to compete with the cable and satellite industries. As the plans for advanced television shifted from analog to digital technology, it became clear that HDTV could coexist with other digitally transmitted channels. Stations could also have four or more standard-definition (SDTV) transmissions in combination with various data and audio channels. When the FCC issued rules for the new technology in April 1997, it made HDTV optional for broadcasters who use the new digital television (DTV) channels. Broadcasters must now decide how to use the new digital technology: whether to transmit a single HDTV image, multiple SDTV images, or a combination of the two.

Under the FCC's mandate, a separate broadcast spectrum was allocated and a rollout schedule was established for digital television in the United States.

Each of the four major television networks must have an affiliate with digital television facilities in the top ten markets by May 1999. By that date, 30 percent of households in the United States should have access to digital television. By November 1999, digital television should reach the remaining top 30 broadcast markets, thus covering 50 percent of households in the United States. All remaining television stations must construct digital facilities by 2002 (for commercial stations) and 2003 (for noncommercial stations). Production sets and cameras will also need to be replaced. However, since a majority of broadcast materials are already shot on 35mm film (primetime shows and movies, for example), these materials will be ready candidates for HDTV programming.

Cable and satellite program providers also plan to introduce digital service on individual timetables. Since the FCC does not have jurisdiction over channel allocation in cable networks, there is a question as to what the cable companies will do. They may continue



*Viewing a test sequence of the Advanced Television and Signal Processing group's video compression sequence (from left): Research Assistant Wade K. Wan, graduate student Raynard O. Hinds, Research Assistants Eric C. Reed and David M. Baylon, and graduate student Ruben E. Galarza. This research explores different methods of video compression for applications such as the HDTV standard. (Photo by John F. Cook)*



to broadcast conventional NTSC, they may install other HDTV systems (such as the MUSE), or they may choose the Grand Alliance system used by the terrestrial broadcasters.

During this transition period, television equipment and display manufacturers will also face hurdles to keep up with the new technology. In developing a new line of HDTV products, there will be substantial up-front costs associated with engineering, manufacturing, and retooling issues.

Although several producers have begun making HDTV programs, a relatively small number of television viewers have actually seen the technology's spectacular images. Under the FCC's current plan, consumers will continue to receive analog broadcasts until 2006. At that time, all television stations will be expected to stop analog service. It is anticipated that existing analog television sets may be able to receive digital television broadcasts with a set-top box converter. One industry projection estimated the cost of the first HDTV sets at \$4500 and the cost of a set-top box converter at \$150. If at least 10 percent of the viewers in an area have not purchased new sets or set-top converters during the transition period, stations may be able to continue analog service beyond 2006.

## FOUNDATIONS OF ADVANCED TELEVISION: The Science of Image Processing

Image processing involves the manipulation and analysis of visual information. Image coding, compression, restoration, and enhancement are some of the research activities carried out in the field of image processing. Fundamental mathematical procedures called algorithms are applied to visual information, enabling it to be processed in real time by digital computer systems or by specially designed analog video hardware. New algorithms are continually being developed for image coding and compression, feature extraction, and spatial filtering. Computational techniques are used to analyze, enhance, compress, or reconstruct an image.

One major area of image processing involves compressing an enormous amount of video information. These image compression techniques are based on information theory, and many exploit the spatial and temporal relationship between neighboring or adjacent

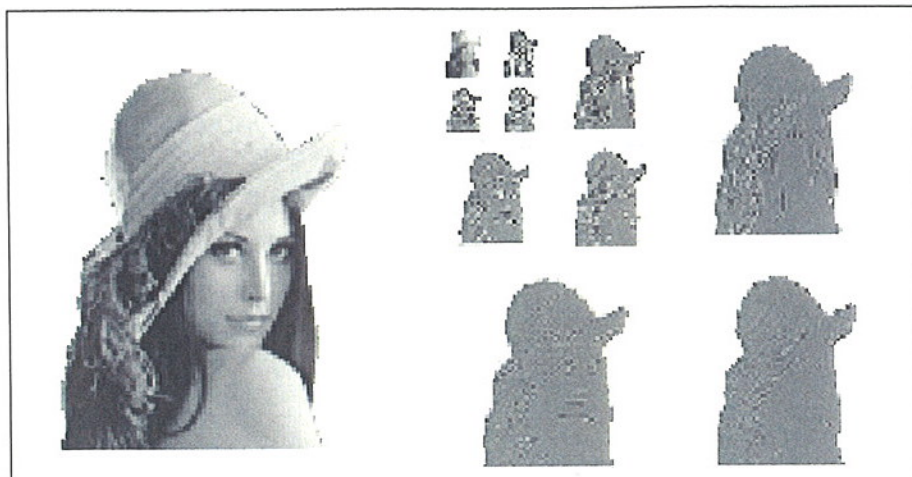


Figure A

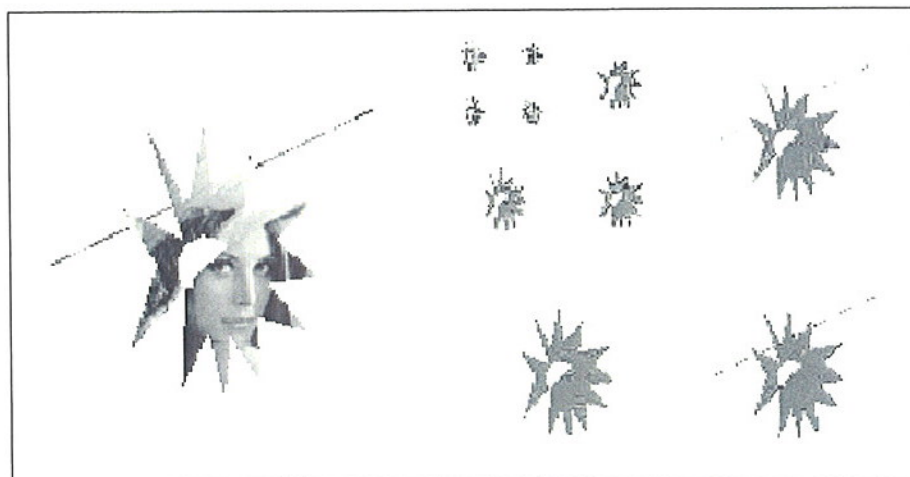


Figure B

*RLE's Advanced Television and Signal Processing group has developed a novel, critically sampled perfect reconstruction wavelet representation for signals with arbitrary regions of support. Figure A illustrates a two-dimensional (2-D) object from an image with an arbitrarily shaped region of support and its two-level wavelet representation that uses the group's innovative approach. Figure B shows a 2-D signal with a much more complex region of support and its two-level wavelet representation.*

pixels (picture elements). To permit a more efficient use of channel capacity (bandwidth) and storage space, redundant information is removed and the image is represented in the minimal number of code bits allowed.

In the field of image restoration, mathematical models are used to characterize the source of an image's degradation. For example, the degraded image might show noise, blur, defocus, ghosts, or distortions caused by the image's sensor, transmission, or display. Quantitative techniques are then used to measure and remove the degradation.

Consequently, restoration involves the selective emphasis and suppression of various picture elements within an image. The image under study can also be improved or enhanced to a more useable or subjectively pleasing form.

Basic research on the modeling of human vision processes, also known as visual psychophysics, has contributed to the understanding of the human visual system and various image-processing tasks. For example, many design parameters in HDTV are based on the results derived from experiments in human visual psychophysics.



## Advanced Television and Signal Processing Group

RLE's participation in the HDTV process has generated several important research directions in the Advanced Television and Signal Processing group (ATSP). Investigations continue to address problems and issues in coding efficiency, robustness under noise, as well as the coding and transmission of very high-quality audio and speech enhancement.

Professor Jae S. Lim and his students have recently worked in the following areas:

**Multidimensional signals represented with arbitrarily shaped signals.** Many signal-processing applications involve the efficient processing of multidimensional (M-D) signals with nonrectangular, or arbitrarily shaped, regions of support. Most high-level image or video representations incorporate 2-D or 3-D models that can decompose a scene into arbitrarily shaped objects or regions. For example, medical imaging can result in 2-D or 3-D images where relevant information is localized in an arbitrarily shaped region. Much attention in this area has focused on the development of representations for infinite-length signals with extensions to finite-length 1-D and rectangular support 2-D signals. In this project, the problem of representing general M-D signals with arbitrarily shaped regions of support is being studied. A novel framework was developed to create critically sampled, perfect reconstruction transform-subband representations for discrete 1-D, 2-D, and general M-D signals that are defined over arbitrarily shaped regions of support. In order to form a basis for an arbitrarily shaped signal, the method selects an appropriate subset of vectors from a basis for a larger signal space. Most recently, several promising wavelet representations were developed for arbitrary-length 1-D signals and arbitrarily shaped 2-D/M-D signals that enable high performance with low complexity. (See illustration on page 10.)

