California Institute
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Engineering & Science

Spring 1989

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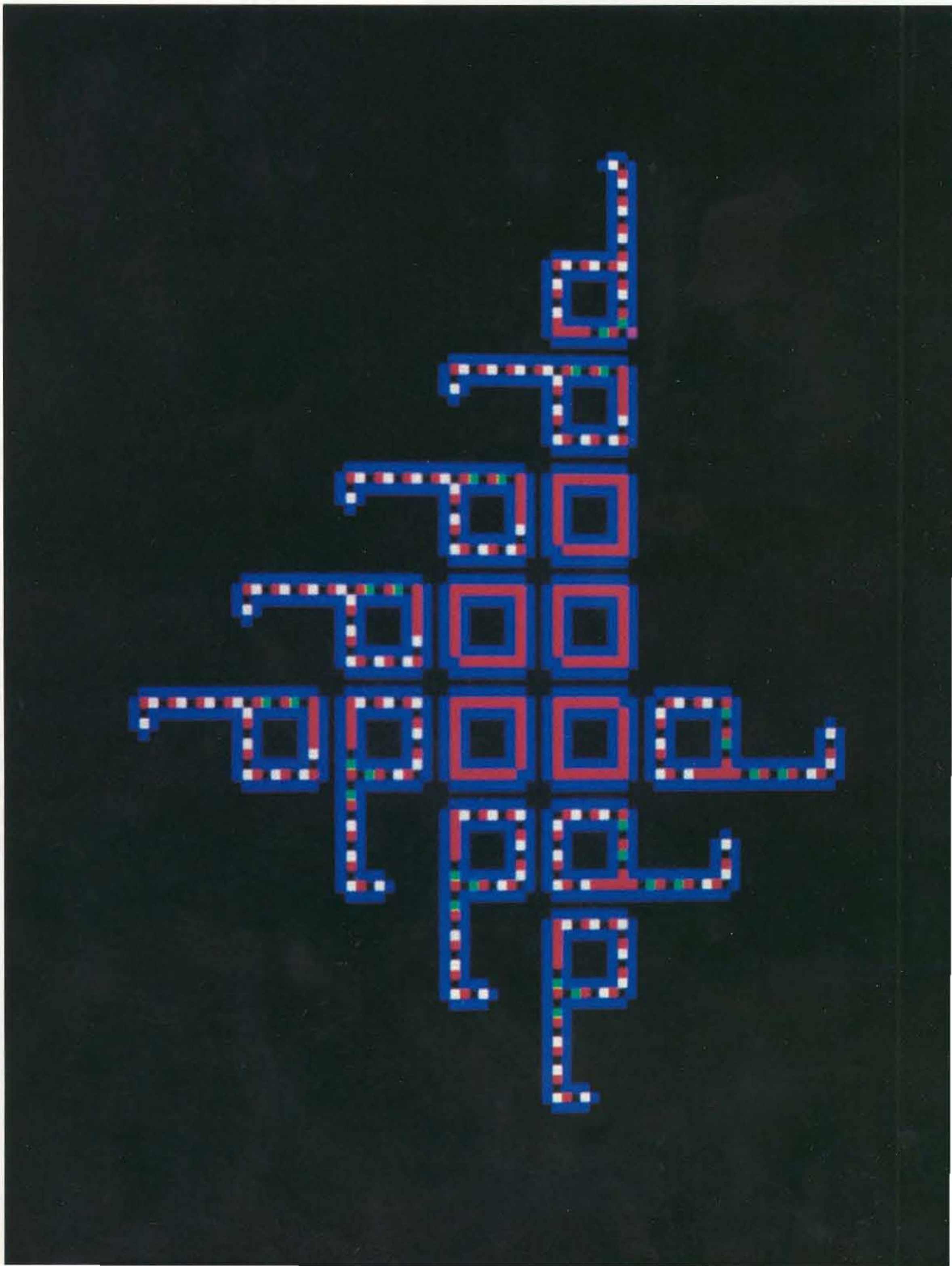
Seeking other worlds

Preserving our own world

New world of research



In November 1982, these two teenagers were lost for nearly a week in the Washington wilderness. With little hope of being seen, let alone surviving.

At night, they huddled together for warmth, so neither would freeze. But their body heat drew them even closer to safety.

This is a picture of 2 lost boys in a 20,000 acre forest.

They were spotted from a rescue helicopter equipped with an extraordinary infrared scanning device. The Probeye® thermal imager, developed by Hughes Aircraft Company.

It records heat, just as photography records light. In this case, by detecting body heat, it helped rescuers penetrate the dense snow-covered forest to save the stranded boys.

