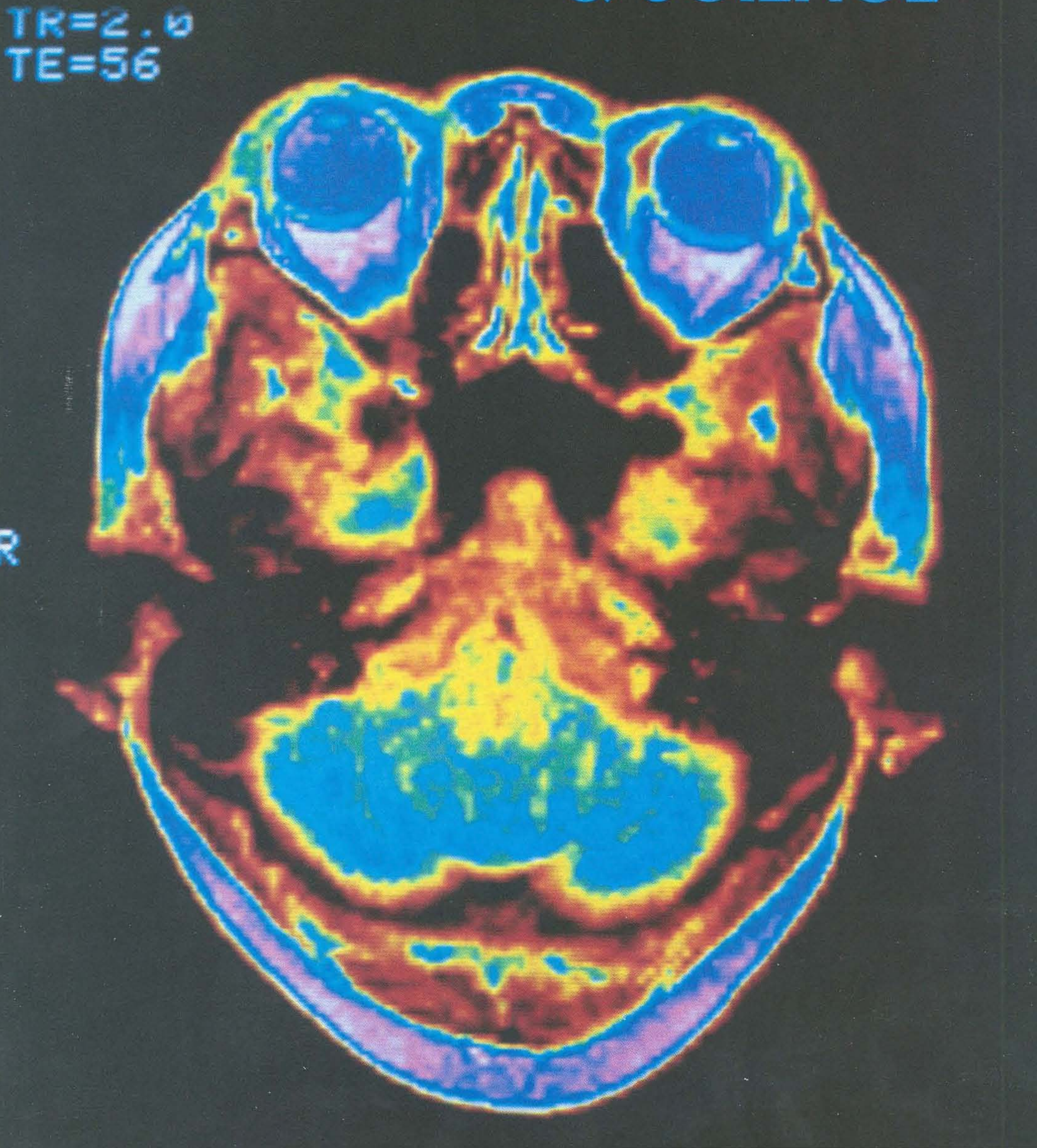
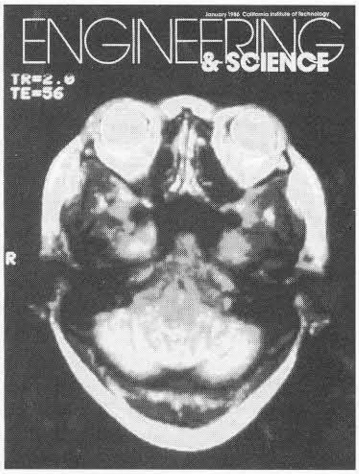
January 1986 California Institute of Technology

ENGINEERING & SCIENCE

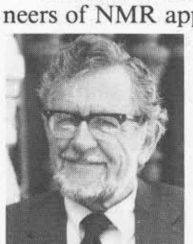


In This Issue



Magnetic Magic
On the cover — an NMR image of the brain in transaxial section taken through the middle of the eyeballs and ears. The colors are false, and their gradations from white through magenta to red to black represent combinations of proton density and rates of relaxation by which NMR differentiates among various kinds of tissue. NMR stands for nuclear magnetic resonance, a laboratory technique used for 40 years to study a wide variety of molecular properties. In "Biomedical Applications of NMR," beginning on page 10, Institute Professor of Chemistry John D. Roberts explains how NMR works and how the technique has been applied in recent years to the imaging of biochemical processes in human beings. The article was adapted from his Seminar Day talk last May.

Roberts is one of the pioneers of NMR applications to



chemistry and biochemistry. After earning his BA (1941) and PhD (1944) from UCLA, Roberts came to Caltech in 1952 and has been professor since 1953. His work demonstrated with extraordinary clarity the power of NMR as a tool for studying molecular structure and dynamics. Said a colleague, "If Roberts had not entered the field of NMR at an early stage, I believe that the field would have developed differently and far less effectively." He has also served as division chairman (1963- 68) and provost and vice president (1980-83).

Spaceman Wang
As the first (and only) scientist-astronaut from Caltech's Jet Propulsion Laboratory to fly on the space shuttle, Taylor Wang has been in great demand to recount his experiences — including a warm welcome in his native China. His good-natured wit in describing his life as an astronaut delighted his Watson Lecture audience at Caltech last October; that talk, "A Scientist in Space," is adapted here beginning on page 17.

Born in Shanghai, Wang came to the United States via Taiwan and earned his BS, MS, and PhD degrees in physics at

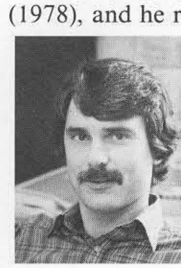
UCLA. He's worked at JPL since 1972 where early on he recognized the potential of zero gravity in doing containerless experiments. He invented the acoustic levitation and manipulation chamber in the drop dynamics module for investigating fluid behavior in space. When this experiment balked on Spacelab 3, Wang spent 2 ½ days inside the apparatus in a heroic rescue — justifying NASA's decision to put scientists in space.

Shaken Structures
Jim Beck and John Hall, both assistant professors of civil engineering, visited Mexico City 12 days after the September 19 earthquake. Although they couldn't get into all the structures simply by donning hard hats and trying to appear official, their four days of observations provide some interesting insights into why buildings failed. These are described in "Engineering Features of the Recent Mexican Earthquake," which starts on page 2. Unofficial though their investigations were, they may be of particular importance since few official engineering studies were done in the rush to clear away the ruins. And the structural failures in Mexico City will force a closer look at other areas that may have similar soil characteristics.

Hall received his BS from West Virginia University (1972),

MS from the University of Illinois (1973) and PhD from UC Berkeley (1980). He's been at Caltech since 1980.

Beck's PhD is from Caltech (1978), and he returned here to



join the faculty in 1981. His BSc and MSc (1970) are from the University of Auckland in New Zealand.

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Engineering Features of the Recent Mexican Earthquake — *by James L. Beck and John F. Hall* *Page 2*
Caltech civil engineers document the extensive damage to modern multi-story buildings located on Mexico City's dry lake bed.

Biomedical Applications of NMR — *by John D. Roberts* *Page 10*
A laboratory technique for studying molecular properties now offers great potential in medical imaging.

A Scientist in Space — *by Taylor Wang* *Page 17*
A JPL physicist travels out of this world to do his experiments in zero gravity.

Tiny *Tale* Gets Grand *Page 24*
Electron beam lithography reduces a page of Dickens to micrometer size to meet a long-standing challenge.

Departments

Research in Progress *Page 27*
Comet Composition
To Shop or Not to Shop

Random Walk *Page 31*

Engineering Features of the Recent Mexican Earthquake

by James L. Beck and John F. Hall

The unique mid-level collapse of the hotel shown above may have resulted from a discontinuity in the structural system. This case presented quite a dilemma for the demolition crew, because the hotel is leaning over a row of undamaged apartment buildings in the rear. The leaning portion of the structure was finally removed piece by piece.

THE EARTHQUAKE OF SEPTEMBER 19, 1985 produced the worst earthquake disaster in Mexican history. Mexico City, although not devastated, sustained a huge blow in which as many as 10,000 lives may have been lost. About 250,000 people, of a population of 18 million, lost their dwellings, and more than 300 multi-story buildings either collapsed or were seriously damaged. Public buildings, such as schools, hospitals, and some government housing projects, were particularly hard hit, resulting in a large loss of life.

Transportation and communication systems, on the other hand, fared well. The subway and the international airport were functioning again soon after the earthquake. Long-distance telephone transmissions were interrupted because of the collapse of the office building housing the equipment, but the local telephone system still worked. Utilities also suffered only minimal damage. Water supplies eventually ran short because of damage to the distribution pipelines in the eastern and southeastern regions, but electrical power continued to flow to most of the city. The collapsed Regis Hotel was the source of the only major fire from gas leakage, although a number of smaller fires broke out elsewhere.

The earthquake occurred at 7:18 a.m. on Thursday and had a Richter surface wave magnitude of Ms=8.1. A large aftershock of magnitude Ms=7.5 followed on Friday evening. The main shock was centered 250 miles from Mexico City on the Pacific coast, near the town of Lazaro Cardenas on the border between the states of Michoacan and Guerrero (figure 1). The rupture zone extended for about 125 miles parallel to the coast along a tectonic feature called the Cocos subduction zone, which stretches for more than 1,000 miles along the Pacific coast of Central America. This feature is the source of many large earthquakes that have shaken the central and southern parts of Mexico in this century, including the 1957 Acapulco quake (Ms=7.5) and the 1979 Petatlan event (Ms=7.6), both of which produced serious damage in Mexico City.

In this subduction zone, part of the floor of the Pacific Ocean, called the Cocos plate, is being forced under the landmass of Mexico, which lies on the North American plate. This is happening at a rate of about three inches per year. This relative motion builds up large strains at the interface of the two plates where they are locked, and the earthquakes result from episodic release of the strain energy by localized rupturing of the interface. Primarily on the basis of this simple physical model, some seismologists had anticipated that a major earthquake would eventually occur in the area of the recent event. They had labeled this area the Michoacan seismic gap, because it had not ruptured completely for more than 70 years, while neighboring regions had produced earthquakes several times during this period. For the same reason, a major earthquake is expected to occur eventually in the Guerrero gap, which lies between the rupture zones of the 1979 Petatlan and 1957 Acapulco earthquakes. In such an event, structural damage is likely to occur once again in Mexico City.

We visited Mexico City 12 days after the September earthquake and spent four days walking around the city observing the damage to buildings. Although we found it informative, there are limits to what we could learn in this way. The collapsed buildings, for example, left little visual evidence of the weaknesses that had precipitated their collapse, and it was difficult to gain entry to seriously damaged buildings to inspect their interiors. But what really stood out was the extent of the damage to modern multi-story buildings, which is perhaps unprecedented. A survey by engineers from the National Autonomous University in Mexico City (UNAM) revealed that buildings of 6 to 15 stories sustained most of the damage. Distribution of severe structural damage throughout Mexico City, based on this survey, is shown in figure 2. Most of the damage is confined to those areas of the city that are on the dry lake bed. The Aztecs originally founded their city on an island in this ancient lake.

Ironically all of the old colonial buildings and the majority of the old low-rise buildings built before the introduction of a modern building code in 1957 apparently survived the earthquake with little damage. This surprising result demonstrates an important principle in earthquake-resistant design. Whether or not damage occurs depends not so much on the absolute strength of the structure as on its strength relative to the seismic attack imposed by the earthquake. The seismic forces generated in a structure depend on both the amplitude and the frequency content of the ground shaking. Because the ground motion on the lake bed was of a long-period nature, multi-story structures, which have long fundamental periods of vibration, experienced a seismic attack many times larger than that felt by low-rise buildings, which have much shorter natural periods. This resonance phenomenon accounts for the concentration of damage in buildings 6 to 15 stories high.

Even if the seismic attack on high-rise buildings was much stronger than that on low-rise buildings, the question still remains: Why did so *much* damage occur in the taller buildings? There were probably common factors operating. Poor-quality materials, poor workmanship, and a lack of adherence to the earthquake building code may have played a role in some cases. In our opinion, however, the main reason for the extensive damage was that the intensity of shaking on the lake bed was not anticipated.

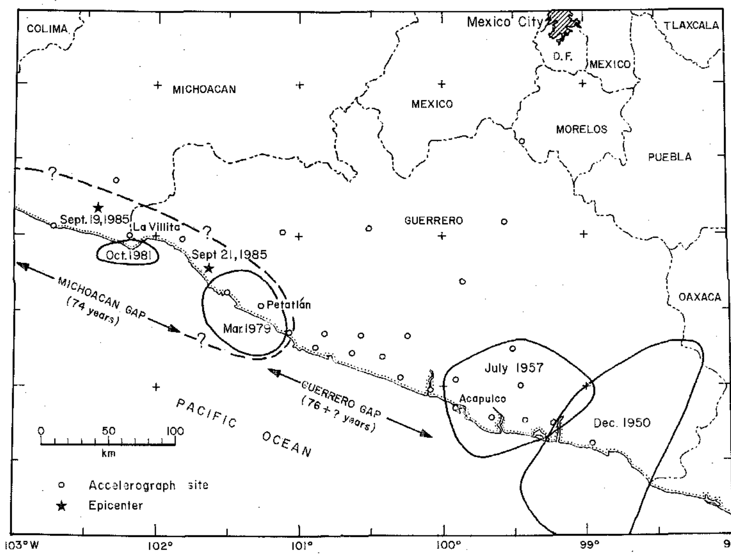


Figure 1 (above): Map showing the preliminary epicenters of the main shock and largest aftershock relative to Mexico City. The estimated rupture zones of the September earthquake and some earlier events along the Cocos subduction zone are also shown. This figure is adapted from a report on the coastal accelerograph array by Brune and Prince and their colleagues.

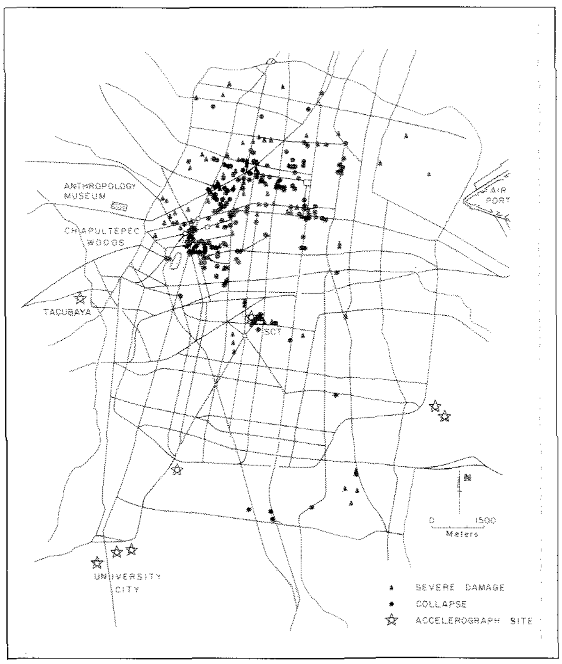


Figure 2 (left): Distribution of severe structural damage and sites where records of the strong ground shaking were obtained. Only some of the major streets of Mexico City are drawn. Damage is confined to areas on the old lake bed.

Before the earthquake, the seismic provisions of the building code for Mexico City would have been considered adequate by most engineers familiar with the principles of earthquake-resistant design. It was known from earlier strong-motion earthquake records obtained in Mexico City that the ground motion is substantially altered by the sediments of the lake that once existed there. A soft clay layer 50 to 100 feet thick, which underlies the city in the area where the damage was concentrated, acts like a narrow-band filter that greatly amplifies the ground motion over a narrow frequency range. The building code took this into account by assigning the largest earthquake design forces to structures in the period range from 0.8 to 3.3 seconds, which were to be built on the lake bed. In contrast, U. S. codes take advantage of the fact that all strong-motion records obtained in this country show that the energy in the spectrum of the ground motion peaks at shorter periods, so the design forces prescribed in the code usually decrease for building periods longer than about 0.3 seconds.