**Real-time source multiplexing for variable bit-rate encoded video.** Video compression algorithms for fixed-bandwidth systems usually operate at fixed, targeted compression ratios. However, fixed-bit-rate systems may exhibit inconsistent video quality in an image or across an image sequence. Variable bit-rate coding

can be used to achieve a more consistent quality, where bit allocation is allowed to vary more widely as the video statistics change. Although it may be inefficient to transmit a single variable-rate-encoded source over a constant-rate channel, it is more appropriate if several variable-rate sources are combined to share a given fixed bandwidth. In source multiplexing, the bit-rate fluctuations of different sources are effectively averaged, thus making the aggregate bit stream more appropriate for a constant-rate channel.

Video compression and multiplexing systems for bandwidth-limited channels require causal methods to process the video data in order to deliver real-time video programs. However, many video sources, such as movies, are pre-recorded. They can be preprocessed before compression and multiplexing is performed for transmission. By exploiting information about each video sequence before compression and multiplexing, improved video quality can be realized. This research seeks to characterize the gains in video quality that can be achieved by acquiring noncausal information about the video programs that are to be compressed and multiplexed. Preliminary results have shown improved and more consistent video quality after the noncausal processing of a video when compared to causal processing.

**Packet-switched networks and video compression.** Packet-switched networks such as the Internet have become an efficient means to transmit data. In these networks, data has no inherent delay constraints and can handle delay jitter due to variable queuing delays that occur across the network as well as excessive delay from the retransmission of lost data packets. This project investigates how video compression methods can be applied to computer communications over networks like the Internet. Studies also focus on how quality real-time video transmission can be achieved over these networks.

Real-time video cannot tolerate excessive delay, and data packets arriving at the receiver after their scheduled playback point are discarded. Video sequences, on the other hand, are capable of tolerating loss, and block-based video coders, which rely on motion-compensated block prediction to improve data compression, have been used to code video over the networks.

With the resultant packet loss that occurs on congested networks, coding mode selection for each macroblock is important to determining the overall distortion on the decoded video sequence. A method was developed for optimal mode selection in the presence of potential macroblock loss for a set of video coders. Further research will be conducted to determine when motion compensation is permitted.

**Very low bit-rate coding techniques for underwater images.** This project seeks to compress underwater images taken from an unmanned undersea vehicle (UUV) system while preserving image detail and overall video quality. The available communication channel between a UUV system and a remote location may support a bit-rate capacity as low as 10 kilobits per second. However, the video sequence of underwater images may be approximately a few million pixels per second at a resolution of 8 bits per pixel. In order to obtain acceptable video quality, the bits must be used in a highly efficient manner. In this case, the bit-rate reduction required to transmit video of underwater images is by a factor of several thousand. To achieve this high rate of compression, the video system must adapt to the characteristics of the underwater images, which are often blurred and have low contrast. In addition, since a typical UUV system moves slowly when compared to the frame rate, there is a good correlation in the temporal domain, and the group is investigating methods to exploit this temporal redundancy. Work in this area is being conducted in conjunction with the Woods Hole Oceanographic Institute and the Charles Stark Draper Laboratory.

**HDTV format conversions and migration path.** Because the new standard for terrestrial HDTV broadcasting allows for several possible transmission formats, and because the display formats may differ from the transmission formats, it will be necessary to convert between formats effectively. This project examines topics related to the conversion between the different formats under consideration. It is anticipated that, as HDTV technology evolves, other transmission formats will be allowed and additional bandwidth may be allocated for channels.

Another focus of this research

(continued on page 21)



*RLE's Digital Signal Processing group conducts research on algorithms for signal processing and their applications. Although the development of new algorithms is a major focus, the DSP group also strives to maintain close ties to practical applications and implementation issues.*

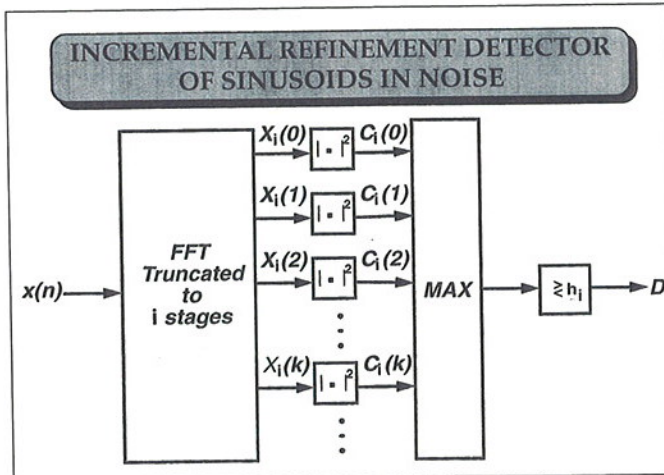


Professor Alan V. Oppenheim's group conducts research in a broad area of signal processing theory and applications, including signal enhancement and recovery, and signal analysis and synthesis using chaotic and other nonlinear processes. From left: Research Assistants Richard J. Barron and Alan Seefeldt, undergraduate Maya R. Said, graduate student Charles K. Sestok, thesis student Shawn M. Verbout, research Assistants Wade P. Torres and Michael T. Padilla, graduate student Lee Li, and Professor Alan V. Oppenheim.

Professor Gregory W. Wornell's group convene in the wireless communications laboratory, where they have developed a variety of new signal-processing techniques for multiuser wireless and broadband communication systems. Clockwise from left: Research Assistant Michael J. Lopez, graduate student Lee Li, research Assistants Haralabos C. Papadopoulos and Albert M. Chan, graduate students Brian Chen and Nicholas Laneman, Professor Gregory W. Wornell, and Research Assistant Stark Draper.

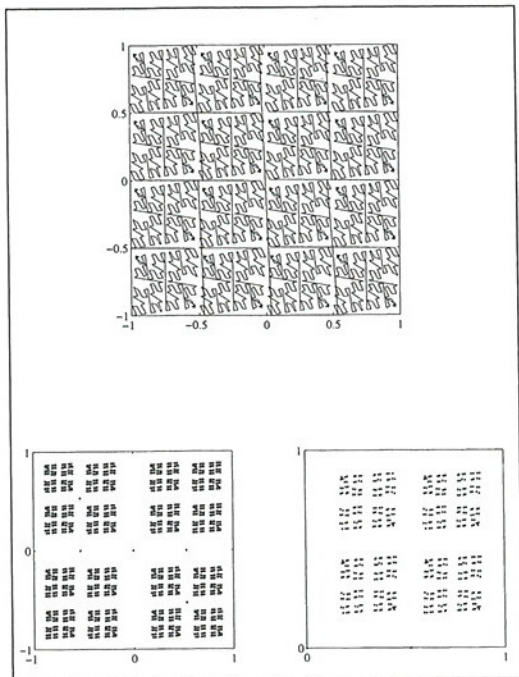


(Photos by John F. Cook)



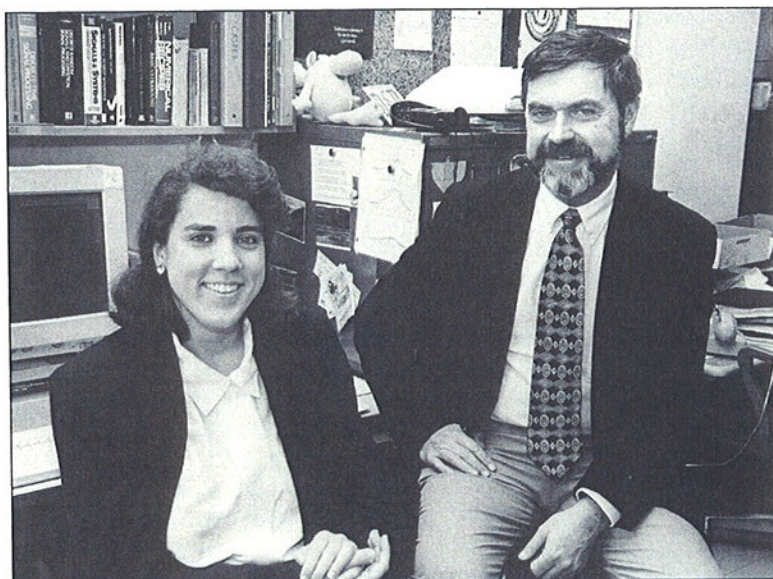
Many signal-processing algorithms naturally have or can be structured to have the incremental refinement property. This property can be exploited to terminate algorithms early when the result is acceptable or when resources are limited. In Professor Alan V. Oppenheim's group, this approach has been developed and studied in several contexts, including the detection of narrow-band signals in noise.