It was the only chance they had.

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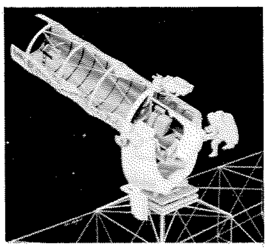

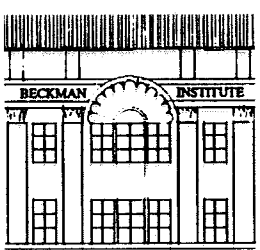

On the cover: A self-reproducing cellular automaton creates a colony consisting of a "live" reproductive fringe around a growing "dead" core, similar to a coral reef. Such "artificial life" was one speaker's answer to "Where Are Our Efforts Leading?" Other steps in this process (courtesy of Chris Langton of Los Alamos National Lab) are shown on page 20.

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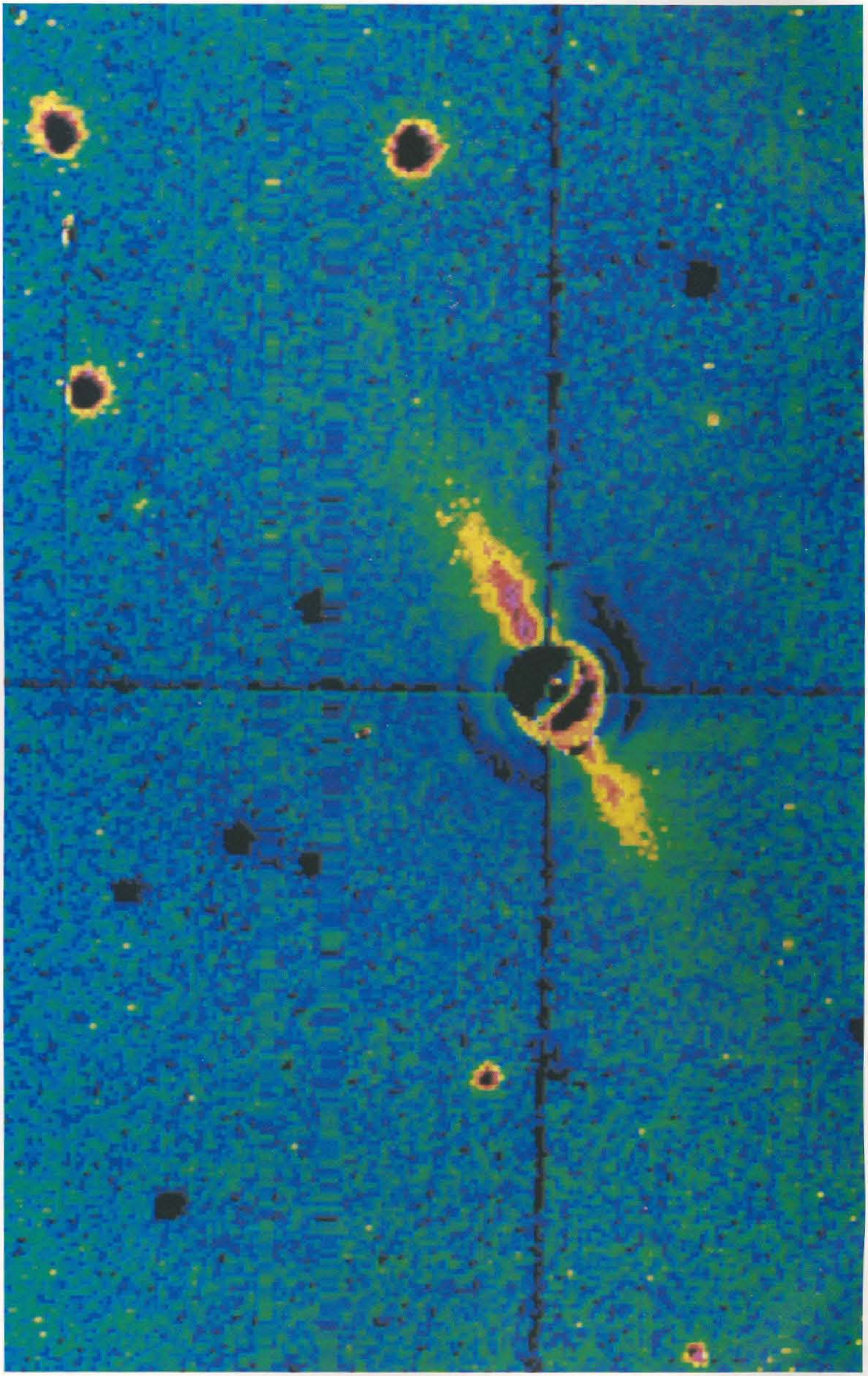