But no one anticipated the amount of amplification of the ground motion in the old lake sediments. A strong-motion record obtained at the SCT site (Ministry of Communications and Transportation) on the lake bed shows a ground acceleration history of long duration, which peaked at 17 percent of gravity and whose frequency content is dominated by a component with a period of two seconds (figure 3). In contrast, the ground motions recorded on firm ground in Mexico City show a broader frequency content and exhibit peak accelerations in the range of 3 to 4 percent of gravity, a factor of 4 to 5 less than at the SCT site. An example of a firm ground record is shown in figure 4, which is from an accelerograph at the Seismological Observatory at Tacubaya on the western side of the city. The SCT record was published two days after the earthquake by Professor Jorge Prince and his colleagues at UNAM, and it plays an important role in establishing quantitatively how strong the ground shaking was on the lake bed. Unfortunately, this record was the only one obtained within the area of damage in the city, but ground motions of a similar general character probably occurred throughout the area.

We believe that the amplification on the lake bed is primarily due to a resonant buildup of seismic waves within the thick clay layer just beneath the surface. Because of this resonance, the duration of the incoming seismic waves is a very important factor in controlling the degree to which the ground shaking amplitudes build up. We feel that this is one of the important reasons why the recent earthquake was more destructive in Mexico City than other large earthquakes that

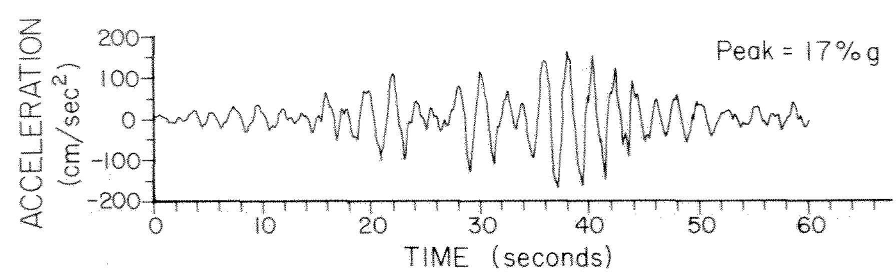


Figure 3: Ground acceleration in the east-west direction at the SCT site on the old lake bed.

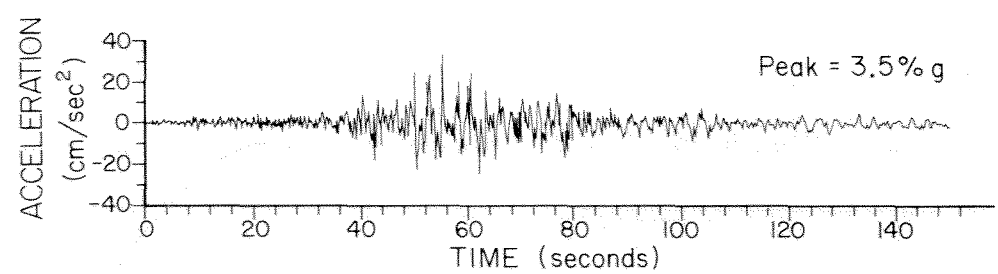


Figure 4: Ground acceleration in the east-west direction at the Seismological Observatory, Tacubaya, which is on firm ground. Note that the time scale is half of that in figure 3.

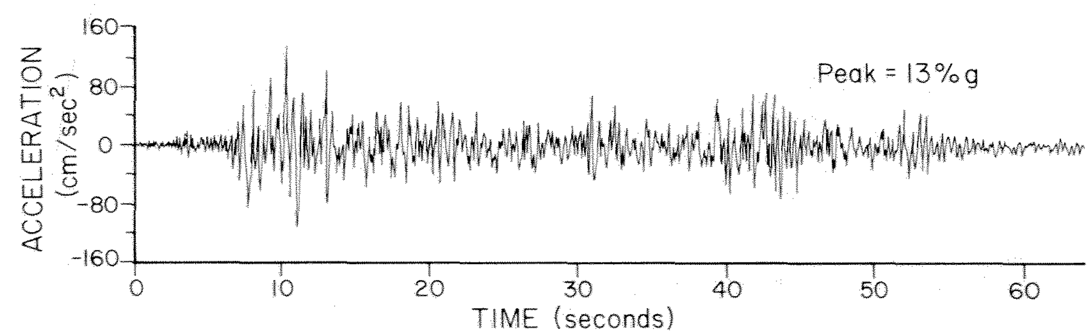


Figure 5: Ground acceleration in the north-south direction at La Villita near the center of the rupture zone on the Pacific coast.

have occurred in the Cocos subduction zone in the last 50 years. The ground shaking lasted longer because the recent event had a longer source duration than previous events in this zone. In fact, long-distance seismograph records from Caltech's Seismological Laboratory indicate that the September event was actually two large earthquakes — one 40 seconds or so after the other. Further support for this comes from some of the strong-motion records obtained in the epicentral region from an accelerograph array installed as part of a joint U.S.-Mexico project headed by Prince of UNAM and Professor James Brune of UC San Diego. For example, the La Villita record from the center of the rupture zone shows a second burst of stronger shaking about 40 seconds after initial triggering of the instrument (figure 5). Notice that the peak acceleration for this record is about 13 percent of gravity, lower than at the SCT site in Mexico City more than 200 miles away. This low value is consistent with peak accelerations of less than 20 percent of gravity exhibited by other accelerograph records obtained over the fault zone, which explains why severe damage was not widespread in the coastal regions.

The longer duration of the main shock on September 19, compared with earlier earthquakes, helps to explain the greater amount of destruction in Mexico City. First, the ground motions had more time to build up to large amplitudes by resonance within the old lake sediments. Second, once structural damage is initiated, it tends to worsen progressively as the number of large-amplitude cycles increases. So for longer shaking, more damage will accumulate.

In addition to the common factors for the widespread damage to high-rise buildings (figures 6 and 7 provide further elaboration), each damaged building showed its own particular weak points. Some of the weaknesses that we observed during our visit are illustrated in the photographs on the following pages. These do not include the cases, such as the General and Juarez Hospitals, where loss of life was high. These sites had been largely cleaned up by the time we arrived.

To structural engineers, the Mexican earthquake was a huge experiment, albeit a tragic one, which has provided invaluable data on the behavior of multi-story buildings in strong, long-period ground shaking. The earthquake is sure to stimulate much research, particularly studies of the phenomenon causing the amplification exhibited in the strong-motion records from the old lake bed compared with those on firm ground. Also, the strong-motion records obtained from the coastal accelerograph array are one of the richest sources of data available of the shaking in the epicentral region of a large subduction zone earthquake and are sure to receive much study by both earthquake engineers and seismologists. The earthquake engineering group at Caltech is planning to cooperate with colleagues from the Institute of Engineering at UNAM in a program to install a more extensive accelerograph array in Mexico City, which will also monitor structural response. The likelihood of future earthquakes shaking the city, particularly in the Guerrero gap, makes this an important project.

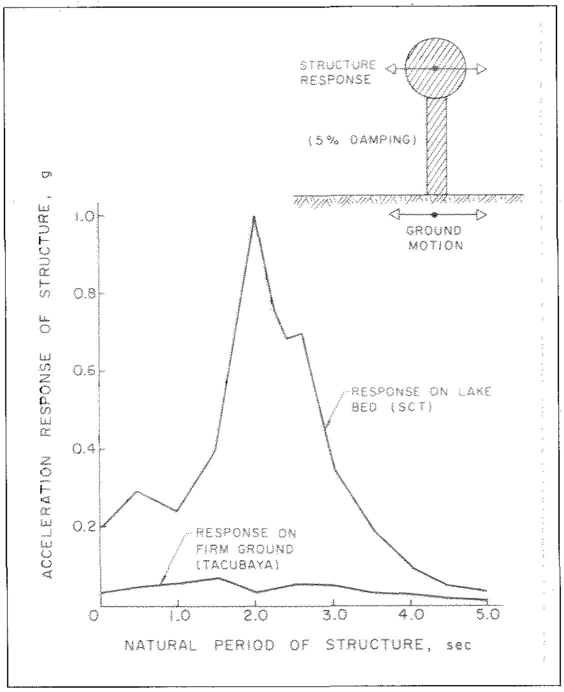


Figure 6: The engineering significance of earthquake ground motion is revealed by the response spectrum, shown here for the Tacubaya and SCT ground motions. A response spectrum shows the maximum response to the earthquake reached by an elastic mass-spring oscillator (i.e. an idealized building) as a function of the vibrational period of the oscillator. The SCT ground motion excites a much larger response than does the Tacubaya motion, especially when the period of the oscillator is near the predominant two-second period of the SCT ground motion, because this is when resonance occurs. Since the fundamental period of vibration of an N-story building is given by N/10 seconds, buildings in the 15-to-30-story range located on the soft clay layer should be most vulnerable.

Number of stories	Percent of all buildings located in the damaged area that either collapsed or suffered severe damage.
1 to 2	2
3 to 5	3
6 to 8	16
9 to 12	23
13 to 15	22
16 to 22	? (3 total buildings)
more than 22	0

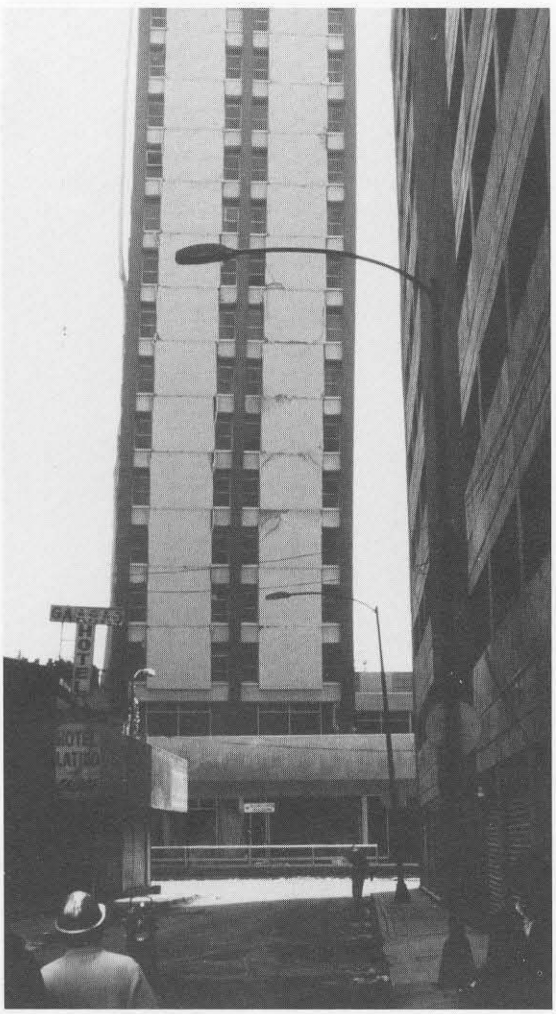
Figure 7: As seen from the table, the most vulnerable buildings were somewhat shorter than predicted by the response spectrum. This difference can be attributed to nonlinear effects; as yielding takes place, a building softens, and its fundamental period of vibration increases. Thus, during the earthquake an eight-story building may enter a resonant condition as its period increases toward the two-second period of the ground motion. On the other hand, a much taller building may leave a resonant condition as its period increases.

In design, ductility is interrelated with strength because if the strength of a building is too low, then the ductility demanded by an earthquake is very high. In Mexico City, lack of strength was evident in the columns of many buildings. When such buildings survived, they did so by narrow margins.

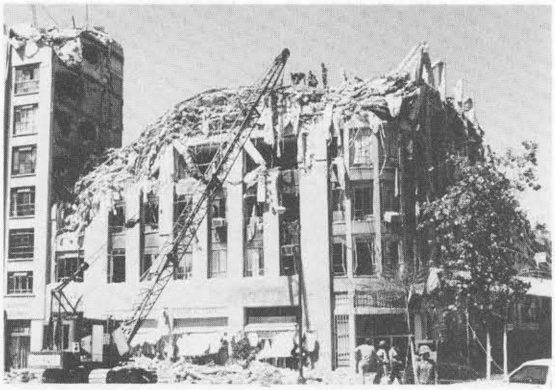
Most of the buildings that suffered full or partial collapses probably lacked ductility, that is, the ability to undergo considerable yielding without losing strength. Since even the best built buildings yield during strong ground shaking, ductility is essential to avoid collapse, especially for long-duration earthquakes when a number of yield cycles occur. In reinforced concrete construction, proper detailing and placement of the steel reinforcing bars is an important element in providing ductility. Perhaps with longer bar anchorages and extra hoops to confine the concrete, the school shown above would have safely survived the long duration of the Mexican earthquake.

Only one of the original three sections of the Nueva Leon apartment building, a twin to the building in the background, remains standing (right, foreground). The close-up (below) of the remaining section reveals weak columns, a number of which failed.

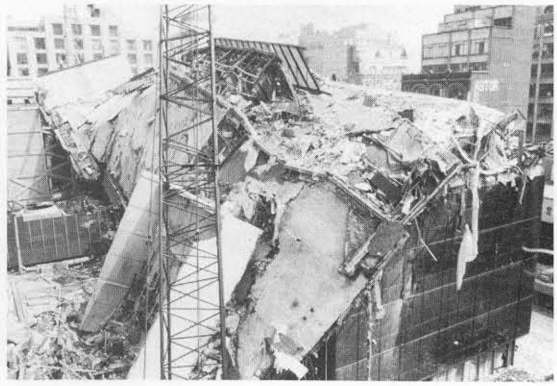
The use of unreinforced masonry to fill in exterior walls between reinforced concrete frames is a common construction practice in Mexico City. The masonry panels, being stiff, attracted a large share of the earthquake load and, being brittle, often failed. So these types of buildings were particularly susceptible to the effects of period elongation described earlier. In addition, use of masonry infills on three sides of a building, while leaving the front open, created a nonsymmetric distribution of stiffness, causing a torsional response that increased the stress on the structural elements in the perimeter of the building. The building above shows diagonal cracks typical of shear overstress.



Steel construction is rare in Mexico City, yet one of the most spectacular examples of damage occurred to the complex of five steel-frame buildings at Conjunto Pino Suarez. The 21-story tower shown at left, one of three buildings that remained standing, is leaning six feet out of plumb at the roof level due to yielding which produced permanent interstory drift. To the right of this tower stood a fourth one, also 21 stories, that toppled onto a fifth tower of 14 stories, bringing it down as well. The toppled tower, shown above, which employed truss beams and box columns, overturned at the third-floor level. Failure may have been initiated in the trusses from buckling of the chords or in the truss-to-column connection by fracture of the weld.



An interesting characteristic of the damage in Mexico City is that a great number of buildings collapsed in their top stories, leaving the lower portion intact. Three examples are shown here. One possible reason for this behavior is that designers tapered the column sizes too severely in the upper stories, permissible if only gravity and wind loads act, but unwise for earthquake loads.

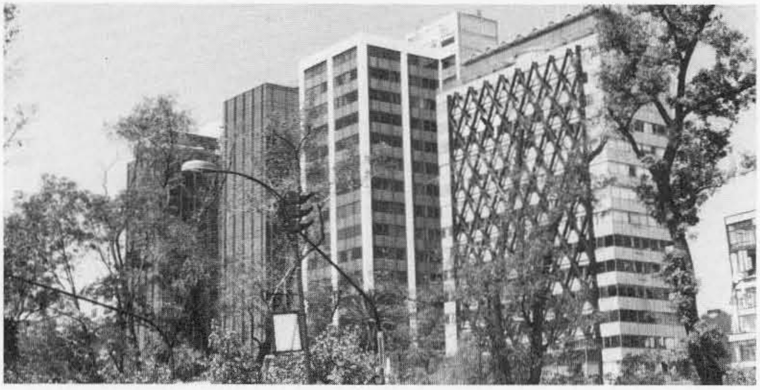


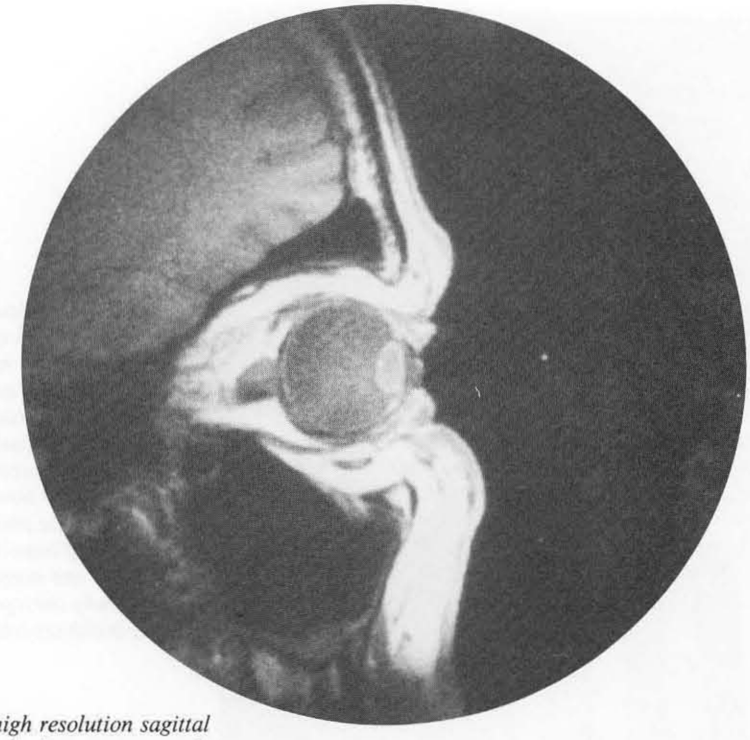
Flat-plate construction, consisting of reinforced concrete slabs and columns without beams, did not fare well in the earthquake. Inadequate shear strength in the slab-to-column connection resulted in pancake failures of the slabs with the columns remaining upright in many cases.