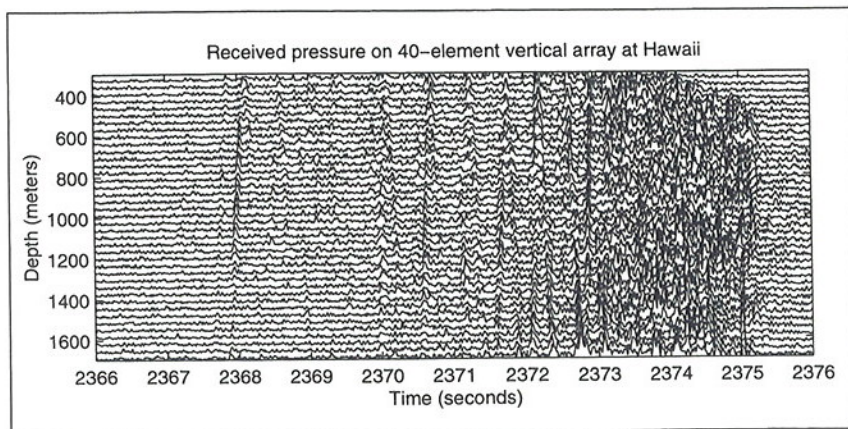


Future high-performance communication systems will make efficient use of sophisticated signal-processing algorithms in both digital and analog domains. An example of these next-generation algorithms include the novel "analog error-correcting codes" developed for wireless and related communication applications by Professor Gregory Wornell and graduate student Brian Chen. These codes employ chaotic dynamical system theory. The self-similar modulation schemes and constellations shown are extensions of this work that have led to new coding strategies.

During the 1960s, many areas of research capitalized on the development of computers by redefining traditional disciplines within a new computational environment. The field of digital signal processing grew out of the flexibility permitted by the use of digital computers to implement signal processing algorithms and systems. Today, DSP uses a variety of both digital and analog technologies that cover a broad range of applications and bandwidths.



Research Assistant Kathleen E. Wage and Professor Arthur B. Baggeroer focus their investigations on advanced array-processing techniques for underwater applications such as ocean acoustic tomography. This work seeks to develop a signal-processing framework to estimate the normal mode decomposition of low-frequency broadband reception.



As part of the Acoustic Thermometry of Ocean Climate experiment, a low-frequency source located off the California coast transmitted broadband pulses to receiving stations in the Pacific. This ongoing experiment seeks to study the long-range propagation of underwater sound and to monitor ocean climate variability using tomographic methods. The figure shows the complex-demodulated time series for pressure at a vertical array near Hawaii, almost 2200 miles from the source. Research Assistant Kathleen Wage and Professor Arthur Baggeroer are investigating methods to estimate broadband mode arrival times using short-time Fourier techniques.



# FACULTY PROFILE:

## Jae S. Lim

Korean native Dr. Jae S. Lim (SB '74, SM '75, EE '78, ScD '78) joined the MIT faculty in 1978. Over the years, his interests have included a broad range of digital signal processing (DSP) research with applications to image and speech processing. He is currently a professor in the Department of Electrical Engineering and Computer Science and heads RLE's Advanced Television and Signal Processing Group.

In addition to developing a new speech model that is now the basis for the voice coding standard for several international satellite communication systems, Professor Lim and his group have contributed to the design of a high-definition television (HDTV) system adopted by the FCC as the new broadcast transmission standard for the United States.

Professor Lim has contributed to more than one hundred journal articles and conference proceedings. He is the editor of *Speech Enhancement* (Prentice-Hall, 1983), co-editor of *Advanced Topics in Signal Processing* (Prentice-Hall, 1987), and author of *Two-Dimensional Signal and Image Processing* (Prentice-Hall, 1990). He has received numerous awards, including the Harold E. Edgerton Faculty Achievement Award.

### • What brought you to MIT?

I came to the United States in 1967 as a high school student and finished my senior year at Mahwah High School in New Jersey. I thought I'd major in economics, but I had a difficult time with a high school economics course, mostly because of my English. Physics and math were easy for me because they were mostly equations.

As I applied to various colleges in the United States, I was concerned about the cost of tuition. My family was still in Korea and it was a very poor country at that time. I didn't know about



Professor Jae S. Lim  
(Photo by John F. Cooke)

MIT, but my math and science teachers suggested that I apply there. MIT's tuition was too high for my family. My father, who was a college professor in Korea, contacted Samsung. They offered to pay my tuition for four years if I was admitted to MIT. Fortunately, my math and science teachers wrote very good letters for me, and I got in. At MIT, I liked physics and calculus, and they led me naturally to electrical engineering. Signal processing was far from my mind. In fact, in the late 1960s, it hadn't really been born yet.

### • What attracted you to Lou Braid's psychophysics research in RLE?

After my sophomore year, I was drafted into the Korean army and served for three years. When I returned to MIT in 1973, I wanted to finish my degree as soon as I could, and I had to write a thesis. Before the service, I lived in the Conner section of Burton House. Lou Braid was our faculty in residence. I knew him well and, when I returned, I asked if I could do my thesis with him. Lou was a very good teacher. He'd tell students in Conner that they could ask him any question about 8.01 (basic physics), and he guaranteed that he could answer it. He was right, and I was very impressed by him.

Lou supervised my thesis work with Bill Rabinowitz and Nat Durlach on intensity perception. I was able to finish

in 1974, one year after I returned from the service. In all, I spent three years as an undergraduate. After finishing my bachelor's degree, I continued with the topic of intensity perception for my master's thesis.

### • What was the nature of your work in the area of speech enhancement systems, which seek to improve the intelligibility of speech corrupted by noise or interference?

It wasn't until after my master's thesis that I considered looking into other areas. It's not a good idea to focus on one area, particularly in the early years of an engineer's career. I had been with Lou's group for three years, and I thought it would be good to experience a different research group before I graduated.

I had been introduced to signal processing in 1973, when I took 6.015 with Al Oppenheim (the current Signals and Systems, 6.003). Later, in graduate school, I took 6.341 (Discrete-Time Signal Processing) with Russ Mersereau (SB '68, SM '69, EE '70, ScD '73). So, I joined Al Oppenheim's digital signal processing (DSP) group in 1976. It may have delayed my graduation a year, but it was a worthwhile investment.

In Al's group, I began work on the development of speech enhancement systems. First, I looked at existing systems. The most promising system was much more complicated than it should have been. At that time, speech enhancement systems didn't use the information that we had about speech. I thought it might be useful to incorporate that information, and that's where the speech modeling work came from. People used speech modeling for applications such as speech compression, but they weren't using it for speech enhancement. By incorporating the speech modeling work, we were able to take a different approach to speech enhancement. That was the focus of my doctoral research.

### • What prompted your change in research to digital image processing?

When I joined the faculty in 1978, I went to Lincoln Lab for a year to work with Al Oppenheim. Lincoln didn't have a strong research program in image processing. Al wanted to create one, and I



helped him do this with Steve Pohlig and Dan Dudgeon. Since I had a firm grounding in digital signal processing, getting into image processing research was easier than my earlier change from psychoacoustics to speech processing. The basic theories aren't drastically different. Also, when you know how our knowledge of speech can be applied to developing speech-processing systems, then you can see how our knowledge of images can be used to develop image-processing systems.

• *How did you become involved in advanced television research?*

In the early 1980s, the American economy wasn't doing well and the consumer electronics industry was almost nonexistent in this country. Everything was made in Korea, Taiwan, or Japan. Japan was making progress with high-definition television (HDTV), and many broadcasters and manufacturing companies here were worried about the future of our consumer electronics industry. There was no HDTV research going on in the United States. Companies were laying people off, and the first thing to go was research and development.

Fortunately, Bill Schreiber had the expertise and knowledge in this area. He submitted a proposal to the Center for Advanced Television Studies (CATS), a consortium of broadcasters and television-related companies. That's how RLE's Advanced Television Research Program (ATRP) was created in 1983. It was through Bill's work in RLE that I became interested in advanced TV systems.

From a theoretical viewpoint, three elements are needed in advanced TV development: video compression, audio compression, and digital transmission technology. I had experience in audio compression from my speech processing work. Video compression was part of my image processing work. Digital transmission technology, however, I didn't know much about, but the first two areas were enough to attract me to advanced TV work.