Prospecting for Planets

The obvious next step is to go from exploring the planets to exploring the nearby stars and whatever worlds might exist around them.

by Richard J. Terrile

Evidence of what may be a planetary system orbiting the star Beta Pictoris, about 50 light- years away, shows up in this image made in 1984 by Richard Terrile and Bradford Smith, using the 100-inch telescope at Las Campanas Observatory. The perpendicular lines are caused by fine silk filaments that support an occulting mask. This mask removes most of the star's diffracted light that normally would hide the circumstellar disk from view.

What will be the next big adventure in space? We have sent men to the moon—about 200,000 nautical miles away. We've landed spacecraft on Mars, about 500 times farther away. And with the Voyager spacecraft we've also visited the outer regions of the solar system—10,000 times farther away than the moon. The obvious next step is to go from exploring the planets to exploring the nearby stars and whatever worlds might exist around them.

Humans have always been curious about the night sky. When man realized the relationship between the sun in the daytime sky and the stars in the night sky, it was a fundamental connection in human thought. We are now at another threshold—where technology has caught up with curiosity, and it's very exciting to be there. We now know enough about the theory of planetary formation and the evolution of stars to indicate that perhaps planetary formation is a common phenomenon—the norm and not the exception. And although the nearest stars are about 10,000 times farther away than the outer planets of our solar system and it would take tens of thousands of years to visit them with a spacecraft, we're at least beginning to understand what it takes to directly image planets around other stars. And we can now build what it takes.

Up until now we've been attempting in other ways to discover whether we're alone in the universe. We are using radio telescopes for a program called SETI, the Search for Extraterrestrial Intelligence. In this program we listen to the other stars to see if any kind of intelligent radio signals are being broadcast from them. And of course we've been broadcasting our own "intelligent" radio signals for about 40 years now—television broadcasts, which have left the ionosphere of Earth and are now expanding at the speed of light in a shell about 40 light-years in radius. Within that shell there are about 800 different star systems, and the broadcast shell is now crossing a new star system about every three days. So every three days there's a new opportunity for somebody out there to say, "Ah, 'The Gale Storm Show.'" It's an intriguing thought. Twenty years ago, when this shell was only half as large, it was crossing a star system about every two weeks. If somebody in one of those star systems had then said, "Aha, there's life on Earth; let's broadcast a reply," and had beamed a strong reply signal, then 20 years after that—today or tomorrow—we might be receiving that reply on our arrays of radio telescopes.

But there will be only a short, finite period of time when the Earth is broadcasting its existence as an intelligent civilization. We're becoming much more efficient in transmitting communication around our planet and are adopting fiber optics, instead of broadcasting all this energy that leaks out past our atmosphere. So, perhaps this isn't the best way to look for life on other planets. The Earth has been around for 4½ billion years and we've only been broadcasting for 40. If others aren't actively signaling their existence but just accidentally broadcasting until their technology gets better, the odds are 1 in 100 million that we'll connect.

Our galaxy, like others, contains about 200

Jupiter-sized planets among the 200 billion stars of the Milky Way could be very common—perhaps even the rule rather than the exception.

billion stars. To get an idea of what 200 billion stars might look like, we can make a model of a galaxy on the floor, using grains of salt to represent the stars. (This is an experiment you should try at home. It's safe; it's nontoxic; you don't need to wear goggles or any safety equipment; and you can do it unsupervised as long as you clean up afterwards.) A container of salt that you can buy for 25 cents contains about 5 million grains. It turns out that we would need a carload of salt (200 containers) to make a billion stars on our floor, and in order to get enough to represent all the stars in the galaxy, we would need a whole trainload of salt.

To spread this trainload of salt out to make our model, we'll have to calculate how far away each grain has to be from its neighbors. We know how far away the stars are, and we know how big they are, so we can figure this out easily enough. (In this model, with our Sun a grain of salt, the Earth is about 2 inches away from it, and Jupiter would be about 10 inches away and would be the size of a mote of dust.) In our model the stars themselves—the grains of salt—would have to be separated by about 7.5 miles. (You can understand why stars rarely collide.) The floor I would need to spread them out on would be about one and a half times the distance between Earth and the Moon.

The message of this little experiment is that space is mainly empty space. And there are enormous numbers of stars out there—a lot of salt grains—and many opportunities for variety in the stars and the stuff that might be orbiting around them.