During the earthquake, buildings swayed back and forth; a 15-story building may have swayed as much as two feet at the roof level in each direction. Closely spaced buildings thus have the opportunity to damage each other through impact. These photos show examples of impact damage; the lower one suggests another reason why the top portion of some buildings collapsed.

***M**ost multistory buildings in Mexico City are founded on piles. Those piles that are not long enough to bear on the firm stratum below the soft clay layer may have slipped downward during the earthquake. The result, as shown in the top photo, was a tilted building. Although the overturning failure shown in the lower picture appears to be foundation related, it was probably initiated by collapse of a corner column in the basement, which was then followed by uprooting of the pile at the opposite corner as the building overturned.*

***B**elow: Even in the severely damaged areas of Mexico City, many buildings survived undamaged, some without even a single broken pane of glass. Why did some buildings fare well while others suffered? Were building collapses due to gaps in engineering knowledge or to sloppy design or construction? Is the building code adequate? These questions remain partially unanswered. Unfortunately, a lack of detailed documentation of the damage following the earthquake, the subsequent demolition and removal of many buildings without inspection or material testing, and the legal difficulty of gaining access to the structural plans of the buildings may prevent these questions from being completely answered.*





Very high resolution sagittal section of a human eye, made by proton NMR and a surface coil as receiver to improve the signal-to-noise ratio (GE).

Biomedical Applications of NMR

by John D. Roberts

The NMR images used in this article were kindly supplied by the Medical Systems Group of the General Electric Company or the NMR Imaging Laboratory of Huntington Medical Research Institutes and identified, respectively, by GE or HMRI in the figure captions.

NUCLEAR MAGNETIC RESONANCE (NMR), a laboratory technique that has been around for 40 years, has in the past decade been applied to medical imaging. Its potential for studying blood flow and metabolic processes in the heart and brain, as well as abnormal tissue, is enormous, and NMR offers advantages in competition with other noninvasive imaging techniques, particularly in not using ionizing radiation.

Nuclear magnetic resonance (NMR) spectroscopy was first demonstrated independently by physicists Edward Purcell (Harvard), Felix Bloch (Stanford) and their associates, work that was recognized by the award of a Nobel Prize in 1952. Caltech got into the field almost immediately through the perspicacity of Chemistry Professor Don M. Yost, who carried out some truly pioneering studies. Two outstanding Caltech graduate students of that period, John Waugh, now at MIT, and James Shoolery of Varian Associates, have contributed enormously to the continued development of NMR. My own work, starting 30 years ago, involved early applications of NMR to organic and biochemistry and helped to demonstrate the usefulness of NMR for studying molecular structure and molecular dynamics. There is no method as generally powerful as NMR for the study of liquids or substances in solution.

The history of NMR has been punctuated with quantum leaps associated with new technical developments: higher field magnets, more stable frequency oscillators, more sensitive detectors, and particularly advances in signal processing. In 1973, Paul C. Lauterbur (now at the University of Illinois) showed the potential of NMR for making images, and a technical explosion in that application followed. The NMR Imaging Laboratory at the Huntington Medical Research Institutes (HMRI) in Pasadena, starting in 1982 under the direction of Dr. William G. Bradley (Caltech BS 1970), has been a leader in both clinical and basic research in NMR imaging. Currently the whole-body imager at HMRI has had a greater throughput of patients than any other imager in the world.

What is NMR and how can it be applied to imaging? On the one hand, we have to be able to achieve spatial resolution, that is, measure distances between objects. On the other, we have to be able to establish a contrast scale that will differentiate materials of, say, the eye's lens from the vitreous humor, from bone, or from the brain.

Let's start with the N — for "nuclear." The nuclei of all atoms are positively charged and very much smaller than the negatively charged electron clouds surrounding them. Many nuclei have a property that corresponds to spin. Although the nuclei of ordinary oxygen and carbon don't have spin, the nuclei of hydrogen atoms (protons), the H in H_2O, do have this property. As the nuclei spin, their charges circulate and generate magnetic fields in the same way that charges moving in a circular loop of wire generate a magnetic field. And that's the M — the "magnetic."

Such magnetic nuclei, which have north and south magnetic poles, ordinarily have no preferred orientation in space. But if we put them in a magnetic field, they tend to line up with the field in a manner analogous to the way that a compass needle lines up in the earth's magnetic field. This, then, is the magnetic property that we use in NMR — the tendency of the nuclei to align in an applied electromagnetic field and produce a more favorable energy state.

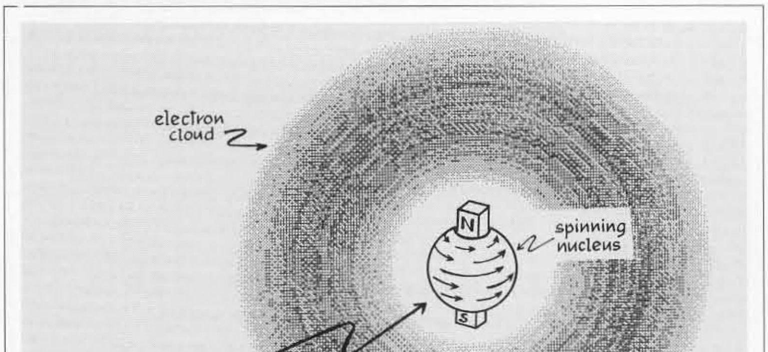
The next thing we do is to change the orientation of the nuclei in the field — turn them over and make them point the other way. Because this is a less favorable state, we have to put energy into the system. This energy can be obtained from a radio transmitter with the proper frequency. The phenomenon of turning over the nuclei by a transmitter putting in just the right amount of energy is called "resonance" and provides the R — the last of our string of NMR letters. The transmitter frequency, ω, to obtain resonance is equal to the magnetic-field strength, H, times a nuclear constant, γ, ($\omega = \gamma H$). This relationship holds very precisely, which is important to us. In the magnetic fields that we use for imaging at HMRI (about 3,500 gauss), the resonance frequency for protons in water is 15 MHz.

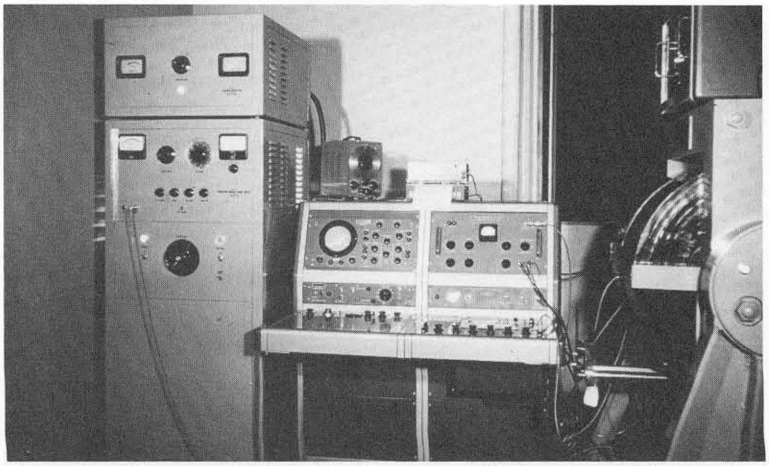
There are many ways to detect NMR signals. For most spectroscopy and imaging, we turn the magnetized nuclei from the favorable state to the unfavorable state by a short burst of energy at the resonance frequency and analyze the change in magnetization as the nuclei return to the favorable state — a process that can take from milliseconds to minutes depending on the kind of magnetic nuclei and the nature of the sample.

The magnets used for whole-body medical imaging must be large enough to accommodate reasonably hefty adults, and it is difficult to fabricate a high-field electromagnet with electrical coils surrounding an iron yoke with the necessary large gap between the pole faces. Superconducting solenoids are particularly useful where we need a large magnet with a high magnetic field. Superconducting magnets most often use coils of niobium-tin wire cooled with liquid helium to 4 K (-450° F). At this temperature, the electrical resistance of the coils drops to zero, and currents induced in the coils will circulate and generate magnetic fields indefinitely, as long as the coils are kept cold.

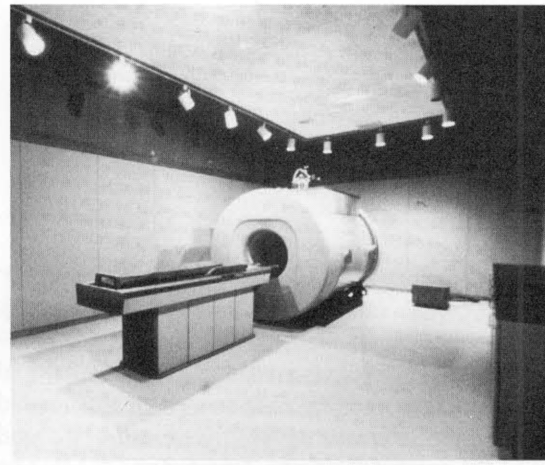
But how can NMR be used for imaging? You can't do it by the ordinary ways in which you see things as the result of diffraction, reflection, and so on, because the radio

Schematic representation of an atomic nucleus surrounded by its electron cloud. Nuclear spin results in generation of a magnetic dipole that can become aligned in an external magnetic field. The size of the nucleus is here greatly exaggerated with respect to the size of the surrounding electron cloud.





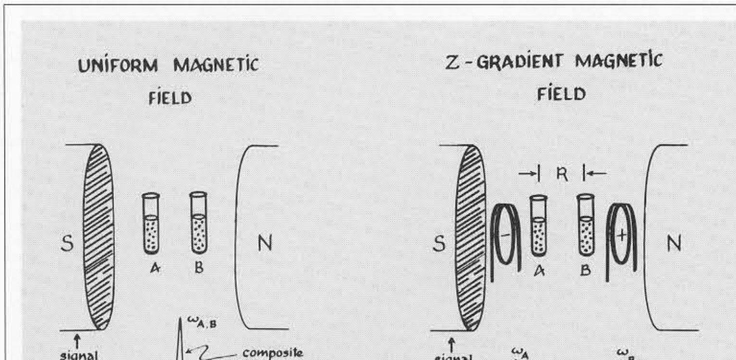
Above: Caltech's first Varian 40-MHz NMR spectrometer installed in 1955.



Above right: Diasonics whole-body proton imaging apparatus at Huntington Medical Research Institutes, operating at 15 MHz with a superconducting magnet (HMRI).

waves we're using in NMR have enormously long wavelengths relative to the 0.5 mm resolution that NMR imagers now routinely achieve. Expecting that radiation with a 20-meter wavelength (corresponding to 15 MHz) could image the brain would be like expecting a toy boat to measurably perturb ocean waves. So the technique must be different from the usual imaging techniques based on light waves, x-rays, or electrons. The key to spatial resolution in NMR imaging is the fact that the resonance frequency is equal to the nuclear constant times the magnetic field. Thus we can control the resonance frequency precisely by controlling the magnetic field.

The use of this relation can be illustrated by resonance signals from two identical water samples. First we put them in a uniform magnetic field. The resonance frequency of both samples will be exactly the same, and so if we do our nuclear resonance experiment, we will get a single composite signal from them. Now, suppose we change the system by having a gradient in the magnetic field such that the field at one sample is different from that at the other. The two samples will then come into resonance at different radio frequencies. If the field gradient is linear and we know how fast it changes with distance, the distance between the samples can be calculated simply by determining the difference in resonance frequencies. If there is a 50-Hz difference in frequency for a particular field gradient with two samples 5 cm apart, then we know that a 100-Hz difference corresponds to samples 10 cm apart.



Below: NMR signals expected from two otherwise identical samples in a uniform magnetic field (left) and a field with a gradient (right). The relation $\omega = \gamma H$ tells us that the signals from the sample will superimpose in the uniform field and will have different frequencies in the gradient field, provided that the gradient is not zero along the line of separation, R, of the samples.

We can actually measure the *x*, *y*, and *z* coordinates of particular volume elements in, say, the brain by using *x*, *y*, and *z* gradients to localize the frequency that comes from that volume element. So the magnetic-field gradients are the keys to getting the spatial information. The way we normally do this in practice is to set up the gradient along one axis and activate the nuclei at the proper frequency for a particular segment of that gradient and then analyze the signals while using additional *x* and *y* gradients during the return of the nuclei to the favorable orientation. This can give us an image of a slice through the subject. We can routinely obtain images for 20 such slices in 4 to 17 minutes. Longer times give better resolution.

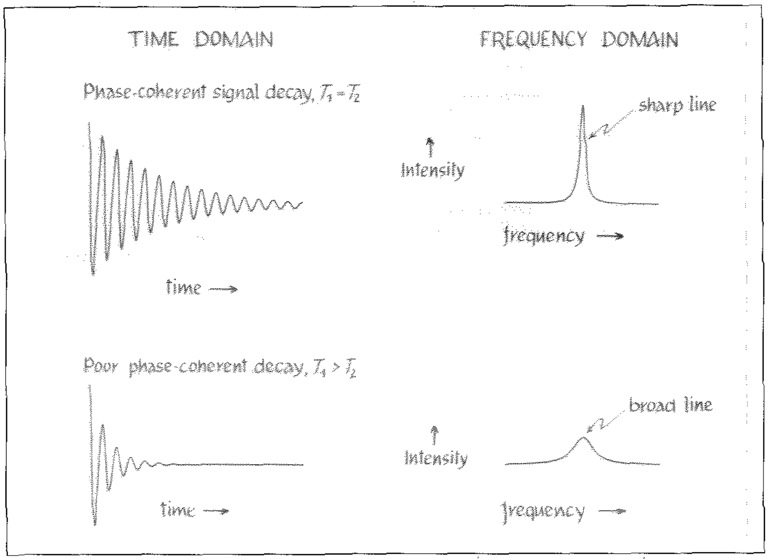
Unlike other imaging techniques, NMR allows us to change the orientation of the slice without moving the patient. By simply applying the gradient in the *x* direction, we can excite the nuclei in slices parallel to the *y-z* plane to get sagittal images (representing vertical slices parallel to a plane through the nose and the back of the head). And by changing the gradient to analyze slices parallel to the *x-z* plane, we can get a coronal image (representing vertical slices through the head parallel to the ear-to-ear plane).

But how do we differentiate between the various kinds of tissue we have after getting distance information? This is vital information for images. We must be able to distinguish between blood, fat, muscle, and so on. This is a more difficult problem, whose solution can be illustrated as follows.

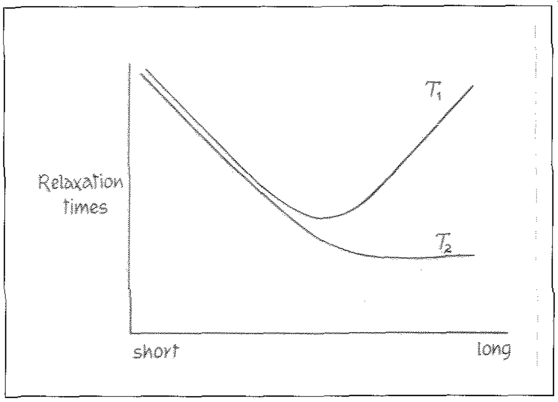
A small volume element, such as a single drop of water in a magnetic field (as in an imager), will contain a given but very large number of magnetized protons. If we hit these protons with a short burst of energy at the right radio frequency, they respond analogously to identical bells hanging in a row from an essentially weightless beam and all set to ringing at once by a hammer blow on the end of the beam. The bells swing together, ring together, and ring down together. There are two aspects of this that are important to note: One is the rate of loss of the energy imparted to the bells when you hit the end of the beam. The other is the rate of decay of the ringing sound. In our nuclear case, the rate of loss of excess energy and the rate of loss of the radio signal are different forms of what is called NMR relaxation.