In 1987, the FCC announced the formation of the Advisory Committee on Advanced Television Service (ACATS) because broadcasters and other people in the industry wanted the FCC to look into HDTV and advanced TV issues.

There are many versions of this story. One version is that the broadcasters didn't really have an interest in standardizing HDTV, but they wanted to ensure that spectrum was kept for themselves. Mobile communication systems and cellular telephones were competing for spectrum space. If the spectrum were given to other communication systems, the broadcasters worried there'd be nothing left for them. Some people say that's why they asked the FCC to look into advanced television.

I became involved in 1989, when Bill announced his plans to retire. ATRP was then located at the Media Laboratory, after having been in RLE for several years. I believed that the work Bill was doing was very important for MIT, but I was content with my DSP work in Al Oppenheim's group and wasn't interested in taking charge of ATRP. So, I encouraged Dennis Martinez, a former student of mine, to join the Media Laboratory so he could lead ATRP. The arrangement didn't work out.

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## From a theoretical viewpoint, three elements are needed in advanced TV development: video compression, audio compression, and digital transmission technology.

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Around the time Bill decided to retire, the CATS sponsors were planning to leave MIT, and they invited research proposals from other universities. I was concerned that unless I took over the program, there'd be no advanced TV research at MIT. So, when the CATS called later to discuss the possibility of working with our group in RLE, I was reluctant, but showed my enthusiasm for advanced television work. They were familiar with my DSP work and had visited my lab in previous years. They suggested I submit a proposal so

MIT would be represented among the universities that were applying for funds.

The CATS sponsors decided to fund not only us, but also several other universities. Now we had to justify our existence, because there was competition. It wasn't like previous years when MIT was the only place funded by CATS. After having submitted proposals to and discussing plans with CATS in 1989, I assumed the leadership of ATRP in 1990.

• *What was involved in the FCC's selection process for a new broadcast standard?*

The FCC initially received twenty-three proposals from universities and companies for a broadcast system standard. MIT submitted two from Bill Schreiber. The FCC realized they couldn't test them all, and some weren't even serious proposals.

The FCC announced that they would require a testing fee from each system proponent because these systems would take a long time and lots of money to evaluate. We had to raise money to test our system, and in the end, the fees totaled more than \$1 million per system. Also, the FCC wanted to test real-time systems, not computer simulations. Building a system that operated in real-time then cost more than \$10 million. In addition, fifty to one hundred dedicated engineers would be needed for one to two years. Because of all of this, even the major companies didn't want to be on their own. So, AT&T teamed up with Zenith; Sarnoff, Philips, and Thomson became a team; and MIT joined with the General Instrument Corporation.

The FCC ACATS conducted a proposal review and six systems were selected for evaluation. One system wasn't HDTV (it was enhanced or extended-definition TV), so its proponents voluntarily removed it from consideration. Five systems now remained. One of those was from NHK, which was Japan's analog system. The four other systems were digital. Of those four, one was from General Instrument alone, another from the MIT-GI team, another from the AT&T-Zenith team, and another from the Sarnoff-Thomson-Philips team. These systems were extensively



evaluated. In fact, during the three months it took to evaluate the MIT-GI system, several of my students and I practically lived in Washington so we could monitor the testing.

• *What was the impetus behind the Grand Alliance?*

It took almost two years to evaluate the six systems. By late 1992, the evaluations were complete. During the testing period, the proponents had talked about how they could now build better systems than the ones that had just been tested, because we now understood their limitations and had more experience with such systems.

In February 1993, the ACATS technical panel concluded that the analog system was definitely the worst, but none of the four digital systems was best in every category. In one category, one system was the best, while in another category, a second system was the best. They couldn't decide on one system. Why not have everyone improve their system as they claim they can, and then reevaluate them?

So, the FCC presented two options. One option was that the FCC would retest all four systems. Selecting the order in which the systems would have been tested is a story in itself. The second option was to form an alliance of all four system proponents, have the proponents select the best system, and build it. The FCC would then simply verify that its performance was better than the four systems previously tested and use that as the standard. The seven companies participating as the four system proponents discussed the technical, commercial, and financial issues. We decided another competition wouldn't be fruitful. So, we decided to choose a system ourselves and submit it as the Grand Alliance HDTV system.

In 1993, the Grand Alliance was formed, with the four system proponents having an equal say in the technical decisions. MIT had one of four votes in all technical decisions that were made in the design of the Grand Alliance system. All of us had started in competition with each other, then we went through a phase of cooperation, and finally we came up with the Grand Alliance HDTV system. That became the basis of the digital television standard for the United States.

• *What insights have you gained from this experience?*

In terms of the standardization process, I was naive. Coming from a technical university, I thought the best technology should win—will win—and nothing else mattered. It turned out, a lot more mattered. When you propose a standard like this, there are many issues—technology, money, prestige, and personal factors—and they were mixed together.

If I had to evaluate the technical standard that the United States established, it will certainly serve its purpose. It will work, it's technically a good system, and it will serve the nation well. Do I think it's the best possible system? No. We came about 85 percent close to the optimum. When you consider the diverse groups of people, the different interests, and all the discussions that presented totally opposite views, I'm impressed that the product we developed is so good.

In a country like the United States, different players have different interests. Coming from MIT, I had one perspective. Phillips had another perspective, Zenith had another perspective, the broadcasters had their perspectives, and the FCC had yet another perspective. They're all different and they fuel the direction in many ways. That's why it took such a long time. What's truly amazing, and the real strength of this country, is that when it was all over, roughly the right decision was made.

• *Who should set the broadcast standards in this country?*

When you standardize anything, that means you put restrictions on it. I like as few restrictions as possible. On the other hand, the public's interest may not be served when we do that. It's like having laws. We should have as few laws as possible. However, it doesn't mean that we should have no laws. Standards for the public airwaves, such as the terrestrial broadcasting standard, should be set by the FCC. If several companies had introduced different transmission standards, you'd need different TV sets to receive all the channels. That certainly would go against the public's interest. By establishing a technical standard, under the FCC's supervision, we avoid a lot of confusion.

• *What are the advantages of digital transmission?*

Our current NTSC (National Television System Committee) system was established with a 1940s and 1950s technology base. Because of that, it has a great amount of inefficiency. Broadcast spectrum wasn't that valuable in the beginning because there were only a few TV and radio stations, and there wasn't much competition for spectrum space. Now, we have more TV channels and more communication systems, particularly with the addition of cellular telephones. So, the spectrum has become increasingly expensive.

With a digital system, four or five times more information can be transmitted within the same spectrum space at a much lower power level. In essence,

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Coming from a technical university, I thought the best technology should win — will win — and nothing else mattered. It turned out, a lot more mattered.

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we're converting one existing channel into four or five possible channels. Also, many channels are currently not used because of the inefficiency of the NTSC's spectrum usage. Those unused channels will be recovered after the conversion process to digital transmission is complete.

The transmitted picture also will be much clearer. With digital transmission, you either get everything or nothing. Now, when we watch TV with an over-the-air broadcast signal, some channels are good. But the wind may blow, and then the picture will wobble. In other instances, we know channels are there because we can see a little bit of the picture, but there's all this snow. With digital service, very little of that will happen. Either we will see very clear



pictures without snow, echoes, or ghosts, or we will be out of the transmission's range and we won't see anything.

• ***Could you describe the multiple transmission formats used in HDTV?***

In the current NTSC system, there's only one transmission format—an interlaced 525-line format. So, how can we transmit materials with different formats? For example, film sources have a format fundamentally different from video. In the NTSC system, these different sources must be converted into one format. Currently, material at 24 frames per second must be converted to 60 frames per second before transmission. This means we're transmitting redundant information repeatedly, and that's a great inefficiency. In contrast, by using multiple transmission formats, we can transmit at 24, 30, or 60 frames per second. We're also allowed to have different spatial resolutions.

Another advantage is that, for programs like news, we may not need HDTV. Because all we'd see is the announcer's face in more detail. In that case, we wouldn't transmit in HDTV format; we'd transmit in a lower definition format. The remaining spectrum could then be used to transmit another video program or something else like the *New York Times* or the *Wall Street Journal*. All this flexibility is built into the system with multiple transmission formats.

• ***How do you view the convergence of the various communication industries?***

The digital TV revolution will be significant because TV's interoperability with computers and telecommunications networks will become much better. Eventually, there will be home entertainment and information centers that integrate everything. In other words, you'll be able to use your TV set not only to watch TV, but you may also use it as part of your PC or other telecommunications services such as video telephones. In the end, this integration of television, personal computers, and telecommunication services may define the true significance of the digital television revolution.