We're looking for a mote of dust next to a grain of salt 7.5 miles away—at the closest.

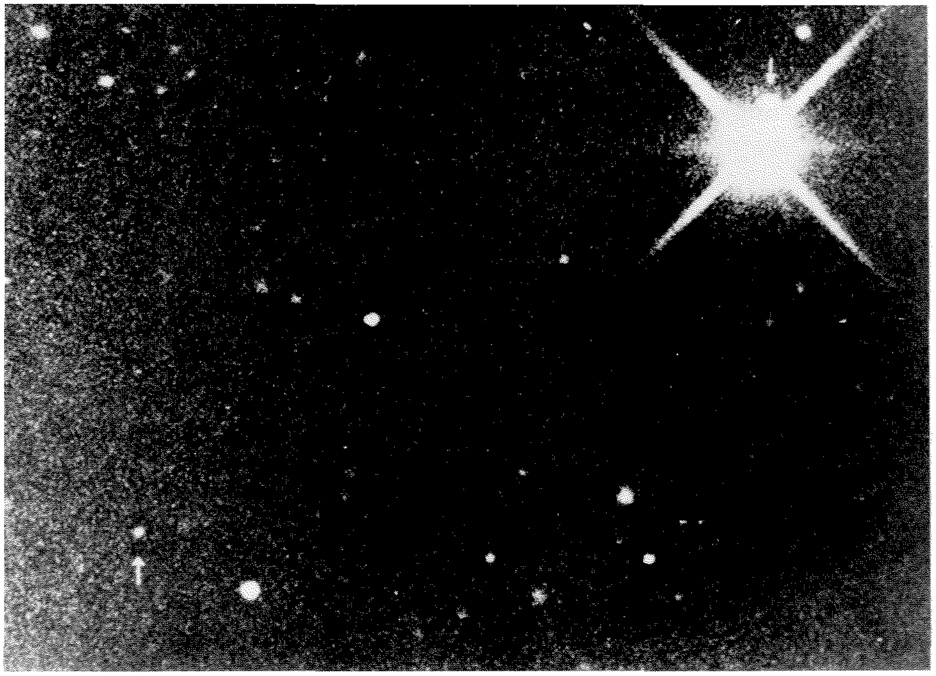
So, how are we going to find a planet orbiting around a star? We're looking for a mote of dust next to a grain of salt 7.5 miles away—at the closest. If we were to look at the Earth from far away, we could in fact determine that there was something very peculiar about this planet (even if we saw it 50 years ago before we were broadcasting TV). We would know from its spectrum that the Earth's atmosphere is composed in part of oxygen and methane, which normally should not coexist in equilibrium in the atmosphere. Something has to be continually supplying the methane and the oxygen, and the thing that's doing it is biology. If we were to measure a planet's spectrum and see oxygen and methane in its atmosphere, we would have to conclude that no known geological processes could maintain this kind of chemical configuration and that there must be something—perhaps biology—acting to do that.

Seeing the atmosphere of an Earth-like planet from such a distance, however, is going to require putting an immense construction such as the Arecibo Radio Telescope, which is 1,000 ft. in diameter, in Earth orbit or on the Moon and operating it at visible wavelengths. Since projects like this would cost multiple billions of dollars, it was important to look for something we could do in the meantime with current technologies and current budgets—something on the planetary mission scale in the $100-million range.

If we back off from looking for Earth-like atmospheres, what else can we do? We could look at nearby stars for a Jupiter-like planet, which is 10-11 times the size of the Earth. It's both farther away from the star and bigger. But still, Jupiter in visible light is about a billion times fainter than the center star, and looking for something very faint next to something bright isn't easy. We can't look for anything more than about 10 percent larger than Jupiter though, because that's the limit on planet size. For example, if you cram Jupiter and Saturn together to make a larger planet, you actually end up getting a smaller planet. Since the atoms in the center of Jupiter are already squashed together under pressure, the more mass you add, the more those atoms are crushed, and the planet begins to contract. The interior would get hotter and hotter until it ignites and becomes a star.

In looking for Jupiter-sized planets around nearby stars, we can derive some clues from what we already know about the way planets form. We know that in our solar system the planets lie in a flattened disk; they're all more or less in the same plane. When the cloud out of which the solar system formed collapsed, with the sun condensing in the center, it tended to flatten down at the poles with angular momentum holding the remaining debris—ice, rocks, and so on—in orbit around the center. As pieces of the debris collided with each other, coalescing into planets, they lost energy and wound up in circular orbits in the same plane. Almost all the angular momentum of the original disk resides in the planets; in fact, Jupiter contains more than 90 percent of the angular momentum of the solar system. This process of gravitational collapse also occurred in the individual planets, leaving debris in the form of satellites and rings.