Now, if our bells are all identical and they are hit so that they swing in unison, we might expect their ringing to decay away at the same rate as the extra energy is lost. This is an ideal case which may not actually happen with real bells or with real nuclei either. The reason is that otherwise identical bells, or identical nuclei, may not be in exactly the same surroundings. In any case, we can differentiate the characteristic time associated with the rate of loss of excess energy (which we call T_1) and the characteristic time associated with the loss of the ringing sound (which we call T_2). The rate of energy loss may be different from the rate of ringing loss if, for any reason, the bells do not ring with exactly the same frequency. Then their rings can interfere with each other, and the ringing signal will disappear before all the energy is lost. We cannot expect that the ringing signal will ever persist after all the extra excitation is lost by relaxation, so T_2 will always be smaller or equal to T_1.

What difference does that make to the nuclei we use in NMR? When T_1 is long *and* equal to T_2 (what we can call phase-coherent signal decay), and we analyze this time-dependent signal decay for its frequency content (Fourier analysis), we get a sharp line. When T_1 is much greater than T_2 (poor phase-coherent decay), that is, the ringing sound goes away much faster than the excitation energy is lost, we get a broader line when we analyze for frequency content. Differences in line width provide us with one way of differentiating between biological materials.



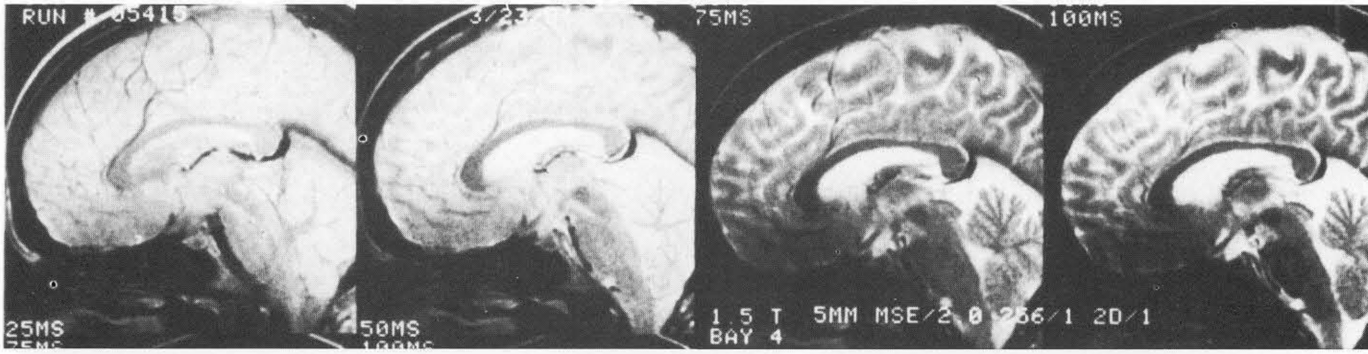
Above: Time domain signal-decay curves in relation to T_1 and T_2. The two decays have the same T_1 but different T_2 values. Analysis of the frequency content (Fourier transform) of the two decays shows a much sharper line in the frequency domain for the longer T_2 value.



Left: Relationship between NMR relaxation times, T_1 and T_2, of molecules in solution with the average times required for molecular reorientation as the result of collisions. Reorientation of large molecules is generally slow and will be further decreased in media that are viscous.

Researchers have found that T_1 and T_2 tend to be more nearly equal when the molecules that make up the material being investigated move quickly with respect to one another — that is, when the material is non-viscous, like water. When the molecules begin to move more slowly, the material becomes viscous (like honey or maple syrup), and T_1 and T_2 values both become smaller and begin to diverge from one another. Surprisingly, with some very viscous materials present in the body, we find that T_1 goes through a minimum and starts to become larger, while T_2 continues to decrease with increases in viscosity.

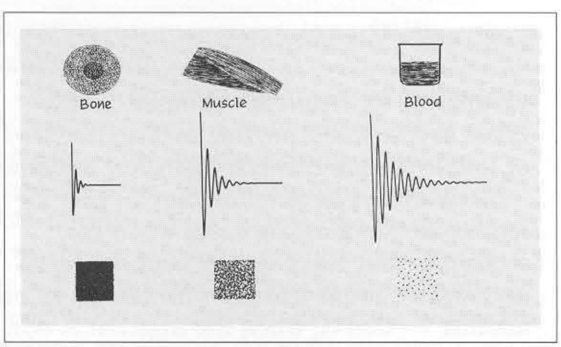
Several factors determine the strength of NMR resonance signals of protons. Obviously, the more protons you have, the stronger the signal will be. Biological materials such as blood, cerebrospinal fluid, fat, muscle, brain white and gray matter, and bone have different proton contents. Bone has the smallest, with blood, muscle, fat, and



Sagittal brain images as a function of time allowed for relaxation; here, differences arising from T_2 are emphasized over the range 25-100 milliseconds (GE).

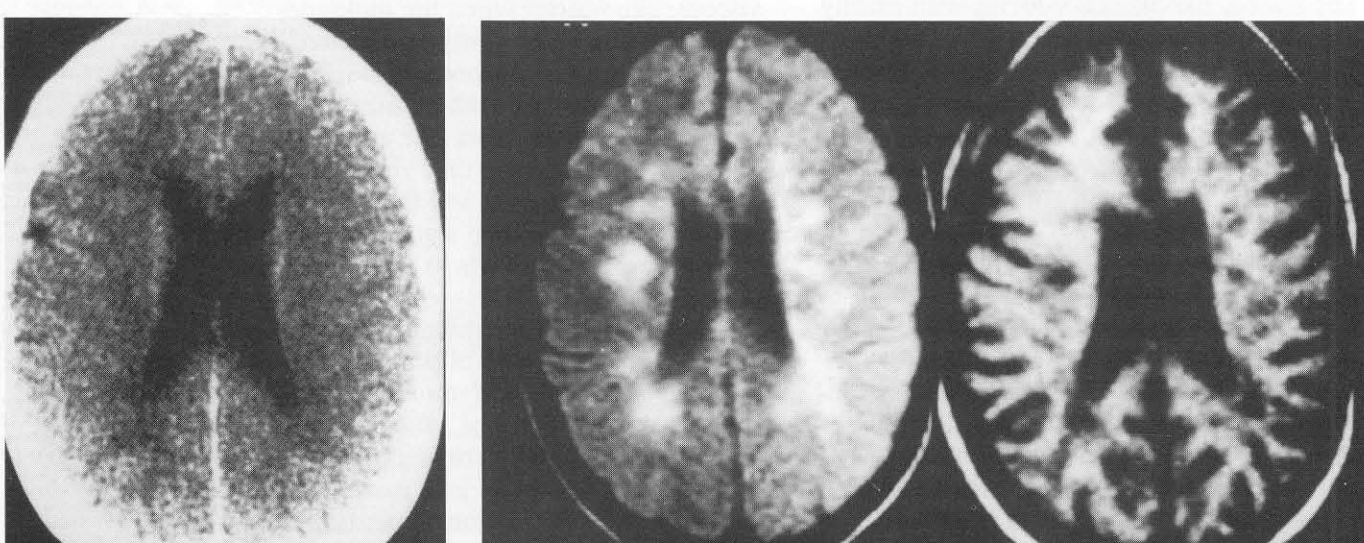
cerebrospinal fluid having increased amounts in that order. The T_1 and T_2 values are also very different for these materials, so we can use T_1, T_2, proton content, or combinations of these to establish a contrast scale. For clinical purposes, a combination of proton content and T_2 is most often used.

To illustrate how this works, let's consider bone, which has little water in it, so it's not going to give a very strong proton signal. Further, it has short T_2 values, so the resonance signal will decay away rather quickly. The signal from bone will therefore be weak and fast decaying. So, if we sample the signal from bone at different periods after the initial excitation pulse, it will always be weak. We can color such weak signals as black or very dark gray. Muscle has many more protons per unit volume and longer T_2 values, so it will give a stronger signal that decays more slowly than that of bone. We could assign medium gray to muscle and light gray to blood, which will also have a strong signal with an even slower decay.

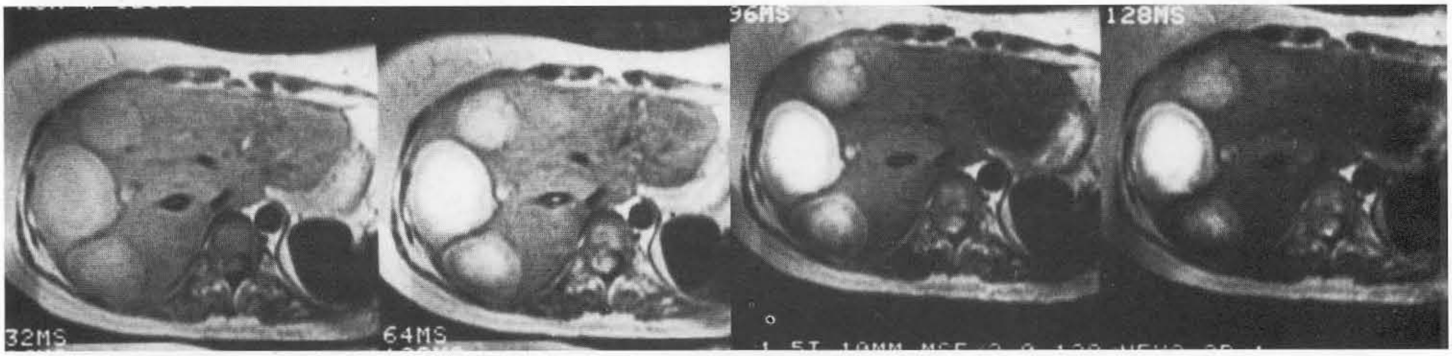


Right: NMR signal intensities and relaxations to provide a contrast scale for bone, muscle, and blood.

We can see in the illustrations above the remarkable difference in contrast in brain images as a function of time. The images correspond to different decay times for sagittal slices ranging from 25 to 100 milliseconds after the original excitation pulse. In the areas that remain light, the protons are losing the "ringing" very slowly. Others (the darker areas) lose the major part of it more rapidly. The overall signals are decreasing in intensity all the while, but each of these pictures has been brought up to the same average intensity by turning up the brightness as one might do on a TV set. At the outset, only a small fraction of the signals has decayed, and there's not much differentiation between the tissues on the basis of the differing T_2 values. However, as time unfolds, large differences develop because the signal from some of the materials decays much more rapidly than others. Rapid decay produces the dark areas;



Below: CT (x-ray) section (left) of patient suffering from multiple sclerosis compared with transaxial NMR images, T_2 (center) and T_1 (right) (HMRI).



Section through the body, showing how a cancerous growth in the liver becomes prominent in the image as more time is allowed for relaxation. The range is 32-128 milliseconds (GE).

slow decay produces areas that remain bright.

A comparison between CT (x-ray) and NMR scans of a patient with multiple sclerosis shows that the x-ray image provides relatively little differentiation between different areas of the brain. But in the T_2 and T_1 images of the same patient you can see some marked white areas. These are demyelinated areas, where the insulation (myelin) covering the nerves has decomposed with a consequent increase in water content and T_2 values. The way in which the abnormal areas stand out makes the NMR scan favored in this case.

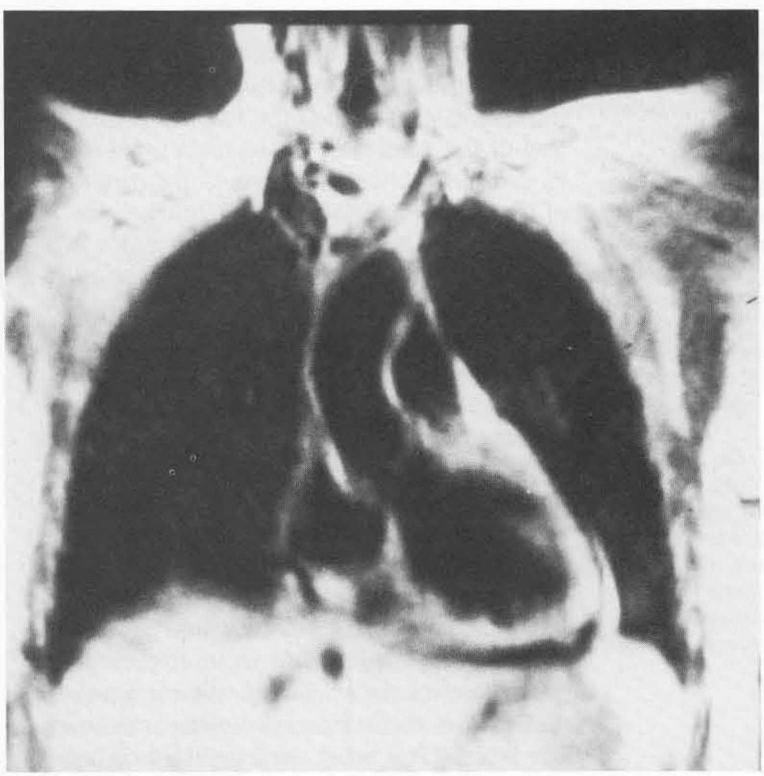
Of particular interest is the fact that the water (proton) content, T_1, and T_2 values of cancerous tissues are, in general, substantially greater than those of normal tissue. By delaying the observation time and allowing the T_2 effect to become more prominent, cancerous tissue in, say, the liver, stands out very brightly, as shown in the illustration above.

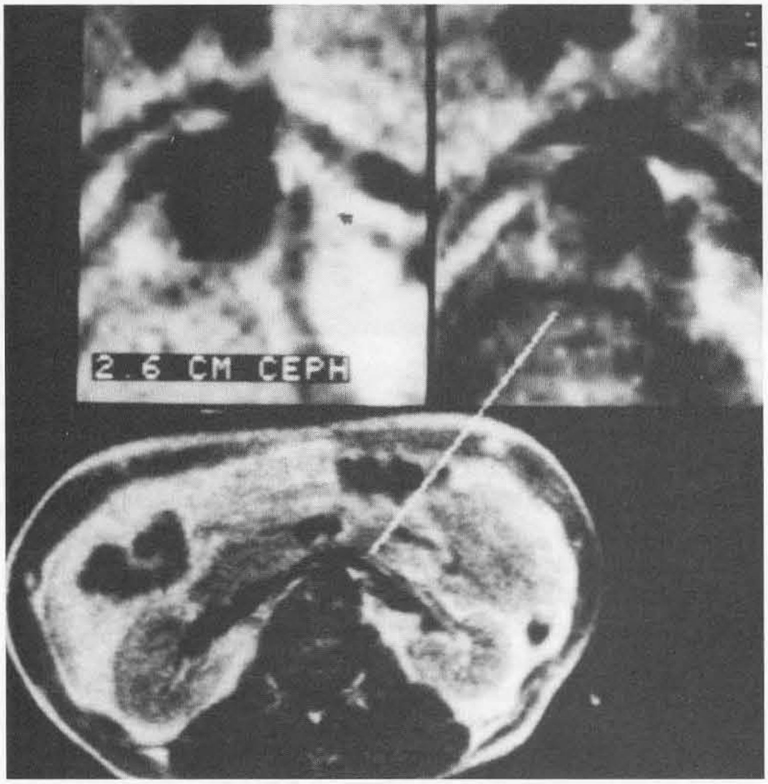
In just the last few years, remarkable NMR pictures have been made of the heart. The heart is a very difficult organ to image by either NMR or x-rays, because it pulsates and therefore needs relatively short exposure times to give unblurred pictures. Unfortunately, NMR is not exactly a 1000-speed film; it's more like a relatively slow film, and so we have to repeat our snapshots many times and then add them together to get a useful picture. Thus we need to start the excitation pulse and the analysis period at particular times in the heart cycle. Proceeding in this way, we can make images of the heart at different parts of that cycle.