• ***What will happen now that the Grand Alliance has finished its work?***  
There is still unfinished work related to

the standardization issue. Under the current FCC standardization, for example, it isn't possible to transmit a progressively scanned video with a spatial resolution of 1080 lines at 60 frames per second. I believe that future research efforts will address these types of issues. Many technologies also must be developed, even as we implement the current standard. With the current FCC standard,

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***In the end, this integration of television, personal computers, and telecommunications services may define the true significance of the digital television revolution.***

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there's a fair amount of restrictions but there's also a good amount of freedom. I'd like to see how we could exploit that freedom to improve TV technologies. I'd also like to explore the integration of TV with other telecommunication systems, and I want to investigate the application of our video compression work to video communications over computer networks.

• ***Will HDTV be used in areas other than consumer electronics?***

HDTV will be useful in many scientific and medical applications including the transmission of x-rays, surgery, and telemedicine. Another good application of HDTV will be remote education. For example, when an internationally recognized MIT professor gives a lecture, it would be wonderful to show it to the whole world. Right now, with NTSC equipment, there are many limitations, such as how big the visual materials can be, how small the letters on the blackboard can be, and where the speaker must stand in relation to the camera. With HDTV, a speaker can give a lecture without much camera movement, and viewers would be able to see both the blackboard and the speaker clearly

because of the system's high resolution and improved aspect ratio. The amount of resolution in HDTV compared to the NTSC system is about six to seven times better.


• ***What's the most challenging aspect of your research?***

It is to identify the problems that are significant and that can be solved with reasonable effort. I have always thought of engineering as an applied science. It should apply to real-world problems. In our research group, we look ahead five to ten years and think about which real-world applications will be significant. In the process of trying to solve real-world problems, many interesting technical questions arise. If we choose the right question, we can develop beautiful theories that have applications to real-world problems. Having the intuition or sixth sense to identify a good problem takes a lot of experience.

• ***Why did you choose to teach?***

My father was a professor in Korea and I thought being a professor was the only job in the world when I was growing up. How wrong I was! In a sense, I think I was predestined. Being a professor requires both teaching and research, and I like the combination of the two. Through research, we develop innovative technology. This experience is essential for teaching that is real and relevant. By teaching at a place like MIT, we can identify and work with the best young minds in the world to develop advanced technologies. Also, in research, there are few near-term accomplishments. Sometimes, nothing will happen for many years. However, in teaching, there are more short-term accomplishments. In fifteen weeks, you're done teaching a course, and you feel that you've accomplished something in that short period.

• ***What are your thoughts on receiving an Emmy Award?***

This is MIT's award, and I've accepted it on behalf of my students and the Institute. If MIT were in the business of TV, it probably would have many awards like this. The Emmy is certainly a prestigious award. I think it's very unusual. 





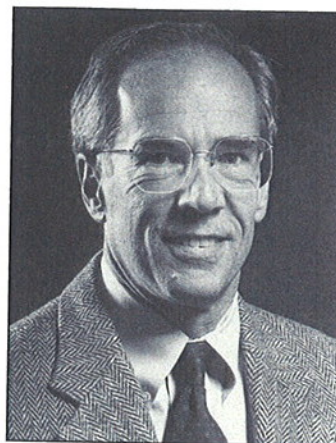
**Dr. Anantha P. Chandrakasan** was promoted to associate professor in the Department of Electrical Engineering and Computer Science, effective July 1, 1998. Professor Chandrakasan joined RLE's Circuits and Devices group in September 1994. Concurrently, he was appointed as assistant professor and to the Analog Devices Career Development Professorship. Professor Chandrakasan came to MIT from the

University of California at Berkeley (BS'89, MS'90, PhD'94), where he completed postgraduate research in low-power integrated circuit design. Professor Chandrakasan's research interests include low-power techniques for portable real-time applications, video compression, computer-aided design tools for VLSI design, and system-level integration. These have applications to digital signal processing and wireless communication technologies. Professor Chandrakasan is a member of Eta Kappa Nu and Tau Beta Pi. (Photo by John F. Cook)



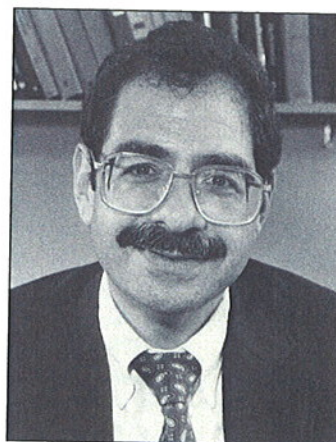
**Dr. Dennis M. Freeman** (SM'76, PhD'86), W.M. Keck Foundation Career Development Professor, was promoted to associate professor in the Department of Electrical Engineering and Computer Science, effective July 1, 1998. Professor Freeman, a principal investigator in RLE's Auditory Physiology group, is involved in developing instrumentation that visualizes the microscopic motion of biological and synthetic

structures. He has developed a video-based technique that measures the sound-induced motions of inner-ear structures and is extending this method to other biomedical and engineering applications (see *RLE currents*, fall 1997). Professor Freeman, who has been affiliated with RLE since 1974, joined the faculty in the Department of Electrical Engineering and Computer Science in 1995. In addition, he is a research affiliate with the Eaton-Peabody Laboratory at the Massachusetts Eye and Ear Infirmary. A graduate of Pennsylvania State University (BS'73), Professor Freeman is a member of the Association for Research in Otolaryngology, the American Association for the Advancement of Science, the Institute of Electrical and Electronics Engineers, the International Society for Optical Engineering, and the Acoustical Society of America. (Photo by John F. Cook)



**Dr. Erich P. Ippen** (SB'62), Elihu Thomson Professor of Electrical Engineering and Professor of Physics, was elected vice president of the Optical Society of America for 1998. He will become the society's president-elect in 1999 and serve as its president in 2000. Professor Ippen, a principal investigator in RLE's Optics and Devices group, is widely known for the development of ultrashort-pulse optical sources and measurement

techniques. He and his research group have studied femtosecond spectroscopy of solid-state materials, ultrafast nonlinearities in semiconductor waveguides, and ultrashort-pulse optical fiber devices. Professor Ippen also received two prestigious awards in 1997. He was the recipient of the 1997 Quantum Electronics Award by the IEEE Lasers and Electro-Optics Society, which recognized him for pioneering work in ultrafast optics, optical diagnostics and novel methods of modelocking. In addition, the American Physical Society named him co-recipient of the 1997 Arthur L. Schawlow Prize in Laser Science. Along with colleague Dr. Charles V. Shank, director of Lawrence Berkeley Laboratory, Professor Ippen was cited for pioneering work in developing femtosecond sources and for leadership in applying these sources in broad areas of science. (Photo by John F. Cook)



**Dr. Marc A. Kastner**, Donner Professor of Physics, was appointed head of MIT's Department of Physics, effective February 1, 1998. He succeeds interim department head Professor Thomas J. Greytak, who was appointed after Professor Ernest J. Moniz was named undersecretary for the U.S. Department of Energy. Professor Kastner joined the MIT faculty in 1973 and served as head of the Division of Atomic,

Condensed Matter, and Plasma Physics (1983-1987) and as associate director for the Consortium for Superconducting Electronics (1989-1992). Since 1993, he has been director of MIT's Center for Materials Science and Engineering. As a principal investigator in RLE's Quantum-Effect Devices group, he has contributed to the understanding of the electronic structure of amorphous semiconductors and the physics of high-temperature superconductivity. His recent research on the single-electron transistor has increased understanding of quantum-

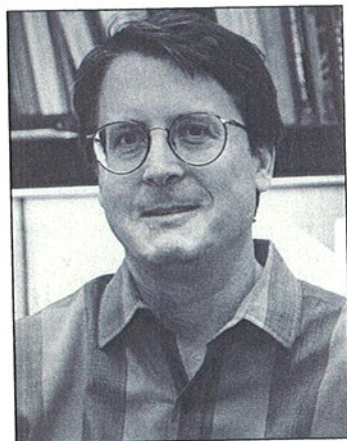


mechanical processes in semiconductor devices. In 1990, his research group fabricated the first semiconductor single-electron transistor. Professor Kastner is a graduate of the University of Chicago (BS'67, MS'69, PhD'72) and a fellow of the American Physical Society and the American Association for the Advancement of Science. (Photo by John F. Cook)