Gravitational collapse isn't a very efficient mechanism; it's almost impossible to sweep up all the debris into the Sun, so, if other stars formed in the same way as the Sun—and it's likely they did—then it's a very reasonable assumption that they also left behind debris and planets. The formation of planets leaves characteristic signatures (areas swept clean of debris) in the disk, but because such disks are obscured by the bright light from the stars themselves, they have been impossible to see until recently. This began to change in 1983, when IRAS (the Infrared Astronomical Satellite) mapped out the entire galaxy in infrared wavelengths invisible to the human eye. The Milky Way lights up brilliantly in the infrared, even its center, which is normally obscured by dust at visible wavelengths. IRAS showed us some extraordinary things. Most exciting to me was the evidence that some nearby stars are surrounded by cold material—material in orbit around the stars.



Triton (arrow), one of Neptune's satellites, is a factor of 230 less in brightness than the planet, and is nearly obliterated by the scattered and diffracted light from Neptune. A coronagraph solves this problem, allowing a better look at Triton. (A still better view will be taken by Voyager II when it encounters Neptune and Triton in August.) The arrow at lower left indicates Nereid, another satellite of Neptune.

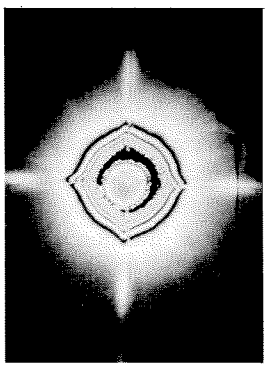
With these hints from IRAS about which stars would be interesting to look at, Brad Smith (professor of astronomy at the University of Arizona) and I set out to find a star with a disk around it, using the 100-inch telescope at the Las Campanas Observatory in Chile. On page 2 is a photograph of what we found—Beta Pictoris. It's 50 light-years away, one of the nearest thousand or so stars.

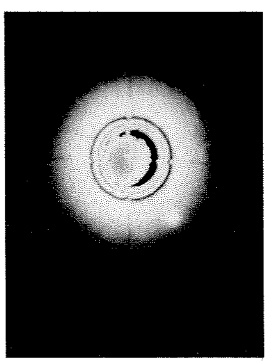
In a normal image of Beta Pictoris light from this star is so bright that it obscures any hint of a disk. Fortunately, we can now record these images, using special optics to mask out the light from the central star, and then further process the images in a computer. What we now see, sticking out from behind a blocking mask, is an edge-on disk extending far out beyond the star—about 20 times the radius of our own solar system. Although we're seeing the disk edge-on in this picture and can't see the center directly, our work has indicated that the center of the Beta Pictoris disk is, in fact, clear of material. We believe that this is because planets have already formed in the center of this disk, and, indeed, we may be looking at a very young solar system—perhaps only 1 to 2 percent of the age of our own, with much of the raw material that made the planets left over in an extended disk far larger than the extent of the planets. It took an extraordinary instrument and extraordinary observing conditions to make this photograph because the disk is about 100 million times fainter than the star. We have since seen it again and again with different telescopes, so we're sure that this isn't just an artifact.

Although IRAS has provided some clues about where to look for potential planetary systems, it hasn't enabled us to see a planet. There are some indirect techniques used to look for planetary systems. An orbiting planet will gravitationally disturb a star, causing it to wobble slightly, and a technique called astrometry can pick out a star's wobble against background stars. This same wobble will cause the star to accelerate toward and away from Earth, so it's also possible to see small Doppler shifts in the spectral lines of such a star. But these indirect methods require long observation times—from years to decades. We wanted a direct detection method—something we could see right away. Once you get a picture, once you've separated the light from the star, then you can make measurements on that light independent of the star and look for evidence of oceans, atmospheres, and so on.

To detect a planet directly we had to solve the problem of finding a very dim object next to a bright one. For example, in the picture of Neptune and its satellite Triton above, Triton (arrow), which is only a factor of 230 less in brightness, is nearly obliterated by the diffracted light and scattered light from Neptune. Diffraction comes from the telescope mirror's finite size, which causes light to spread out. Fortunately this problem was solved in the 1930s by French solar astronomer B. F. Lyot, who tired of traipsing off with all his gear to places like New Guinea to study the Sun in eclipse. A total solar eclipse, when the Moon covers the Sun, leaving only the the Sun's corona

We need to be able to control the average height of something the size of Arizona to within two-tenths of an inch.