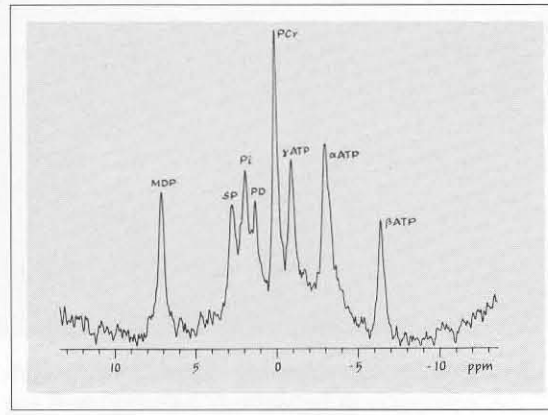
NMR techniques do very nicely for noninvasive measurements of the diameter of the aorta and for detecting deposits of cholesterol and lipids associated with hardening of the arteries. Dr. Bradley of HMRI has made some important studies on the use of NMR to investigate blood flow. Earlier we indicated that blood should have a contrast of light gray in NMR imaging. But in the image of the aorta on the following page it shows as black. Why would this be? Remember that, when we start at time zero, we use a gradient and are able to pulse the protons in a particular plane or slice of the body a few millimeters thick. So in a midriff cross-section, we pulse only the blood that is in that aorta slice at the particular time. When we analyze the signal from the protons in the same aorta slice some 28 milliseconds later, the blood we magnetized earlier has already moved farther down, wholly out of the slice. It has been replaced by magnetically unexcited blood, which of course gives no NMR signal and hence comes out black in the image. This way of analyzing blood flow can detect turbulence in flow and has very general potential for analysis of the mixing of liquids.

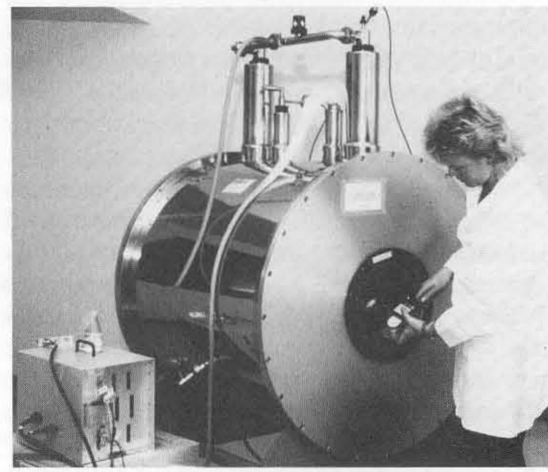
Still another burgeoning application of NMR is the study of metabolism. Dr. Dominique Freeman, a Boswell Postdoctoral Fel-

Images made during different parts of the heart cycle by having the NMR excitation pulse synchronized to particular parts of the EKG waveforms (GE).









Above: Midriff section showing aorta (at ends of white line, enlargement upper right) with blood appearing black as the result of flow. The light gray area visible in the aorta between 7 and 10 o'clock at the upper right is a deposit of fatty matter characteristic of atherosclerosis. The inset at upper left is taken further down the aorta, and here the deposits are essentially absent (HMRI).

Top right: Phosphorus NMR spectrum of a living rabbit heart. The key resonances for energy metabolism are the three α, β, and γ peaks of adenosine triphosphate (αATP, βATP, γATP) and the single peaks of phosphocreatine (PCr) and inorganic phosphate (P_i).

Bottom right: Dr. Dominique Freeman arranging for a phosphorus NMR spectrum in a high-field, large-bore superconducting magnet system made by General Electric and set up at the Huntington Medical Research Institutes.

low at Caltech, and Harold Mayr from the University of Vienna are working at HMRI in collaboration with Dr. Richard Bing, studying the metabolism of phosphorus, rather than protons, in a living rabbit heart. The phosphorus NMR spectrum (shown above, right) from such a heart has several interesting features. The spectrum is complex, but we can see three different resonance peaks coming from the three different phosphate atoms of the molecule ATP (adenosine triphosphate), which is the fuel for contraction of the muscle in the heart; a peak from P_i, inorganic phosphate, one of the products of the reaction of the muscle contractions produced by the ATP; and a peak from PCr (phosphocreatine), which brings the phosphorus into the heart muscle in the proper form to be easily converted to ATP.

We can study a heart with diseased muscle under stress and see how the concentrations of these metabolites change in comparison with normal heart muscle. Then, when the stress is removed, we can then see how fast the recovery to unstressed conditions occurs. Many people have serious problems in regenerating the proper balance of phosphorus metabolites after periods of stress.

In principle, we could make images of brain slices to determine the distribution of ATP within the brain and also determine how fast this ATP is being used up. This is still beyond the reach of current technology — but not far out of reach. It's very tantalizing. The problem is that phosphorus is 10,000 times more difficult to detect in living tissue than protons. For one thing, the concentration of phosphorus is much lower than the concentration of protons in living tissues. Also, phosphorus has a smaller resonance frequency, and its nuclei are not as favorable to observe as protons.

The uses of NMR in biology and medicine offer a most fertile field of research. Caltech has been very much in the forefront of chemical NMR in the past. Now there's a wonderful opportunity for collaborative work between Caltech and HMRI on these exciting new processes, and we should take full advantage of it. Some years ago, during Harold Brown's presidency, Caltech considered starting a medical school but decided not to proceed for a number of good reasons. Collaborative work with HMRI would give Caltech the opportunity to become involved in various aspects of medical research without the problems of running a medical school. NMR is just one of the several possible attractive modes of present and future collaboration to the benefit of each institution. □

Taylor Wang adapts to weightlessness inside the Spacelab. With gravity reduced, legs no longer are needed to get around, faces change shape and feel different, and time must be taken to forget a lifetime on the earth's surface.

A Scientist in Space

by Taylor Wang

WHY DOES A SCIENTIST want to go into space? Scientists have one fatal flaw — they're obsessed by their experiments. And I'm no exception to that; I will even go out of this world to do my experiment.

Space has one thing to offer that you cannot get anywhere else — extended zero gravity. One type of experiment that takes full advantage of zero gravity is what we call containerless experiments, and this is what I happen to be interested in. Now for the first time you can do an experiment without a container — you can leave the thing in mid-air and take your hands off. In the laboratory when you do this the sample will start dropping; it will hit the ground in less than a second, and the experiment's over. So if you want to do anything, you have to do it fast or you don't do it at all.

The particular experiment that I'm interested in is called equilibrium shapes of the dynamics of a rotating and oscillating drop. It requires about 30 minutes of zero gravity because everything has to be very slow moving; it's always in an equilibrium state, a quasi-static condition. You can do it on an airplane, flying up and down like a rollercoaster, with the plane essentially flying in formation with the experiment package, which is free floating inside it. If the pilot or the weather isn't so good, the package will bounce around inside like a Ping-Pong ball, and you will have lost your lunch for nothing. Unfortunately, on an airplane zero gravity can last only about 20 seconds. You can make it last a little bit longer, but by that time you will have dived into the ground. I'm not sure I want to go that far yet.

Or you can use a drop tower. You could dig a very deep hole, say, all the way to China, and in principle you could get about 30 minutes experiment time. I don't think the two countries are that friendly to each other yet. So the only option to do the experiment is to go into space.

I'm really looking at two experiments. Investigating the equilibrium shapes of a rotating spheroid is one of them. This is actually a very old experiment, going back 300 years. Newton, looking at the equilibrium shape of the earth, was the first to pose this question. And lots of calculations have been done since then but there hasn't been a single definitive experiment to verify the theory. The second experiment is on large-amplitude oscillations of drops, and this calculation is about 100 years old. (I only do old experiments.) Both these experiments require an extended gravity-free environment. It is not that they have been waiting for me all this time; it just so happened that the space environment was not available until now. I have been interested in this area for a long time, and I was fortunate to be in the right place at the right time when the space opportunity turned up.

When you rotate a drop, you start from a perfect sphere. As it rotates, it goes to an axysymmetric shape, a little flat at both poles. But once you get to a certain point, the so-called bifurcation point, the axysymmetric shape is no longer stable, and it goes to a non-axysymmetric shape. We are trying to understand what this bifurcation point is. Everybody accepts it because a lot of people have calculated it. In fact, almost every mathematician at one time or another has done some calculations on the bifurcation point. So the point itself is very well defined. The question we're concerned with involves the stability of various shapes, how they behave to one another, and how the system works dynamically.

In the large-amplitude oscillation experiment, we stimulate a droplet and it goes into various oscillation modes. If you introduce a larger amplitude, the drop not only goes into oscillation but into a fission process. Now, you may ask the question: If this is a containerless experiment and you're not touching it, how do you stimulate the drop? There are many ways you can do it, for example, with an electric or a magnetic field. We use an acoustic field, which causes less perturbation to the droplet. We create a potential well, which is almost like a bag to hold the drop. Since we can control the frequency and the beating, as well as modulation and amplitude, I can make the drop do what I tell it to do — rotate, or oscillate, or change its shape, or move around, or sit someplace. The acoustic field gives me a great deal of freedom to do what I want with the sample, but yet not touch it.

After NASA accepted our proposal in 1974, we started to develop the experimental hardware, which we finished in 1980. Now, during all that time it never occurred to me that I might actually conduct the experiment in person. But in 1982 NASA started thinking about the crew for the Spacelab 3 mission, for which our experiment was scheduled, and asked the question: Is it better to train a career astronaut as a scientist or to train a career scientist as an astronaut? NASA headquarters finally opted for the latter, since this mission would be primarily science oriented.

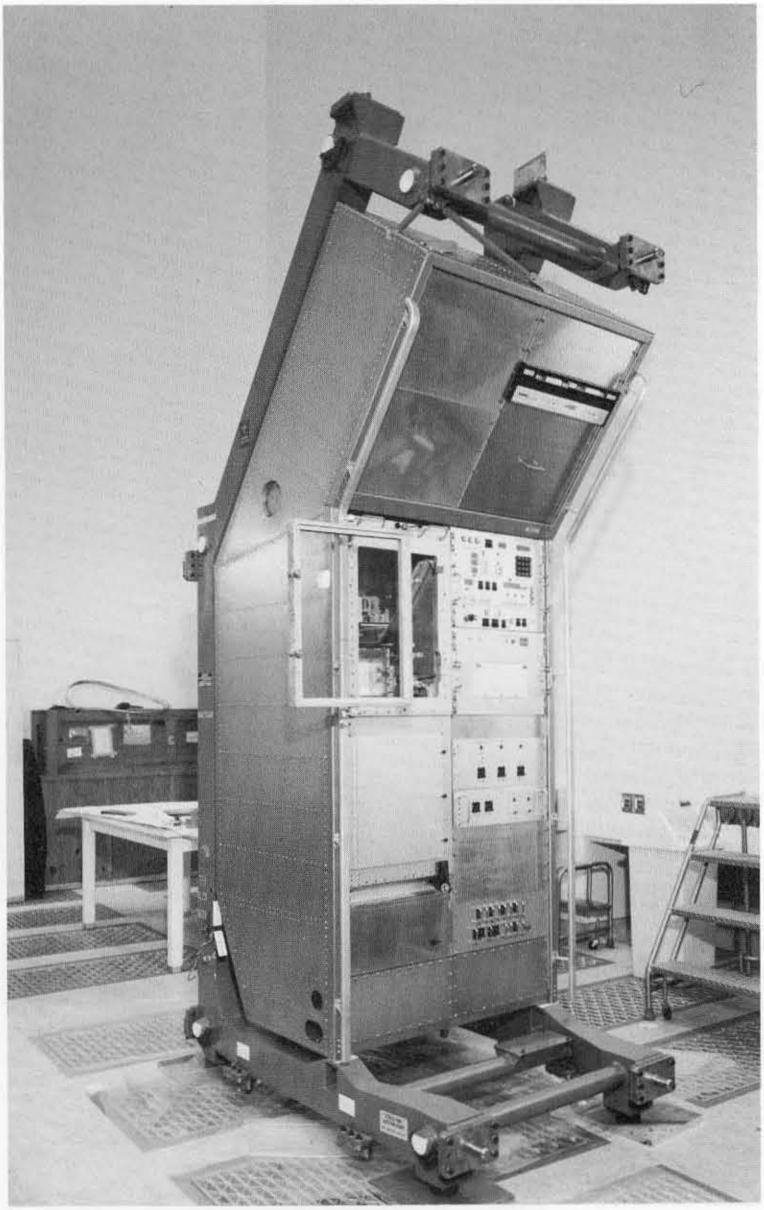
So NASA announced an open selection for scientists to train as astronauts, and I put my name in. I didn't think I would get selected, but I thought I could at least establish a bottom line. For a potential astronaut you couldn't get much worse than me.

I still haven't figured out why they chose me as one of the four candidates. But since they did, I wasn't going to make a big fuss out of it. The others include Eugene Trinh, a fluid dynamicist, also at JPL by way of Yale; Lodewijk van den Berg, a materials scientist from the Netherlands; and Mary Helen Johnston from the Marshall Space Flight Center; she's also a materials scientist at the University of Florida.

Since we had to be full-fledged members of the flight crew, that is, we had to carry our own load, the training (which consisted of four components) was quite rigorous. The first component is scientific training, that is, we are trained to conduct other people's experiments, not just our own. There were 14 experiments on the flight, covering many disciplines that we had to learn something about. It's very interesting because we normally wouldn't have a chance to be exposed to some of these things — life science, materials science, fluid mechanics, astrophysics, atmospheric science, and so on.

The second component of the training involves adaptation training. Going into space often causes problems with so-called "space adaptation syndrome," which is sort of like car sickness. NASA is very concerned about this because, with a limited number of crew members, each with his own assignments, if some members get too sick to function, the others will have to pick up the slack. And since we are very busy, this is difficult to do. Even worse is what could happen when some individuals become irritable when they feel physically uncomfortable. If some large, strong individual decides to pick a fight, we might be in trouble — maybe not even coming back.

Unfortunately there's no way to determine who will and who won't get sick, so NASA has a rather different screening process — they make everyone sick. And then they observe us to see if we can still function. They blindfold you and stick electrodes all over you (they want to find out everything about you, more than you care for them to know), put you in this thing that they rotate at a rapid speed, changing speed just for fun. They also make you do head movements. When you just sit there it's no problem, but once they make you move your head, you start to feel the sensation. After you've gotten to the stage where they want you, they make you do things to see whether you can still obey orders and do things in the proper order.

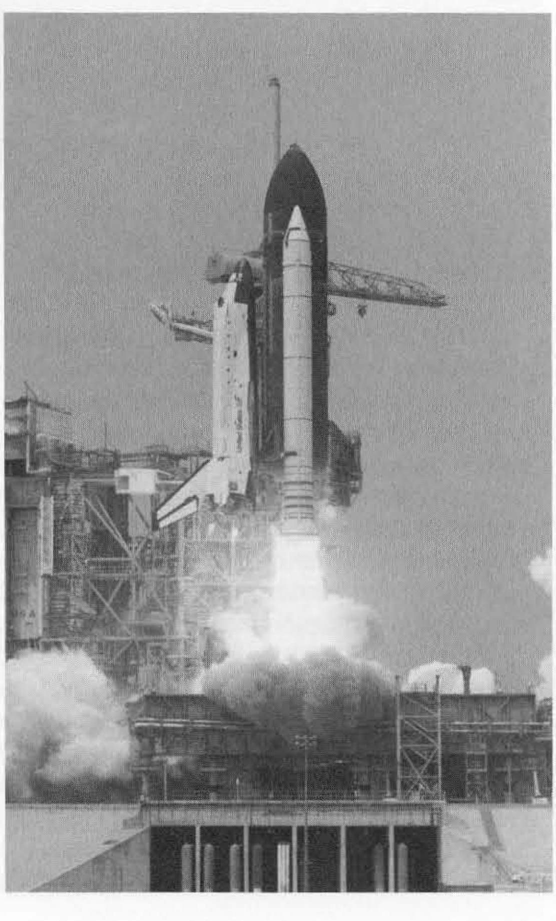


After fabrication and testing at JPL, the Drop Dynamics Module (DDM), for the study of free liquid drops, awaits the Spacelab 3 mission.

If that doesn't get you, they put you in a small room, called an elevator, and after checking whether you have claustrophobia or not, they close it up. The elevator goes up and down and twists and turns and yaws and does whatever is necessary to guarantee that you will have space adaptation syndrome. Then there's further testing. None of us is very belligerent, and we all survived. I didn't exactly enjoy it, but I survived.

The third component involved space shuttle training — familiarizing ourselves with the whole spacecraft. There are about 4,000 switches and 6 computers on the spacecraft. We are supposed to know what all the switches are for —so in case the five career astronauts all die on me, I can bring the spacecraft back. But it's mainly to train us

Several hours before liftoff, the astronauts don their suits and helmets in the "white room" at the launch pad. After entering the shuttle and strapping themselves in, the payload specialists relax for two hours while the flight and ground crews prepare for liftoff.