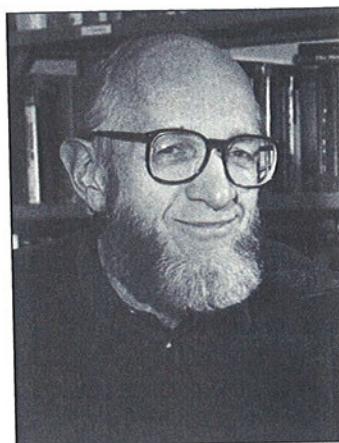
**Dr. David C. Kring** (PhD'94) was appointed as research engineer in RLE's Circuits and Systems group, effective March 1, 1998. Previously, Dr. Kring was a research engineer in MIT's Department of Ocean Engineering, where he also completed his postdoctoral research. His work in RLE will involve the development of an innovative boundary element code for a project that involves hydrodynamic analysis of

large non-rigid offshore structures. Contributing to the Circuit and Systems group's research in time-domain analysis of ship and body motions, this code will help to combine recent achievements in higher-order element and precorrected-fast Fourier transform algorithms. Dr. Kring is a graduate of the Webb Institute (BS'88) and an associate member of the Society of Naval Architecture and Marine Engineers. (Photo by John F. Cook)



**Dr. M. Charles Liberman** was named director of the Eaton-Peabody Laboratory at the Massachusetts Eye and Ear Infirmary in March 1998. He succeeds Dr. Nelson Y.S. Kiang, who served as director of the laboratory from 1962 to 1996. Dr. Liberman is associate professor of physiology in Harvard Medical School's Department of Otology and Laryngology. He has served as Eaton-Peabody's acting director since 1996. An

affiliated faculty member at the Harvard-MIT Division of Health Sciences and Technology, his research interests include auditory physiology, neuroanatomy, and neurophysiology. Dr. Liberman is a Harvard graduate (AB'72, PhD'76) and a member of the Association for Research in Otolaryngology, the American Association for the Advancement of Science, and the Society for Neuroscience. (Photo by John F. Cook)



**Dr. William T. Peake** (SB'51, SM'53, ScD'60), Professor of Electrical Engineering and Computer Science, announced his retirement after serving on the MIT faculty for thirty-nine years. As a principal investigator in RLE's Auditory Physiology group, Professor Peake has investigated signal transmission in normal and pathological auditory systems. His work has emphasized the acoustic, mechanical, and

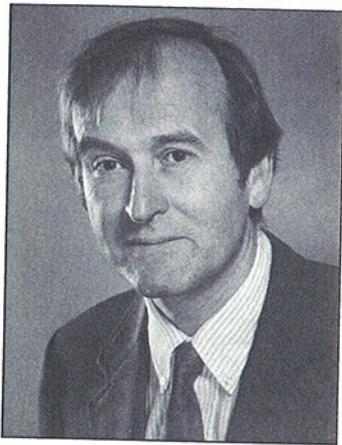
electrophysiological processes of the ear and interspecies comparisons. Professor Peake has also served on faculty at the Harvard-MIT Division of Health Sciences and Technology and as a research associate at the Eaton-Peabody Laboratory at the Massachusetts Eye and Ear Infirmary. He plans to continue his research at RLE and EPL, where 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 seeks to develop a theory that would integrate our understanding of signal processing in the ear across several vertebrate species. (Photo by John F. Cook)



**Dr. Rajeev J. Ram**, Assistant Professor of Electrical Engineering and Computer Science, received an award under the National Science Foundation's Faculty Early Career Development program. Professor Ram, a principal investigator in RLE's Optics and Devices group, plans to develop a noninvasive current probe based on magnetic force microscopy that is capable of monitoring current distribution in

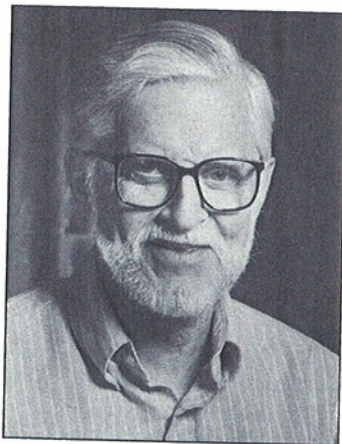
electronic devices and circuits. The CAREER program recognizes outstanding new faculty members who intend to pursue academic careers that involve both research and education. Professor Ram's work has focused on the quantum optics of microcavity lasers and on electron dynamics in quantum structures. A graduate of the California Institute of Technology (SB'91) and the University of California at Santa Barbara (SM/PhD'96), Professor Ram joined the MIT faculty in 1997. He has conducted a wide range of theoretical and experimental research, including the development of high-speed semiconductor lasers and studies of the dynamics of microcavity polaritons. (Photo by John F. Cook)





**Dr. Henry I. Smith**, Joseph F. and Nancy P. Keithley Professor of Electrical Engineering, received the Robert H. Hill Memorial Award presented by Suss Advanced Lithography, Inc., of Waterbury, Vermont. Professor Smith, a principal investigator in RLE's Quantum-Effect Devices group and head of the NanoStructures Laboratory, was cited for his outstanding contributions to the advancement of x-ray lithography.

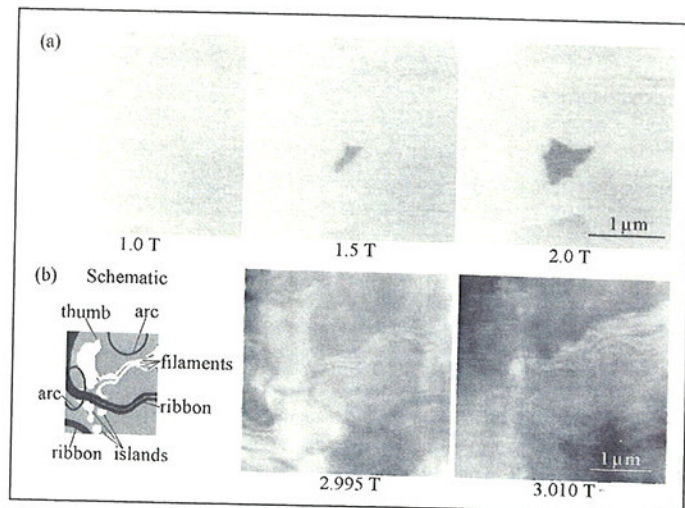
Professor Smith is widely acknowledged for his work in submicron structure technology and his leadership in teaching and promoting submicron structures. A second Hill award was made to Dr. Franco Cerrina, professor of electrical and computer engineering at the University of Wisconsin at Madison and director of its Center for X-ray Lithography. The awards were presented on October 6, 1997, in honor of Robert Hill of IBM, who was a vital contributor to IBM's program in x-ray lithography and whose efforts made it an economical alternative to optical lithography. (Photo by John F. Cook)



**Dr. Kenneth N. Stevens** (ScD '52), Clarence J. LeBel Professor of Electrical Engineering, was one of sixty new members elected to the National Academy of Sciences on April 28, 1998. Election to membership in the National Academy of Sciences recognizes distinguished and continuing achievements in original research. It is considered one of the highest honors accorded an American scientist or engineer. Professor

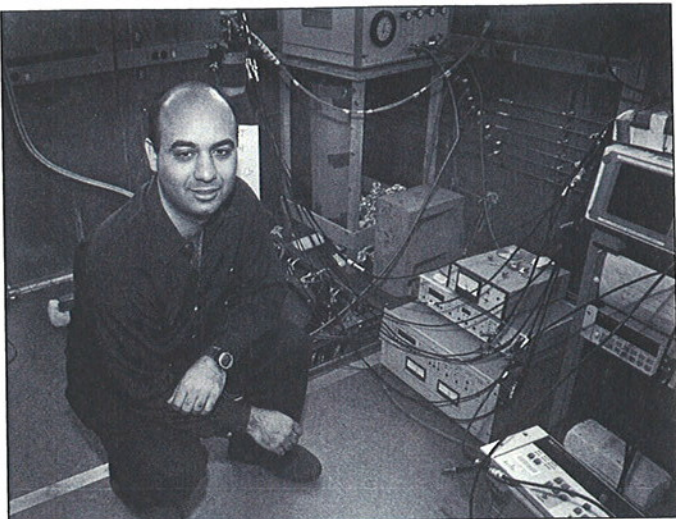
Stevens attended the University of Toronto (BAsC '45, MASc '48) and came to MIT in 1948 as a teaching assistant in the Department of Electrical Engineering. A faculty member of RLE's Speech Communications group since 1958, he has received numerous awards for his fundamental research in speech synthesis and the analysis of speech production processes, and has been central to the development of speech communication research at RLE. 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, procedures can be developed to recognize words in speech and to assess disorders in speech production. Professor Stevens is a fellow of the American Academy of Arts and Sciences, the Acoustical Society of America, and the IEEE, and is a member of the National Academy of Engineering. (Photo by John F. Cook)

In the early 1980s, scanning probe microscopes (SPMs) astonished scientists with the first real-space images of the silicon surface. An offspring of the scanning tunneling microscope (STM) invented in 1981 by Gerd Binnig and Heinrich Rohrer at IBM Zurich, the scanning probe microscope is one of several instruments used to study the surface properties of materials from the atomic to the micron level. Today, SPMs are used in a variety of disciplines, including fundamental surface science and routine surface roughness analysis. One of its most spectacular applications is the three-dimensional imaging of structures—from silicon atoms to micron-sized protrusions on the surface of a living cell. As an imaging tool, the SPM has a large dynamic range that encompasses the domains of both optical and electron microscopes. It allows probing under various conditions (such as air, gas, liquid, and vacuum) and permits the selective manipulation of single atoms on a solid surface. Thus, it has the ability to measure many physical properties such as surface conductivity, static charge distribution, localized friction, magnetic fields, and elastic moduli.