Sirius, the brightest star in the night sky, is shown with the pupil mask (bottom) and without (top). The mask removes diffracted light, revealing a companion star, which is fainter than Sirius by a factor of 10,000.

visible, has long provided a valuable opportunity to study our star. Lyot thought up the idea of simulating these conditions in the telescope with a coronagraph, an instrument that sticks a little mask in front of the Sun and essentially creates a miniature solar eclipse in the telescope. Today we use that same instrument on telescopes to create star eclipses. Lyot's coronagraph gets rid of 99 percent of diffracted light—a factor of 100.

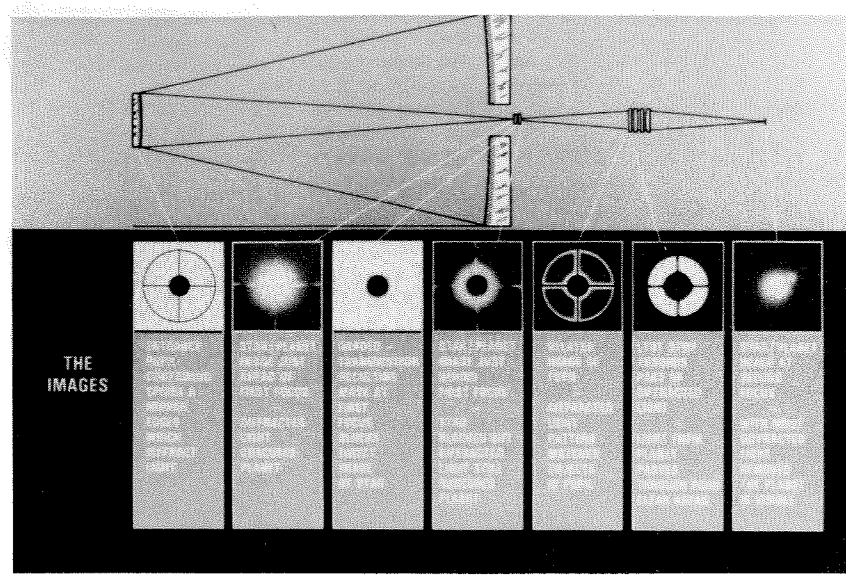
To photograph Beta Pictoris at the Las Campanas 100-inch telescope, we used a more sophisticated version of that original coronagraph affixed to the telescope base. It's a compact instrument, four feet long, complete with optics, including in the camera system a charge-coupled device (CCD), an extremely sensitive and efficient detector of photons. We then processed those images by computer to enable us to see these faint disks. Using the coronagraph, all the light that falls on the 100-inch mirror is focused on a dot about the size of a pinpoint. The tiny mask is suspended by silk monofilaments about 10 microns in diameter—about one-tenth of the diameter of a human hair. Masking off the light from the star has a peculiar consequence further down the telescope: Diffracted light from the telescope mirror is concentrated around the edges of the mirror. We place a second mask (called a pupil mask) in the coronagraph, which blocks off this concentrated diffracted light.

Sirius, the brightest star in the night sky, is shown at left with and without the pupil mask of the coronagraph. Without the mask, diffracted light comes out as bright streaks, which make it difficult to see Sirius's companion star. With a coronagraph (the lower illustration) all that streakiness has disappeared, and the companion star is easily visible.

Our calculations have shown that we need to be able to reduce diffracted light by a factor of 1,000—get rid of 99.9 percent of it. And we've come close to this by using transparent masks instead of solid blocking masks in the coronagraph. Our transparent masks, which are dense in the center and tail off at the edges—like a fuzzy, blurry spot—allow us to concentrate the light in the telescope more efficiently, so that we can then remove more of it. In laboratory experiments we're now only a factor of 2 (instead of 10) away from what we need, and we think our goal is within reach.