The ultimate E-ticket ride — liftoff of the Space Shuttle Challenger on April 29, 1985 carrying Spacelab 3 into orbit for a week of scientific investigations.

not to panic when the alarms go off and the lights start flashing.

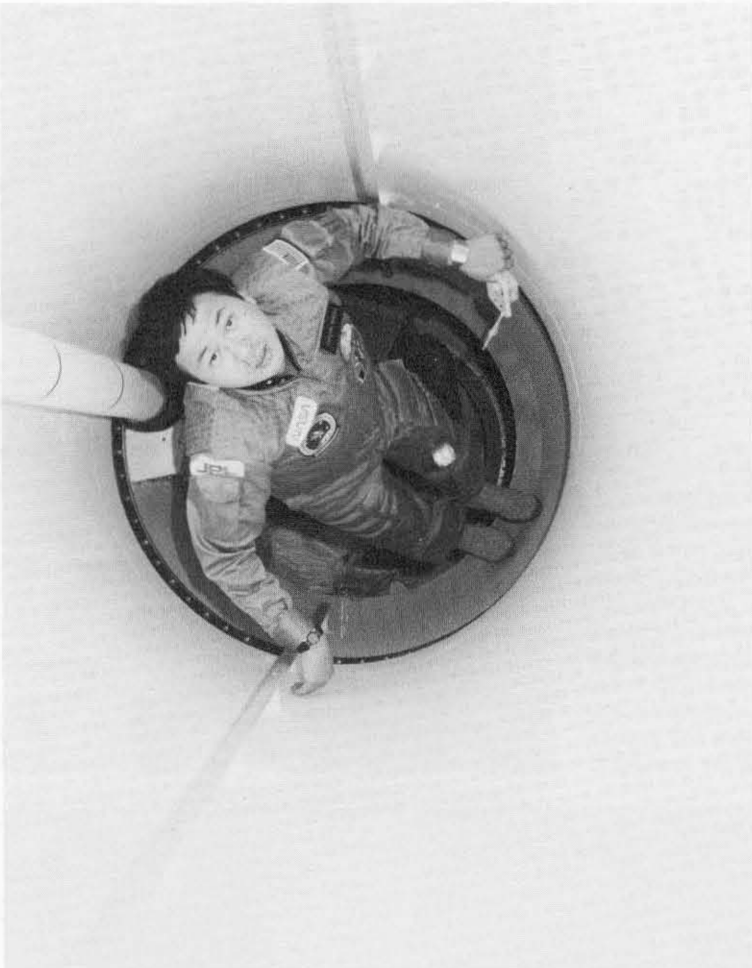
Survival training was the fourth category. Before launch the spacecraft is strapped to two of the biggest sticks of dynamite that this country ever built. And if those two sticks of dynamite don't work quite right, especially just before launch, there will be nothing left within 10 miles. And so just in case (they keep on emphasizing that point — "just in case") there's some malfunction, the rocket is about to go off, everybody else is long gone, and you are stuck inside the spacecraft, you will know what to do. Essentially what they want us to do is try to get the hell out of there. We're supposed to take a crowbar and pry open a panel above the pilot's seat, press a switch to blow out the window, releasing seven steel cables. We're supposed to climb out the window, grab onto the steel cable and slide all the way down (the spacecraft is about 10 stories high) and run like hell to a bunker 500 yards away. And if we can get into the bunker, we might survive. We've got to do all that in about 10 seconds flat. Well, they told us that we will probably be able to run a lot faster than normal in this situation.

Another aspect of survival training involves what happens if the spacecraft takes off properly but doesn't have enough thrust to go into orbit and has to ditch in the ocean. What do you do? You open the hatch and inflate the lifecraft underneath it, push it out, jump into it, and paddle away and watch the spacecraft (now literally a spaceship) sink. It's not really a spaceship, either, but a space-submarine, because when it gets on water, it dives like crazy. You have again about 10 seconds to do all this.

In September 1984 NASA finally picked the crew members for our particular flight. They included Bob Overmyer, commander of the flight, and Fred Gregory, the pilot. (Overmyer was really the pilot and Gregory the copilot, but in NASA everybody has higher titles.) The Spacelab engineer was Don Lind, and Norm Thagard was the space shuttle engineer. Bill Thornton was the physician, who doubled as zookeeper for the 12 rats and 2 monkeys on the flight. And Lodewijk van den Berg was the other payload specialist or astronaut scientist.

From the time the crew was selected, the seven of us trained as a unit. We not only trained in the four categories mentioned earlier, refreshing them, but we also started to train as a unit to back each other up, just in case one or two of us became incapacitated. And we learned to live with each other's idiosyncrasies, since we would be living in very cramped quarters on the mission. Fortunately we got along well; at least we didn't have any open fights. During this nine-month period we saw each other more than we saw our families. After nine months we finally got tired of each other, and fortunately NASA got tired of us too and told us to go ahead with it.

For the last 10 days before the flight we were in the crew quarters, stuck together without seeing many other people. And we were watched and examined continuously. Just before launch we leave the crew quarters and go into what we call the "white room," right outside the spacecraft. Three volunteers are there — the only people besides us within 10 miles. This is the place to take care of last minute things — body functions, insurance payments, or religious services. And this is the place where, if you change your mind, you still have a chance to get off. But if you don't change your mind, they put this suit on you and send you off, and then they run like hell. Then you are inside, and they are gone; the towers have disappeared on you, and even if you want to change your mind, it's too late.



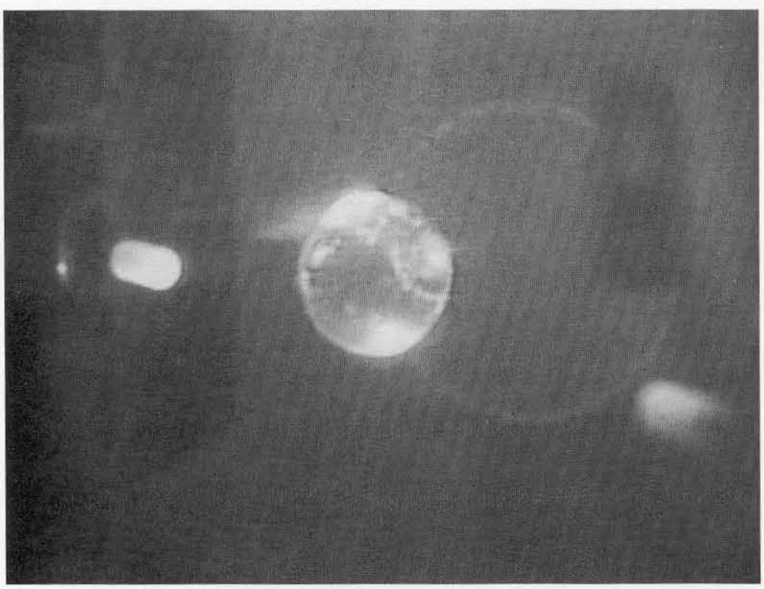
Wang floats through the tunnel connecting Spacelab 3's module to the mid deck of the shuttle.

Fortunately it was a very good launch. The countdown was smooth; there were no hangups or delays. It took about two hours for the spacecraft to get into stable orbit. When you first get in orbit and experience zero gravity, something very interesting happens. For the first time in your life your body says, "I don't need my legs." And so the brain says, "Since I have no need for the legs, let's shrink them." And your legs actually do shrink about an inch in diameter very quickly.

If your legs shrink, where does the excess go? It goes right to your face, and we all had this sort of chipmunk look. It's rather uncomfortable but of short duration, because the face is telling the brain, "I don't want this stuff either; would you get rid of it"? And what happens is that you start to discharge it outside your body. The only problem is that there are seven of us and only one waste management system.

It didn't take too long to adjust to zero gravity, and then we were ready to go into the Spacelab to start work. In the Spacelab

Right: Wang conducts an experiment involving a one-inch drop, visible in the chamber of the Drop Dynamics Module. The DDM uses sound to position and manipulate the drop without any physical contact. The image below is not actually a drop but a one-inch ball used for calibration of the instrument.



everything worked well except one thing — my experiment. I started to turn on the experiment the second day, and it didn't work. Normally when that happens you have to forfeit it, beause it's very difficult to repair an experiment in space. You can't take things apart and put them someplace, because there's no place to put them. And you don't have many tools; all I had was a voltmeter and a couple of screwdrivers. Also, you can't drive the spacecraft to some supply depot to pick up replacement parts.

Because we had a so-called payload specialist (me) on this flight, however, we were given the opportunity to try. Since I could not take the experiment out, the best way to do it was to go inside the experiment. So I lived inside that instrument for two and a half days. During that time all my colleagues could see of my anatomy was my leg. I took the whole instrument apart from the back, trouble shooting line by line, point by point. Although there wasn't a high probability of fixing it, with good support from my team on the ground we were able to discover the problem and find a way around it. We actually did a bypass surgery. Perhaps this provided a justification for NASA's decision to train scientists as astronauts; when experiments don't work out as expected, a trained scientist may be able to react to solve the problems.

I'd like to emphasize the teamwork on these missions. There were about 300 individuals at the Johnson Space Center in Houston supporting our flight. And I had nine people just on my experiment team, working all the time I was working and working even when I got to rest. Arvid Croonquist and Eugene Trinh deserve a lot of credit. I don't think they slept the entire time, to be sure to be there when I needed help.

The best time of the flight for me was when I started to do my experiment. Normally we are supposed to work only 12 hours a day, but in reality we worked about 15-16 hours. Time is such a precious thing in flight that every single second counts. You can always do other things later. So even though I lost two and a half days, I was able to recoup most of the things that I wanted to do by working longer hours.

What the experiment did was spin out a drop, bifurcate, and then become axysymmetric again, and bifurcate again, and so on, again and again to confirm the theory. As I mentioned earlier, this theory has been around for many years, and we didn't expect anything to deviate from the calculations of the bifurcation point, because that's essentially a universal given. And in the axysymmetric shape region it behaved very nicely. But once it actually got to the bifurcation point, it deviated from the theory quite a bit. This was a surprise to us; we didn't think this was in dispute. In fact, when we took it further, to the fission point, we found that the fission point does agree with theory, but the shapes are quite different. Now, I always like this sort of outcome, because I can tell my theoretician friends that they're not as good as they think they are.

People always ask the question: what is it like in space? For one thing, there's no up and no down. So you can live on any of the six surfaces. When we started out, the spacecraft was pretty cramped for all seven of us. But once you get into space, you find that you don't have to live on the floor; you can live off the ceiling, or you can live off the wall, so the spacecraft becomes very spacious. I picked the ceiling for my home base since I spent two and a half days working upside down anyway and was used to it.

In space you can really fly. If you want to go someplace, you don't walk, you just tap your finger in one place and you fly over. Not everything is positive; for example, writing is difficult, but you learn to adjust to these things. The human body is a very adaptive system, and it takes only about a day or two to adjust to the space environment. From that point on you feel quite comfortable in space.

What do we eat in space? A typical menu would consist of dehydrated meat and vegetables. This is a meal you could eat if you had a good appetite. But in space, even if you're not sick, you really don't feel that great. So most of us didn't really eat the whole thing. I brought some Chinese tea along, and that's the one thing that kept me going most of the time — a cup of tea and some nuts. When I came home I had lost about four and a half lbs., and that's quite typical. (We also gain about one and a half inches in height.) One person on our flight, however, had a great appetite. Whatever the rest of us didn't eat, he finished. And when he came back, he had actually gained five lbs. That made NASA history.

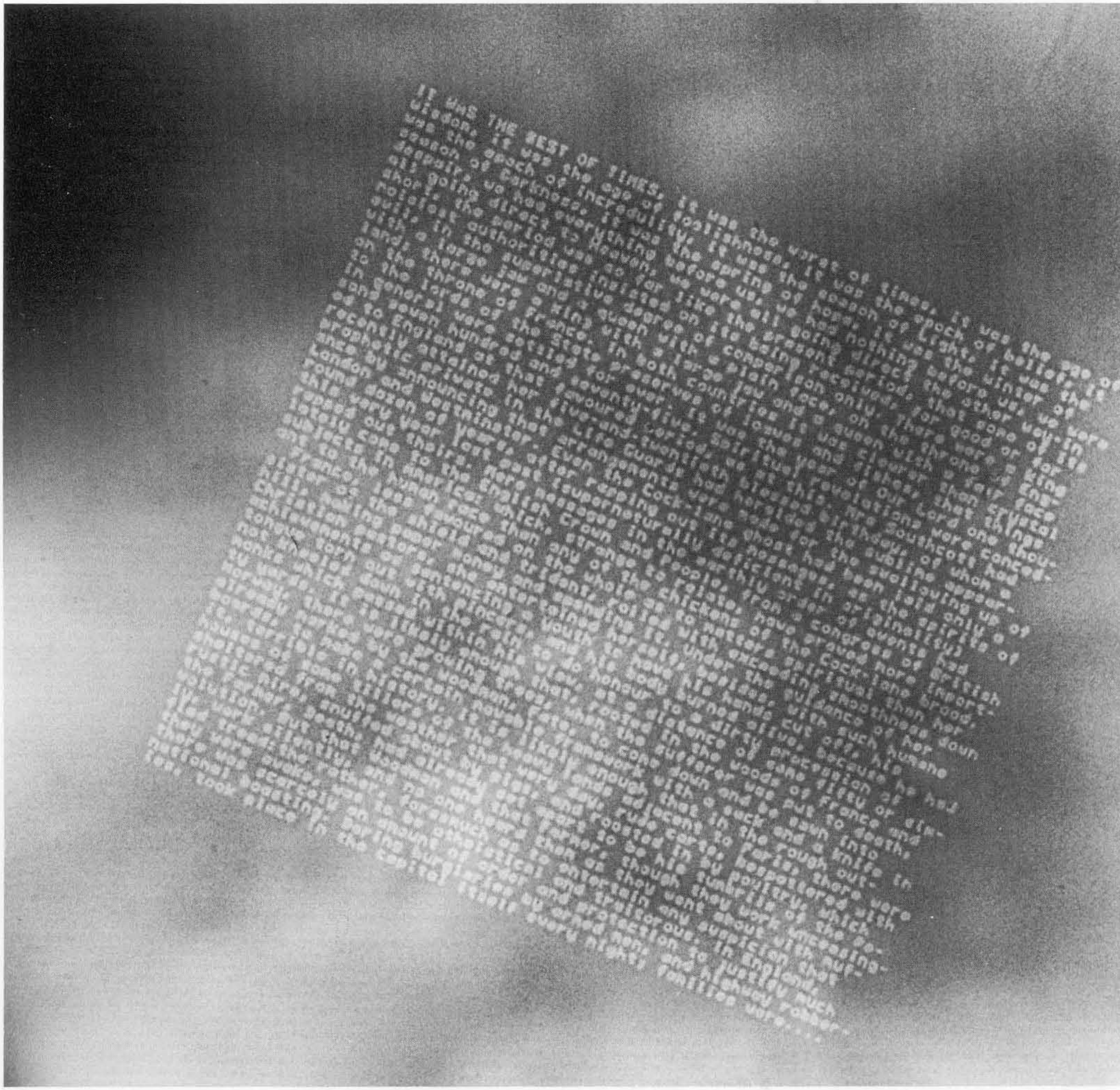
How do we eat in space? There are two ways. If you want to do it the way you would usually eat on earth, you have to move the food toward your mouth at a very slow pace, so the food won't leave the spoon or fork and land someplace that you don't want it to. Or, rather than bringing the food to your mouth, you can leave the food in mid-air and take your mouth to it. That works pretty well unless a colleague gets his mouth to your food before you do.

Putting on clothes in space is also different from on earth. You don't put them on one foot at a time, but two feet at a time, two arms at a time. Because the clothes spring out and take their own form, you don't really put them on at all; you just wiggle yourself in.

When you sleep, you don't lie on something — you just float. So when you're tired you just close your eyes and you can go to sleep wherever you want to. It's very comfortable. The only trouble is that sometimes you float too far and drift into your friends.

At the end of the sixth day and the seventh day, when the experiments were all done, we closed the laboratory and for the first time had time to be tourists. We were given about six hours to look out the window and see the earth and take pictures. Flying at a speed of Mach 25, we went around the earth every 90 minutes. Every 45 minutes we got a sunrise; every 45 minutes we got a sunset. We flew over familiar places and some not so familiar. I especially enjoyed seeing San Francisco, Los Angeles, and Shanghai, where I grew up. Viewing the earth from this perspective gave us a strange feeling. From space we can see that the earth is very beautiful and that all of us are very fragile.