Flow patterns in a two-dimensional electron gas (2DEG), as observed with the new subsurface charge accumulation (SCA) imaging techniques developed by Professor Raymond C. Asboori's group. Top row: A region in the 2DEG where the microscope was used to lower the density of electrons before imaging (magnetic field increases from left to right). At all borders of the black spot, the 2DEG is nonconducting, thus charge can't penetrate the interior despite the fact that it most likely conducts electrons. These results establish the capability to detect separate conducting and nonconducting regions within the 2DEG. Bottom row: Two capacitance images as the magnetic field increases. Bright areas show regions of high charge accumulation. Note the interesting structures and how the small change in magnetic field dramatically alters the image. Not only did Professor Asboori's group observe some features in agreement with theory, but they also found other completely unexpected features, such as bright regions bordered by filaments that grew with increased magnetic field strength, and other unexplained circular and concentric structures.





Professor Raymond C. Ashoori demonstrates the apparatus used to achieve subsurface charge accumulation imaging. Behind him is a helium-3 cryostat, where the scanning microscopy measurements are performed. The cryostat is suspended by bungee cords in order to reduce vibrations. At right are the magnet's power supply and parts of the capacitance bridge used to make the measurements.


(Photo by John F. Cook)

By combining the methods of ultrasensitive charge sensing with low-temperature scanning probe microscopy, Professor Raymond C. Ashoori and his colleagues in RLE's Quantum-Effect Devices group have developed a means to directly observe charge distributions underneath the surface of semiconductor materials. They have used this new technique, called *subsurface charge accumulation imaging (SCA)*, to directly image the nanoscale structures that exist in the quantum Hall electronic liquid. The quantum Hall effect occurs in a two-dimensional electron gas (2DEG), and one of its most impressive consequences is the existence of electronic states that carry electrical currents with no resistance at the edges of a semiconducting sample. The structure of these electronic states has long been a mystery, and Professor Ashoori's group has used SCA as a powerful means for their study. SCA's spatial resolution, which is approximately 1000 times finer than any previous image of the quantum Hall system, has allowed the group to see the behavior of a strongly interacting quantum-mechanical fluid of electrons. To date, their results have shown that although some of the data exhibited structure predicted by theory, many other beautiful and unexplained formations also appeared. Their work was recently published in *Nature* (S.H. Tessmer, P.I. Glicofridis, R.C. Ashoori, and M.R. Melloch, "Subsurface Charge Accumulation Imaging of a Quantum Hall Liquid," March 5, 1998, vol. 392, no. 6671, pp. 51-54).


In an effort to understand the meaning of the images observed with SCA and how these microscopic structures might lead to the quantum Hall effect, Professor Ashoori's group is preparing experiments to study systems in which the scan probe will image the entire Hall bar. Future investigations will focus on several intriguing features in the quantum Hall effect such as skyrmions, edge states, composite fermions, and the fractional quantum Hall effect. In addition to the powerful imaging of structures that create the quantum Hall effect, the SCA microscope has many practical and scientific applications. For example, scientists can now "see" beneath the silicon and silicon-oxide interface, where most transistors perform digital logic

considers issues related to the migration of HDTV to higher resolutions. The need to broadcast at resolutions higher than those now allowed for HDTV is recognized. A currently acceptable goal for terrestrial HDTV is a progressively scanned image with a resolution of more than 1000 lines scanned at 60 frames per second. However, today's transmission and compression technologies cannot support such a high video resolution within the standard 6-megahertz channel. The ATSP group is investigating methods to transmit video at higher resolution formats by using video enhancement bits. This approach would transmit two sets of information within the bandwidth allocated for HDTV. Standard video bits would be transmitted at a standard HDTV resolution that current technologies can support. An advanced HDTV receiver would receive the standard video bits and, with the assistance of the video enhancement bits, would convert standard HDTV to a higher resolution. Standard HDTV receivers would ignore the enhancement bits and simply display the video at the standard HDTV resolution. This highly desirable backward-compatible approach would not render standard HDTV receivers obsolete.

**Speech enhancement systems.** Various techniques have been developed to enhance speech degraded by additive background noise. Model-based enhancement systems, which are based on parameter estimation, have achieved the best results to date. These techniques, however, are limited by the models upon which they are based. A basic yet false generalization of model-based algorithms used for speech enhancement is that each speech segment is assumed stationary for a fixed window. It is known that the duration of stationarity varies for different classes of sounds and speakers. One solution is to find the desired stationary regions in the speech before model-based enhancement is performed. The ATSP group recently developed an algorithm to segment speech into nearly stationary regions using M-band decomposition and adaptive windowing techniques. Noise reduction is achieved by applying a modified Wiener filter based on selective linear prediction. This takes into consideration the local signal-to-noise ratio of the region in question. Continued research in this area seeks alternatives to this technique, which would make it more computationally efficient for real-time applications.

Scientific advances in image processing, coupled with technological advances in devices and systems, have resulted in a wide range of applications for science, industry, and government. In addition to advanced television, other applications for image processing include remote sensing, robot vision, industrial inspection, automation systems, electronic publishing, and optical character recognition. 

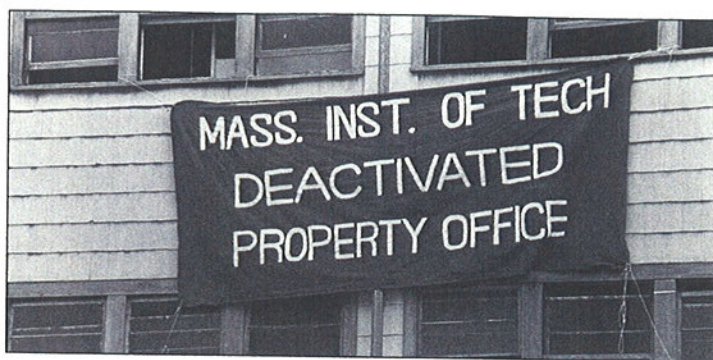
by Dorothy Fleischer

operations by modulating conduction. SCA can also create images of distributions as well as types of semiconductor defects and impurities, thus enabling researchers to observe the mechanisms that affect device performance. Professor Ashoori believes this new type of microscopy will prove extremely powerful in understanding the wide array of physics problems concerning electrical conduction inside materials. 

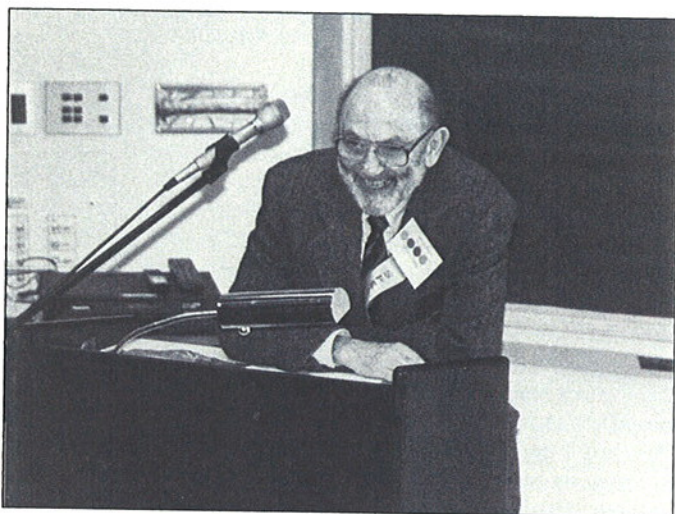


# Building 20: Final Curtain Call

*Friends and former occupants of Building 20 gathered on the MIT campus for a two-day program on March 26 and 27, 1998, that celebrated the building's history as MIT's "Magical Incubator." The reunion also focused on plans for the new Stata Complex, which will be built on Building 20's current site.*



*Hackers festoon a banner on legendary Building 20, announcing its "formal" decommissioning by MIT.*