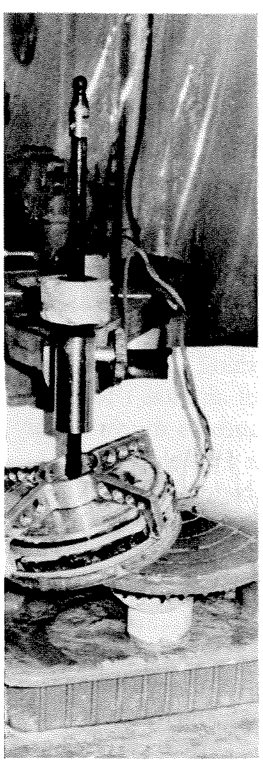
Once we could reduce diffracted light by a large factor with our high-efficiency coronagraph, we needed a mirror that could reduce scattered light by a comparable amount. Otherwise we wouldn't really be any further ahead. Scattered light is caused by imperfections in the telescope mirror itself. Up until now the 2.4-meter Hubble Space Telescope mirror was the smoothest astronomical mirror ever built. The instrument that polishes it is about a foot in diameter. It turns out that that kind of spatial scale on the mirror is a very important one; any kind of tool signatures, any kind of deviation in the shape of the mirror over an area the size of the palm of your hand, say, hurts you. It scatters light into the angles where you expect to see planets. So maintaining exceptionally smooth mirrors at these relatively large spatial scales is the only way to reduce scattered light. For example, if you imagine a mirror the size of the United States, it isn't the little things like mountains or valleys that bother us. What we worry about is the average height of the land over an area the size of, say, Arizona. We need to be able to control the average height of something the size of Arizona to within two-tenths of an inch. To do this, we calculated that we need a mirror about 15 times smoother than the Hubble Telescope—an intimidating realization because that telescope is the smoothest one ever built for astronomy.

But it turns out that astronomy has not been pushing smooth-mirror technology, because there was no need for it as long as the diffracted-light problem existed. But microlithography has. The people who wanted to create smaller and smaller microcircuits required smoother and smoother mirrors to image the masks that create the photoresist patterns. We discovered that for years the Perkin-Elmer Corporation has been building its Micralign mirrors five times



The optical components of the Circumstellar Imaging Telescope are shown schematically at right. The figure also shows the distribution of diffracted light at various stages in the optical train in both pupil and focal planes. The coronagraph isolates and removes diffracted light from the focal plane, allowing a faint planet to be detected near a bright star.

Below: A supersmooth mirror developed for microlithography is polished further for a new career in astronomy.



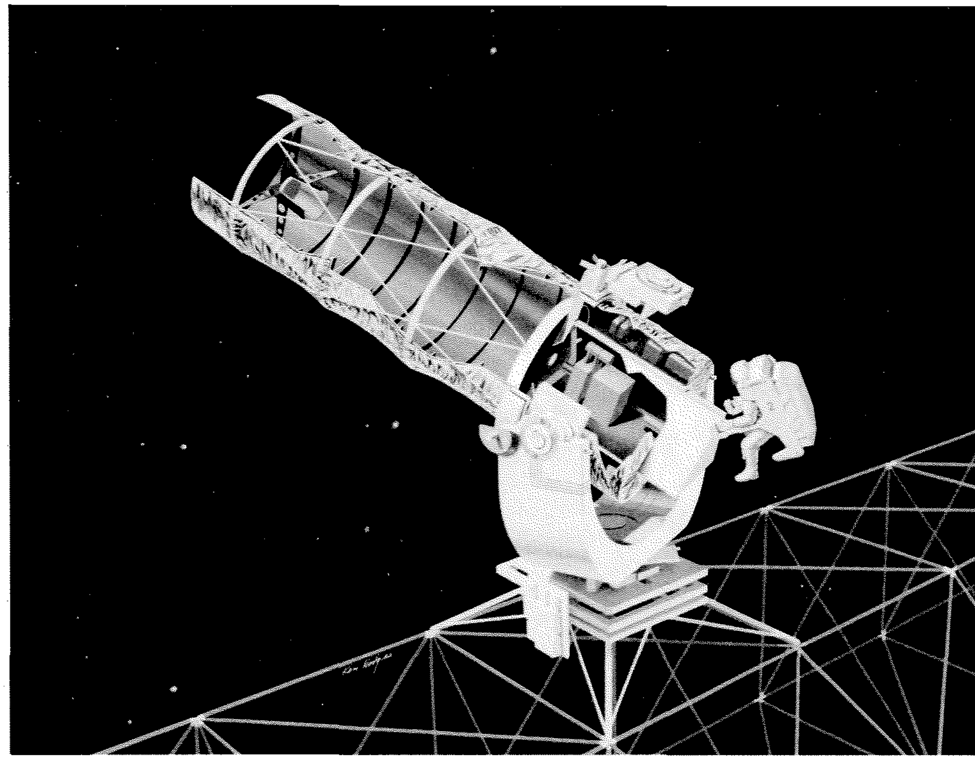
smoother than the Space Telescope mirror. They just crank them out on an assembly line. This was news to me. For years NASA committees have been telling us that building these direct-detection telescopes was impossible; that we shouldn't even think about it. So JPL and Perkin-Elmer started some joint experiments to see if we could continue the polishing process to make a mirror as smooth as we needed. (Just as astronomy was aided here by the gains made in microelectronics, our demands are now contributing something back to improve microelectronic technology.)