When the tourist season was over, we had to come home. After flying around the earth 110 times (2.5 million miles), we landed at Edwards Air Force Base, and the pilot (the commander) put his front wheel right on the yellow line of the runway. We were quite pleased with ourselves. We had a very good flight and accomplished what we set out to do. □


IT WAS THE BEST OF TIMES,

Tiny *Tale* Gets Grand

THE CHALLENGE HAD STOOD for 26 years: "It is my intention to offer a prize of $1,000 to the first guy who can take the information on the page of a book and put it on an area 1/25,000 smaller in linear scale in such manner that it can be read by an electron microscope."

Richard P. Feynman, the Richard Chace Tolman Professor of Theoretical Physics, announced this offer at the American Physical Society's annual meeting at Caltech. It came at the end of his talk, "There's Plenty of Room at the Bottom," discussing the "problem of manipulating and controlling things on a small scale." The talk, and the challenge, were published in the February 1960 issue of *Engineering & Science.*

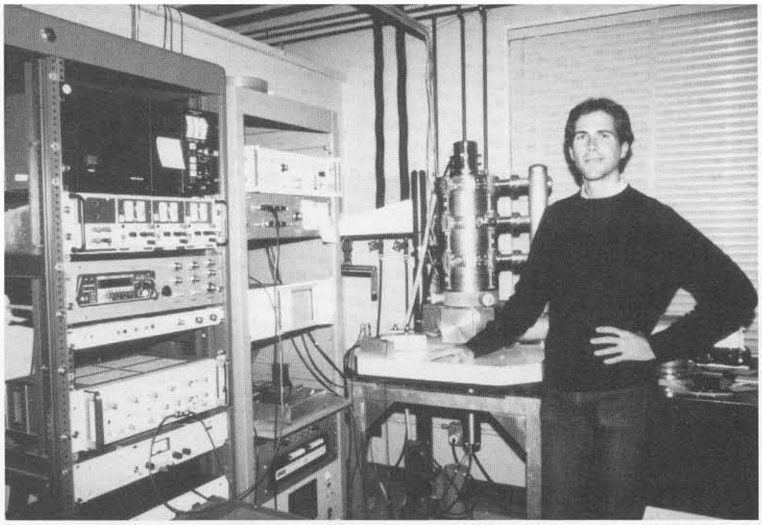
Tom Newman was three years old at the time and not in any hurry. In November 1985 Newman, a Stanford grad student in electrical engineering, collected the $1,000 prize with the evidence shown opposite — the opening page of *A Tale of Two Cities* reduced to an area 5.9 × 5.9 micrometers and magnified back to legible size by an electron microscope.

In his letter to Newman accompanying the check, Feynman wrote: "Congratulations to you and your colleagues. You have certainly satisfied my idea of what I wanted to give a prize for. Others have apparently made as small or smaller marks, but no one tried to print an entire page. And on a 512 × 512 dot printer! Each dot is only about 60 atoms on a side. I can't quite manage to imagine the square 1/160 mm on a side onto which all that is printed. It would be 20 times too small on a side to see with the naked eye. Only 10 wavelengths of light. The entire Encyclopaedia Brittanica, perhaps 50,000 to 100,000 pages of your size would be on less than 2 mm on a side — the head of a small plain pin."

The idea of writing the entire 24 volumes of the Enclyclopaedia Britannica on the head of a pin (and all the books in the world on an area of about three square yards) figured prominently in Feynman's original article, which not only prophesied that such fine writing could be done but also described how to do it.

"A simpler way might be this (though I am not sure it would work): We take light and, through an optical microscope running backwards, we focus it onto a very small photoelectric screen. Then electrons come away from the screen where the light is shining. These electrons are focused down in size by the electron microscope lenses to impinge directly upon the surface of the metal. Will such a beam etch away the metal if it is run long enough? I don't know."

A few months after Feynman's speech, researchers in Germany actually did use an electron beam for fine writing. Newman, who also used an electron beam to etch the prizewinning page, considers Feynman a "visionary" for having had such foresight.



Tom Newman poses with his electron beam lithography equipment.

Feynman offered another prize in 1960 for a rotating electric motor, 1/64th inch cubed. That one was claimed in the same year by William McLellan (Caltech BS 1950), who had spent 2½ months of lunch hours building it with the help of a microscope, a watchmaker's lathe, and a toothpick. It is enshrined on permanent display in East Bridge and is a standard stop on campus tours. Although the article had stated only Feynman's *intention* of offering a prize, and not actually an offer of one, and although McLellan had done it for the challenge of the problem and not for the money, Feynman's conscience began to bother him and he coughed up the $1,000 after all. But the December 1960 *E&S* carrying the news of McLellan's victory, also took note of Feynman's "worried thoughts."

"Daily, he expects to meet the man who has accomplished this spectacular feat. And, daily, the thought haunts him — because, in the meantime, Feynman has been married, bought a house and, what with one thing and another, hasn't *got* another spare $1,000.

"This, then, is a public appeal by *Engineering and Science*, to all inventors, who are now at work trying to write small and collect the Second Feynman Prize — TAKE YOUR TIME! WORK SLOWLY! RELAX!"

The appeal was heeded. But "Plenty of Room at the Bottom" had become a classic of sorts and was still being handed around a quarter of a century later among people interested in such things. R. Fabian Pease, Stanford professor of electrical engineering and Newman's advisor, remembers seeing it first in 1966 when he was an assistant professor at Berkeley. It was another Stanford graduate student, Ken Polasko, who first brought it to Newman's attention and suggested going for the prize. "We had an idea no one had done it," says Newman, "or we would have heard about it." But Newman also thought it was a "neat paper" and "fun to read just for itself," and, like the first prizewinner, he was more interested in the problem than in the money.

The problem fit in nicely with his doctoral research, which concerned improving the throughput of electron beam lithography to make the process useful in the production of VLSI chips and in the ultra-high-resolution fabrication of very small electron devices. Newman had designed a system for such enhancement of electron beam lithography using a multiple-beam approach, in which the beams are independently modulated as they are scanned in an array over a surface, giving, in effect, a dot-matrix writer. (This work was supported by the Army Electronics and Development Command.) At the time the old *E&S* article surfaced, he was looking for a good demonstration of pattern generation for his apparatus — some random, arbitrary pattern. "Text is ideal," says Newman, "because it has so many different shapes."

He chose *A Tale of Two Cities* because it was one of his favorite novels — but also because it had a well-known opening paragraph and a first page of about the right size. He used a beam of electrons about one five-millionth of an inch in diameter to scan the text across a thin plastic membrane. The exposed regions were then etched away by being dissolved in ethanol. Although Newman had all the basic tools already and got a good start on the project over a weekend, it took about a month of concentrated hard work to get the text to a point where it was adequately legible. "Using text was tougher than we had thought," says Pease. "It turned out to be an excellent technological exercise." Eventually Ann Marshall of Stanford's Center for Materials Research was able to tune her electron microscope to get a readable image.

And then Newman sent Feynman a telegram asking if anyone had yet collected the prize. No one had. In addition to being $1,000 richer (Feynman was no longer financially strapped), Newman also passed his PhD orals on December 4. Included as part of his oral presentation was the prizewinning page of *A Tale of Two Cities* as further demonstration of computer-controlled pattern generation in electron beam lithography. □ — *JD*

Research in Progress

Comet Composition

NEXT MARCH 13th will be the culmination of years of effort on the part of Peter Eberhardt, visiting associate in geology and planetary science. He'll be in the European Space Agency's operations center at Darmstadt, West Germany, monitoring data returned by the Giotto spacecraft as it encounters Comet Halley. Aboard Giotto is an instrument Eberhardt helped design — the Neutral Gas Mass Spectrometer (NMS) — that will return precise information on the composition of the gases swirling around Halley. Because these gases are thought to represent nearly pristine remnants of the early solar system, data from the NMS are likely to solve important questions about the state of the solar system before the formation of the earth.

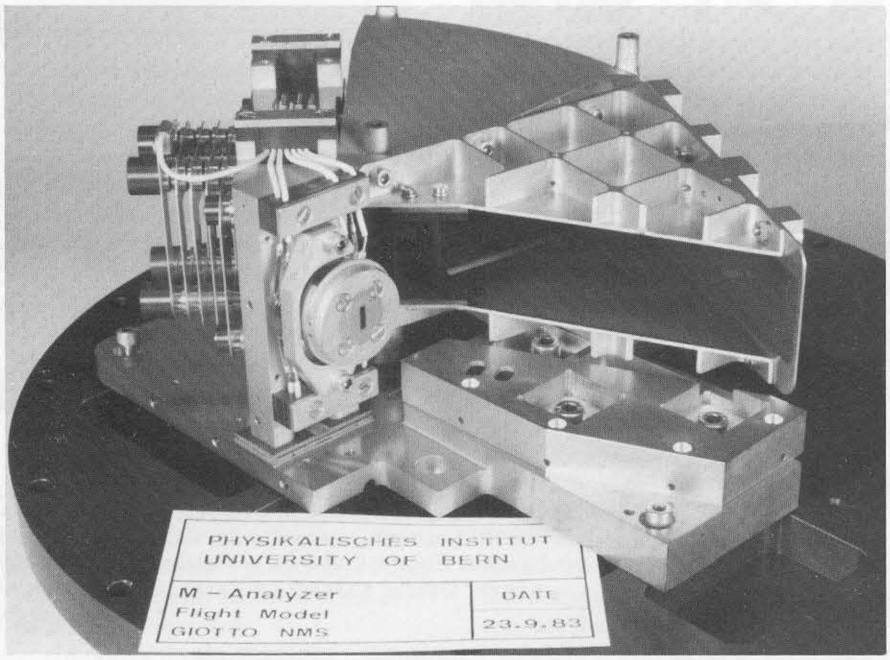
Traveling towards Halley at 69 kilometers per second (154,000 miles per hour), Giotto carries nine other instruments aside from the NMS. There are two other mass spectrometers — one for ions and the other for dust — as well as ion, dust, electron, and energetic-particle analyzers; a camera; a magnetometer; and an optical photometer. Giotto has been aimed to plunge directly into the comet, missing Halley's solid nucleus by only 500 kilometers. If things go according to plan, Giotto will pass through the comet's shock front, its contact surface, and its coma before dust particles destroy the spacecraft or knock its antenna out of alignment with the earth.

Until this happens, the NMS will be sending a steady stream of data back to Eberhardt and his colleagues at Darmstadt. "We will look at the data online as they come in and, if necessary, we'll make changes in the operation modes of the instrument," says Eberhardt. "We'll get quick-look data in real time, but to really reduce the data will take considerable time — probably several years."

Mass spectrometers work by first ionizing a stream of gas and then subjecting this stream of ions to a strong magnetic field. The magnetic field deflects ions of low mass more sharply than ions of higher mass, so ions of different masses will strike different locations on a suitably placed detector. The position of a signal on such a detector indicates the atomic mass of the ionized gas, and the intensity of the signal indicates the gas's relative abundance.

The NMS aboard Giotto consists of several separate modules, each designed and built by a different research team. A group at the University of Bern, where Eberhardt is professor of physics, designed the mass spectrometer itself — the "M-analyzer" — and performed instrument calibrations and environmental testing. A group at the Max Planck Institute in Heidelberg built the E-analyzer, which will measure the temperatures and streaming velocities of the cometary gas. Scientists at the Laboratoire de Geophysique Externe near Paris were responsible for the detectors and ground support electronics, and researchers at the University of Texas, Dallas, built the NMS's electronics and wrote the onboard software.

The design groups had to solve a number of important problems before the idea of sending a mass spectrometer to the comet could become a reality. For one thing, the instrument would have to be capable of detecting anywhere from one single gas molecule to one-billion of them. When the NMS is 100,000 kilometers from the comet, the gas densities will be on the order of 10,000 molecules per cubic centimeter; says Eberhardt, "this is a pretty good vacuum for most people." To measure such a rarefied atmosphere, the signals will be preamplified



A Swiss research group built the M-analyzer, the heart of Giotto's Neutral Gas Mass Spectrometer. Gas molecules enter a small slit, at left center in this photograph, and are separated according to mass by the wedge-shaped magnet at the rear.

by a specially designed micro-channel plate, which contains, in effect, 256 tiny photomultiplier tubes, whose gain can be changed by adjusting the high voltage.

Another problem in measuring such low gas densities is that a substantial fraction of the gas molecules in the vicinity of the NMS will be molecules that have evaporated from the spacecraft itself. To discriminate against these non-cometary molecules, the designers took advantage of the fact that the comet's gas will be traveling at a high velocity relative to the spacecraft. By setting up a potential barrier (an area of high positive voltage) just past the instrument's ionization region, only molecules with high thermal energy will be able to enter.

"What we want to get from the NMS," says Eberhardt, "is the chemical composition of the neutral gas evaporating from the cometary nucleus. How much water, methane, CO, N_2, and so on is there? We will measure also the isotopic composition of the light elements — for instance the ^{18}O:^{16}O ratio, deuterium abundance, and ^{13}C. We'd like to study what happens to the gas when it expands into space, its interaction with sunlight, the spatial distribution of changes with distance. At present we don't really know what the composition of the volatiles is. We have some information from spectroscopy, but we may actually be missing a few major components because they cannot be seen with spectroscopy."

Some of these measurements have important implications for theories about the early solar system. A good example of this is deuterium abundance. The earth is enriched in deuterium, a non-radioactive isotope of hydrogen. Deuterium is twice as heavy as hydrogen, and its relatively high abundance on earth is thought to be due to low-temperature fractionation — before the accretion of the earth a disproportionate amount of the lighter hydrogen in the inner solar system had been lost. The outer planets have much lower deuterium abundances, and this is thought to reflect the solar system's initial conditions. Most scientists believe that Halley's comet formed in the outer solar system so its deuterium abundance should be similar to that of the outer planets.

If all goes according to plan, data on this question and others will start streaming down to Darmstadt on March 13, 1986, three hours and 45 minutes before Giotto's closest approach. As this day nears, Eberhardt is spending part of a sabbatical at Caltech, "I've been fairly busy with the Giotto project in the last two years, busier than I intended to be." Eberhardt will likely remember these months at Caltech as the calm before the storm, a storm that will bring a blizzard of data to bear on some of the most fundamental questions in the solar system. □ — *RF*

To Shop or Not to Shop

THINK ABOUT THE LAST TIME you bought a major durable good — a television, a washing machine, or a refrigerator, for example. Did you just buy the first one you saw in your price range? Or did you compare prices and qualities, going from store to store say, or reading newspaper ads or *Consumer Reports*? If you fall into the latter group, you're known in economic lingo as a "shopper," and the more people there are like you in a given market, the lower prices will be overall.

At least that's the conclusion that David Grether and Louis Wilde, both professors of economics, and Alan Schwartz, professor of law and social science, have arrived at by applying a novel combination of economic theory and experiment. These studies began several years ago when Wilde and Schwartz were developing mathematical representations of markets in which the consumer has only imperfect and costly sources of information. The researchers discovered that their models were difficult to test against competing ones, so — together with Grether — they began a series of experiments designed to test market behavior in the laboratory. They study how buyers interact with sellers in the marketplace by varying such factors as a market's structure, its proportion of shoppers to non-shoppers, and the amount of information available to buyers and sellers.

Their laboratory is a simple classroom and their subjects are paid volunteers who take the part of buyers and sellers. Although no actual goods are bought or sold in these experiments, to properly motivate the subjects, real money must change hands. Sellers purchase "goods" from the researchers and sell them for whatever the market will bear. At the end of the experiment, buyers resell the "goods" they have purchased to the researchers at a predetermined price. All participants get to keep any profits they make, which can amount to as much as $7 per experimental hour.

"We aren't just asking how well these subjects can calculate something that we could in principle simulate on a computer," notes Wilde. "We give them discretion over how to behave and we provide incentives for them to behave in an economically rational fashion. We give them a reason why, if they're a buyer, they should like a lower price, and a reason why, if they're a seller, they should like a higher price. But we don't dictate what prices to transact at or how to behave. Whether they make money or not is their own problem."

In an initial series of experiments Grether, Schwartz, and Wilde have confirmed several theoretical models that predict the behavior of markets having varying proportions of shoppers. If none of the buyers are shoppers, for example, prices stabilize at a very high level. If all of the buyers are shoppers, sellers will charge very low prices, just above their costs. And if the market contains some shoppers and some non-shoppers, at equilibrium the sellers will be selling their goods at an array of prices. This shows that even non-shoppers benefit when a market contains a sizable proportion of shoppers. One of the goals of the research is to determine just what this proportion has to be.

More recently, the researchers have turned to studies in which an "information broker" is interposed between buyers and sellers. Such a situation mimics some of the computer-organized markets or electronic shopping services that have begun to spring up with the advent of television cable systems and personal computers. In this kind of service a prospective buyer can, for a fee, gain access to a list of sellers and their prices.