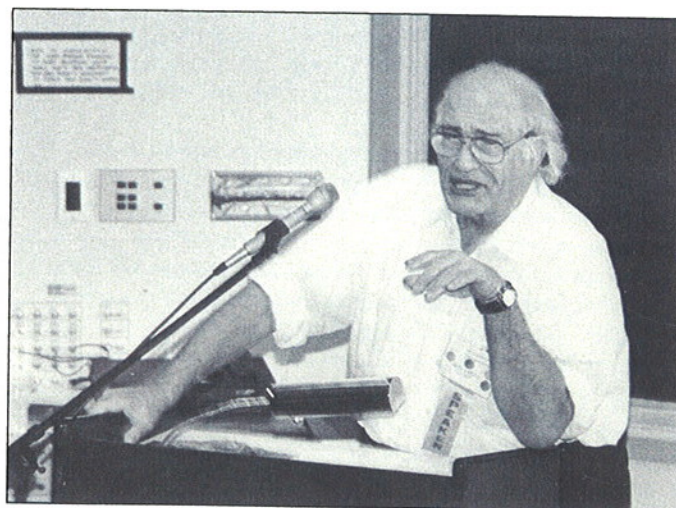


*Professor Morris Halle gives an account of Building 20 as the incubator for MIT's linguistics and philosophy programs: "...in spite of its rather unprepossessing exterior, Building 20 was a great luxury: it was like money in the bank that was not immediately needed and could be invested in projects without guaranteed pay-off. And, as we now look back half a century later on the record of these investments, we see that quite a few of them were successful and grew into major scientific enterprises."*



*MIT President Charles M. Vest addresses the audience at Friday evening's dinner at Walker Memorial, which was held in honor of Raymond S. (SB/SM'57) and Maria Stata. Mr. Stata, founder and chairman of Analog Devices, Inc., is the principal benefactor of a new building complex that will house the computer, intelligence, and information sciences at MIT.*

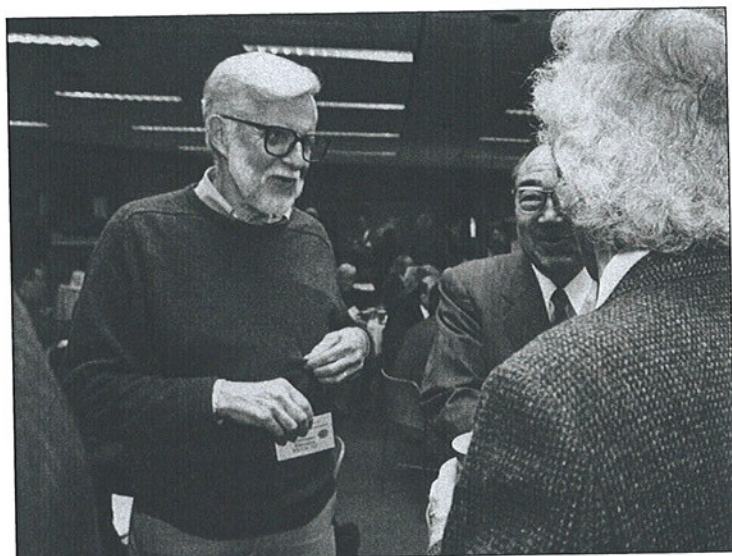
*Professor Jerome Y. Lettvin, a Building 20 denizen since 1953, retells the building's history as a womb for bioscience and bioengineering at MIT. "It's a building with a special spirit, a spirit that inspires creativity and the development of new ideas ... Under the benign guidance of RLE administrators, there was always support for the development of new projects."*







Professor Louis D. Smullin (Rad Lab and SM '53), Jimmy Bussgang (SM '51), and a friend take a moment to share memories of days gone by in Building 20. Humorously, Professor Smullin remembers when the smell of dead squid pervaded the building after the experimental subjects expired in an overheated tank one hot summer weekend. Mr. Bussgang recalls working as a technician in the laboratory where Henry E. "Pete" Singleton (SB/SM '40, ScD '50) and Leon G. "Jack" Kraft, Jr. (SM '49) were building the first correlator.



MIT Professors Kenneth N. Stevens (ScD '52), Robert M. Fano (Rad Lab and SB '41), and Lawrence S. Frisbkopf (PhD '56) reminisce about the old MIT Acoustics Laboratory and the early days of RLE's Speech Communication group. Professor Stevens came to the Acoustics Lab in 1948 as a graduate student. When it closed in 1955, then-RLE Director Jerome B. Wiesner gave permission for its research to be incorporated into RLE.

Dr. Hiroya Fujisaki (SM '59, EE '61) recalls his days in Building 20 as a graduate student and research assistant in RLE's Speech Communication group from 1958 to 1961, and shares them with Mr. Raymond S. Stata (SB/SM '57). Dr. Fujisaki is now a professor at the University of Tokyo and was the longest-traveled participant at the Building 20 celebration.

(Photos by John F. Cook)

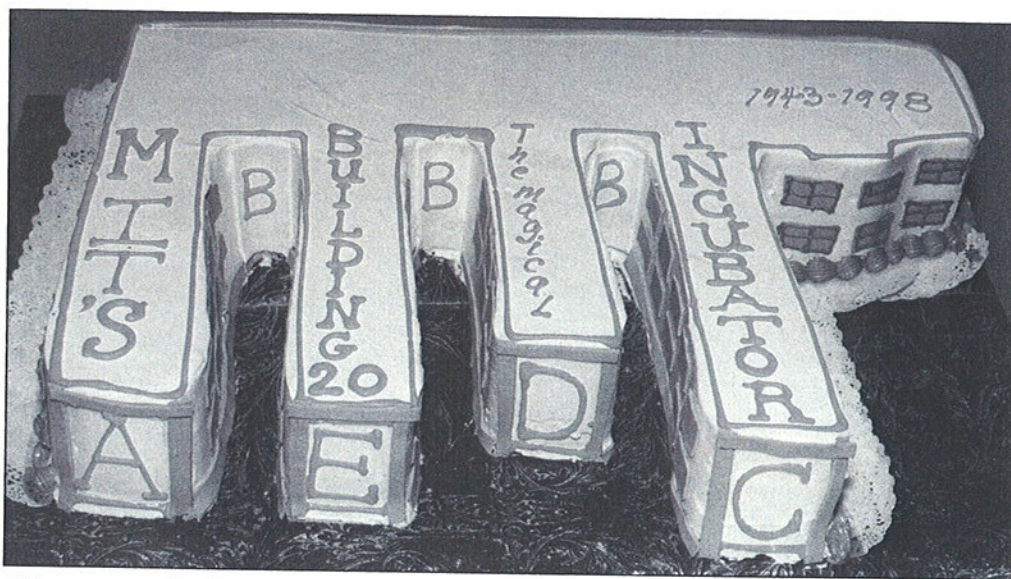


Two colleagues from the class of '54 reunite: Charles Freed (SM '54, EE '58) from Lincoln Laboratory and MIT Professor Hermann A. Haus (ScD '54). Professor Haus remembers being hired by Professor Louis D. Smullin (Rad Lab and SM '39) to work in Building 20's Tube Lab in the summer of 1950. He treasures his memories of working in a building where one could open the windows.





# Building 20: For the Record



When compared to the longevity of Building 20 itself, the true-to-life cake depicting the building was certainly "temporary." (Photo by Graham G. Ramsay)

If you were unable to attend the Building 20 celebration, you can still rekindle memories of the "plywood palace," long after it is gone.

The building has its own Web site at <http://www-eecs.mit.edu/building/20/index.html>. From there, you can share anecdotes, look at photographs, and make connections to related Web sites. In addition, students enrolled in the News, Technology, and Community class are creating another interactive Web site to tell the story of Building 20.

If you do not have access to the World Wide Web, other materials are available. The fall 1997 issue of *RLE undercurrents* (the laboratory's in-house newsletter) featured "A Last, Loving Look at an MIT Landmark—Building 20," which contains interviews with former inhabitants and many photo-

graphs of the building. You can request a copy by contacting *RLE currents*. The issue is also available from RLE's Web site <http://rleweb.mit.edu/>.

"The Legacy of MIT's Building 20" by Paul Penfield, Jr., Nancy A. Heywood, and J. Francis Reintjes appeared in the March 1, 1998, issue of *The Reflector* (vol. XLVI, no. 7, p. 16).

Finally, the staff of the MIT Institute Archives is working on the Building 20 Records Project to preserve records of historical importance before the building is torn down. The archivists are collecting a set of photographs and other historical information on the building.

More photographs from Building 20's two-day celebration in March are on pages 22 and 23.

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