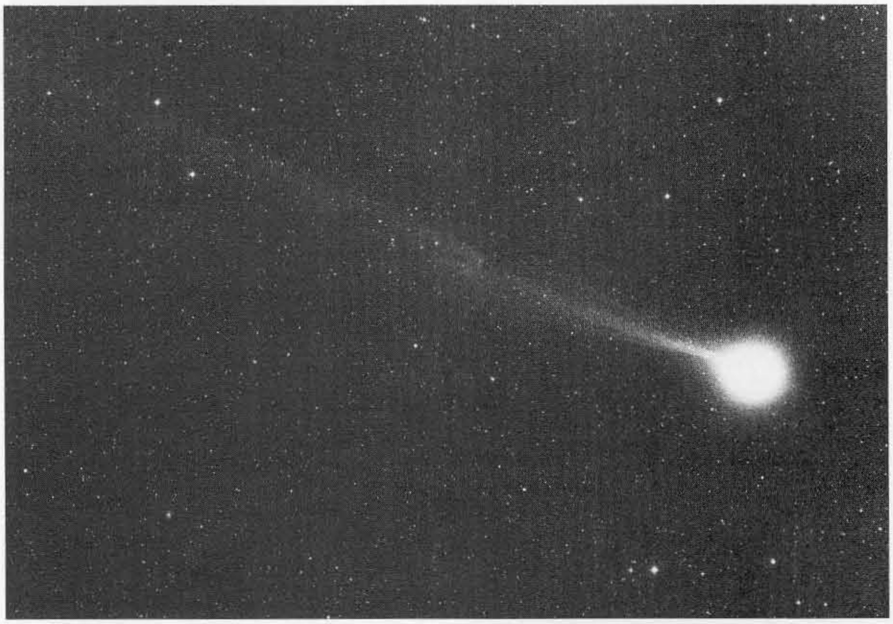
In one of these experiments, the information broker offers buyers the option of purchasing a list containing a limited sampling of the sellers and their prices. This can lead to a situation in which ultimately no buyers take advantage of the price lists and prices remain uniformly high. "You can see why this can be in equilibrium if you think about it," says Grether. If everybody charges high prices, there's no real point in paying money to shop. If nobody pays money to shop, there's no point in charging lower prices because your business won't go up.

But if shoppers can choose to purchase a complete listing of all the sellers and their prices rather than just a sampling, the outcome changes completely. "Generally in this setup," says Grether, "all transactions take place at one of two prices — either a low price — a competitive price — or a high price, with no prices in between. If you're a seller and you're not at the low price, you don't get any business from shoppers at all. So once you come off the bottom, there's no point in coming off a little bit." Only non-shoppers, of course, buy at the high price.

"It turns out," says Wilde, "that small changes in the way people gather information or in the way information is disseminated can have very significant implications on the predicted nature of the market outcome. There are issues about how sellers would get listed on such a marketing service: Do firms demand to be on it? Do they pay a fee to be on it? Does the information service itself go out and sample firms? Is it always the same firms or is it a random sample? The difference, for example, between the information service going out and randomly sampling 10 firms every week versus having a stable of 10 firms it always monitors would lead to completely different outcomes."

Since minor changes in a market's structure can lead to drastic differences in its functioning, this work may have significant implications for government policymakers. "That's the whole nature of the research," says Wilde. "To try to understand how these different features influence the outcome, to ask, 'What would be the socially responsible way to regulate these services, and do we even need to regulate them?'" So one of the most important results of these studies may be to provide lawmakers with data on which to base their regulatory decisions. □ — *RF*

Random Walk



JPL astronomer Eleanor Helin obtained this most detailed image yet of Halley's Comet with the 48-inch Schmidt Telescope at Palomar Observatory. The photo, taken at 7:54 p.m. Pacific Standard Time on December 13th, shows for the first time the full range of features characteristic of a well-developed ion tail. These include tail rays, condensations, a kink, a general helical structure (which shows only as a waviness on the print), and perhaps a disconnection event. A swarm of spacecraft is heading towards the comet, including the European Space Agency's Giotto probe (see page 27).

Dervan, Koonin Honored

PETER B. DERVAN, professor of chemistry, has received the Arthur C. Cope Scholar Award. The award recognizes and encourages excellence in organic chemistry and consists of a certificate and a $15,000 unrestricted research grant.

Dervan pioneered techniques necessary for the accurate analysis of the binding locations of antitumor, antiviral, and antibiotic drugs on DNA. Using the tools of organic chemistry in combination with molecular biology techniques, Dervan is developing a set of rules for the readout of right-handed double helical DNA. This work has major applications in diagnosing disease and in developing novel chemotherapeutic strategies for the treatment of cancer.

STEVEN E. KOONIN, professor of theoretical physics, is the recipient of a Senior U.S. Scientist Award from the Alexander von Humboldt Foundation of Bonn, West Germany. The award will enable Koonin to spend approximately 12 months conducting sponsored research at the University of Frankfurt's Institute of Theoretical Physics.

Koonin uses computer modeling techniques to investigate the structure of the atomic nucleus and the atomic physics of neutron stars. His study of low-energy collisions among the nuclei of heavy atoms has shown these interactions to display both classical and quantum mechanical properties. The models he developed are now standard in the field.

Bonds Issued

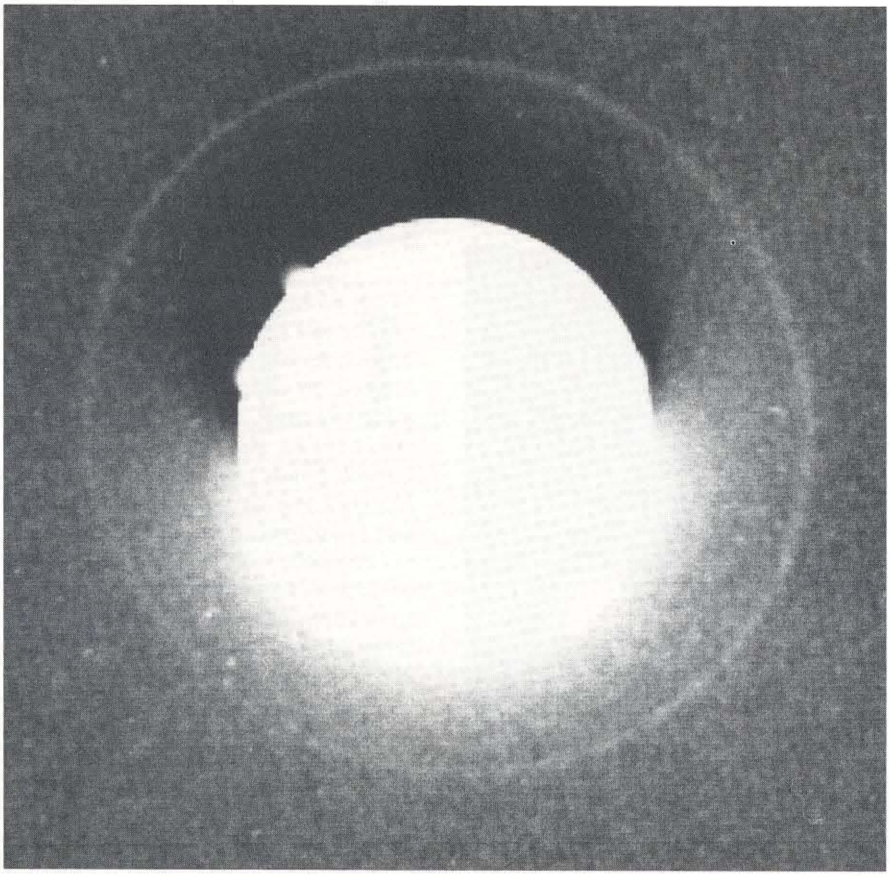
THE BOARD OF TRUSTEES has authorized the sale of $20 million in bonds to finance several important construction projects on campus. The bonds, which are tax-exempt under federal and state law, went on sale in December. The Caltech bonds were rated AAA by Moody's and were purchased by banks and other institutional investors.

Proceeds from the bond issue will be used to construct additional graduate student residences, a parking structure, and a cogeneration plant. The new graduate student apartments will be located on Catalina, just north of the apartments that were completed in 1984. The parking structure, located on the west side of Wilson, will provide about 500 spaces for students, faculty, and staff. If everything goes as planned, the apartments and the parking structure will be completed by September 1986.

Construction of Caltech's second cogeneration plant, to be located in central plant, is expected to begin in February. The initial plant, which uses steam produced by boilers to operate a turbine generator, produces about 20 percent of the campus's power. The new plant, a gas/oil-fired combustion turbine, is expected to provide another 60 percent of campus energy needs.

Happy Birthday, Linus!

ON FEBRUARY 28, 1986 Caltech will salute two-time Nobel Prize winner Linus Pauling, professor of chemistry emeritus, with a daylong seminar in honor of his 85th birthday. The seminar will include talks on Pauling's contributions to chemistry as well as his contributions to the Caltech community. The day will be capped with a banquet in Pauling's honor. For further information, contact Professor Ahmed Zewail at Caltech 127-72, Pasadena, CA 91125.

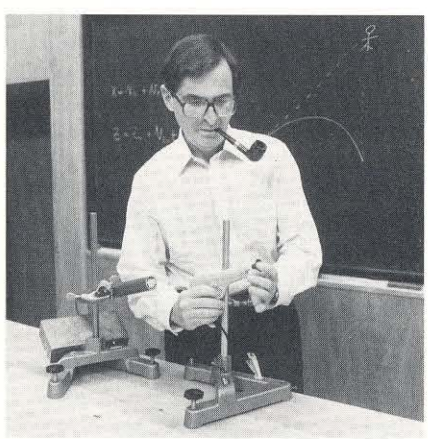


This Voyager 2 photograph of Uranus shows the planet's outermost, or epsilon, ring. The picture is a computerized summation of six images returned November 28, 1985 and is the first to show the epsilon ring unblurred by the earth's atmosphere. This ring, 51,200 kilometers from the planet's center, is the most prominent of Uranus's nine known rings. In this picture the central image of Uranus itself is greatly overexposed. Image processing introduced various other artifacts, including the dark region just above the planet, the diffuse brightening below it, and the small, bright projections from the edge of the planet in the upper left. Voyager 2 will make its closest encounter with Uranus on January 24, 1986.

"Mechanical Universe" Wins Awards

CALTECH'S INNOVATIVE TELECOURSE, "The Mechanical Universe," has won two prestigious awards. At the International Film and Television Festival of New York the series was awarded the Gold Medal in the Scientific Themes Category. And at the Chicago Film Festival, it won the Golden Plaque for educational series.

Funded by the Annenberg/CPB Project, "The Mechanical Universe" consists of 26 programs based on lectures given by David Goodstein, professor of physics and applied physics. A second group of 26 programs is currently under production.



Goodstein demonstrates Newton's Laws.

Developmental Biology Grant

THE LUCILLE P. MARKEY Charitable Trust has awarded the Division of Biology a five-year, $12.5 million grant for the study of developmental biology. Developmental biology, the study of how organisms, cells, and tissues attain their adult form and function, is now becoming an area of intense exploration due to opportunities afforded by powerful new techniques in molecular biology, cell biology, immunology, and microchemical instrumentation. The grant will ensure independent support for Caltech's broadly focused research effort.

"Space Photography" a Hit

THE BAXTER ART GALLERY'S final exhibit, "25 Years of Space Photography," opened at the IBM Gallery of Science and Art in New York City on November 5 in the first leg of an international tour. The 2,800 people who attended opening day at the IBM gallery made it the largest opening in the gallery's history. By the end of November, less than halfway through its run, 53,500 people had viewed the exhibit.

The New York showing has attracted a great deal of media attention. In addition to a review in *Newsweek*, two articles in *The New York Times*, and a report by the Associated Press, feature articles on the exhibit are soon to appear in *Scientific American* and *Harper's*.

"25 Years of Space Photography" will be at the Fresno Metropolitan Museum in May and June 1986, at the Exploratorium in San Francisco in January and February 1987, at the International Museum of Photography at George Eastman House in Rochester, N.Y. in May through August 1987, and finally, in late 1987, at the Cosmocenter in the Netherlands. In addition, the Coca Cola Company plans to exhibit a selection of the photographs at its centennial celebration in Atlanta in May 1986.

The Travel Program Of

Alumni Flights Abroad

This is a private travel program especially planned for the alumni of Harvard, Yale, Princeton and certain other distinguished universities. Designed for the educated and intelligent traveler, it is specifically planned for the person who might normally prefer to travel independently, visiting distant lands and regions where it is advantageous to travel as a group. The itineraries follow a carefully planned pace which offers a more comprehensive and rewarding manner of travel, and the programs include great civilizations, beautiful scenery and important sights in diverse and interesting portions of the world:

TREASURES OF ANTIQUITY: The treasures of classical antiquity in Greece and Asia Minor and the Aegean Isles, from the actual ruins of Troy and the capital of the Hittites at Hattusas to the great city-states such as Athens and Sparta and to cities conquered by Alexander the Great (16 to 38 days). *VALLEY OF THE NILE:* An unusually careful survey of ancient Egypt that unfolds the art, the history and the achievements of one of the most remarkable civilizations the world has ever known (19 days). *MEDITERRANEAN ODYSSEY:* The sites of antiquity in the western Mediterranean, from Carthage and the Roman cities of North Africa to the surprising ancient Greek ruins on the island of Sicily, together with the island of Malta (23 days).

EXPEDITION TO NEW GUINEA: The primitive stone-age culture of Papua-*New Guinea,* from the spectacular Highlands to the tribes of the Sepik River and the Karawari, as well as the Baining tribes on the island of New Britain (22 days). The *SOUTH PACIFIC:* a magnificent journey through the "down under" world of New Zealand and Australia, including the Southern Alps, the New Zealand Fiords, Tasmania, the Great Barrier Reef, the Australian Outback, and a host of other sights. 28 days, plus optional visits to South Seas islands such as Fiji and Tahiti.

INDIA, CENTRAL ASIA AND THE HIMALAYAS: The romantic world of the Moghul Empire and a far-reaching group of sights, ranging from the Khyber Pass and the Taj Mahal to lavish forts and palaces and the snow-capped Himalayas of Kashmir and Nepal (26 or 31 days). *SOUTH OF BOMBAY:* The unique and different world of south India and Sri Lanka (Ceylon) that offers ancient civilizations and works of art, palaces and celebrated temples, historic cities, and magnificent beaches and lush tropical lagoons and canals (23 or 31 days).

THE ORIENT: The serene beauty of ancient and modern Japan explored in depth, together with the classic sights and civilizations of southeast Asia (30 days). *BEYOND THE JAVA SEA:* A different perspective of Asia, from headhunter villages in the jungle of Borneo and Batak tribal villages in Sumatra to the ancient civilizations of Ceylon and the thousand-year-old temples of central Java (34 days).

EAST AFRICA AND THE SEYCHELLES: A superb program of safaris in the great wilderness areas of Kenya and Tanzania and with the beautiful scenery and unusual birds and vegetation of the islands of the Seychelles (14 to 32 days).

DISCOVERIES IN THE SOUTH: An unusual program that offers cruising among the islands of the Galapagos, the jungle of the Amazon, and astonishing ancient civilizations of the Andes and the southern desert of Peru (12 to 36 days), and *SOUTH AMERICA,* which covers the continent from the ancient sites and Spanish colonial cities of the Andes to Buenos Aires, the spectacular Iguassu Falls, Rio de Janeiro, and the futuristic city of Brasilia (23 days).

In addition to these far-reaching surveys, there is a special program entitled *"EUROPE REVISITED,"* which is designed to offer a new perspective for those who have already visited Europe in the past and who are already familiar with the major cities such as London, Paris and Rome. Included are medieval and Roman sites and the civilizations, cuisine and vineyards of *BURGUNDY AND PROVENCE*; medieval towns and cities, ancient abbeys in the Pyrenees and the astonishing prehistoric cave art of *SOUTHWEST FRANCE;* the heritage of *NORTHERN ITALY,* with Milan, Lake Como, Verona, Mantua, Vicenza, the villas of Palladio, Padua, Bologna, Ravenna and Venice; a survey of the works of Rembrandt, Rubens, Van Dyck, Vermeer, Brueghel and other old masters, together with historic towns and cities in *HOLLAND AND FLANDERS:* and a series of unusual journeys to the heritage of *WALES, SCOTLAND AND ENGLAND.*

Prices range from $2,225 to $5,895. Fully descriptive brochures are available, giving the itineraries in complete detail. For further information, please contact:

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