Besides being able to polish a mirror smoother than any that had ever been made, we needed to be able to measure it. It doesn't help you to polish a mirror if you can't tell whether it's really smooth or not. Luckily, again, technology had caught up with our desires, and measurement techniques are good enough to tell us what we need to know. A couple of months ago we finished polishing a supersmooth mirror that is nearly flight quality. It can reduce scattered light by a factor of 700-800 (we need 1,000). So we've gone from *wanting* a mirror 15 times better than the Space Telescope to actually physically *having* one that's about 12 times better.

This mirror is 30 cm in diameter; eventually we will need a 1.9 m mirror for our direct-detection mechanism—the Circumstellar Imaging Telescope (CIT)—which will have to be flown in orbit above the Earth's atmosphere. We would like this telescope to be a free flier—like the Hubble Space Telescope, which will be launched from the Space Shuttle next December. But to be realistic (politically and financially) we think we have a better chance of getting it on the Space Station as an attached payload. The Space Station is wobbly—astronauts are inside bouncing off walls and eating meals and flushing toilets and doing all sort of things that create a disturbance, but we think we can live with those disturbances.

The Circumstellar Imaging Telescope will be able to explore a portion of what astronomers call phase space that is unavailable to other types of telescopes. The 10-meter Keck Telescope, for example, being built on a Hawaiian mountaintop by Caltech and the University of California, will be able to gather enormous amounts of light to see things that are incredibly faint and far away. Orbiting above the Earth's atmosphere, the Hubble Space Telescope will explore a different realm of space—those objects that need high resolution, a greater degree of clarity. But neither of these can see what's happening near very bright objects. This is uncharted territory, interesting because the most exciting objects hide behind the brightness.

We think we will be able to detect and photograph planets around nearby stars with this instrument—in hours or tens of hours instead of years or decades. But that's only the hardest thing it has to do; it's admirably suited to other tasks as well. For example, if we had a coronagraph in orbit now, we would be able to see, despite their brightness, the shells of expanding gas around the nearby supernova that exploded in the Large Magellanic Cloud last year. But since we don't have a coronagraph up there now,



By the mid-1990s the Circumstellar Imaging Telescope, with its 1.9-meter super-smooth mirror, could orbit the Earth as an attached payload on the Space Station.

And then the king of Spain came to mind. I mean, the guy's got a track record, right?

we'll just have to wait for the next nearby supernova; it's only been 500 years since the last one. We also want to study quasars, the most remote objects in the universe. The closest one is about 800 million light-years away. We'd like to explore the fuzzy regions near the quasars, to understand how the quasars form jets and what the material around them is. The active nuclei of galaxies might be another target.

So far our project has been funded by discretionary funds from Lew Allen, director of JPL. He took a gamble on this wacky idea of ours, and I'm pleased that we've been able to deliver something ahead of schedule, at a lower cost and better than we expected. Now we feel more confident than we felt a year ago that there are much fewer risks associated with building one of these large mirrors. But before we try to put an expensive, heavy 1.9-meter mirror in Earth orbit—the $100 million project—we want to take the intermediate step of building a 1-meter mirror to operate at 1 g (an orbiting mirror would have to be built for 0 g and so couldn't really be tested on the ground) and test it in a laboratory to understand how it works and learn to operate it more efficiently. Then we could send it up to 100,000 ft. or so in a balloon. On the ground, the atmosphere tends to break an image up into several pieces, which blurs it; at 100,000 ft. it breaks up into only one piece, and you get a sharply focused, but wobbling, point source instead of a big blob of an image. The light blocked by the occulting mask of the coronagraph could be reflected into another instrument and used to point the telescope to track the wobbling image. We'd have the potential to detect planetary systems around the nearest half dozen or so stars in one night, and could even send the instrument back up a few months later to confirm any results. If we look at half a dozen stars and *don't* find anything, it wouldn't really mean very much statistically; we wouldn't be discouraged. But if we *do* find something, it would mean a hell of a lot.

We could look for new worlds for a mere $5-10 million and do it by the early 1990s. I have in mind October 1992, the 500th anniversary of Columbus's discovery of the new world. I couldn't sleep at night thinking about this. There must be someone I could ask for $10 million. I thought long and hard—and then the king of Spain came to mind. I mean, the guy's got a track record, right? Five hundred years ago he did it. And if he's not interested, maybe I could try Portugal. They missed out 500 years ago, and maybe they'd like another chance. □

In addition to the first pictures of another solar system, Rich Terrile has discovered Saturn's innermost moon and two moons of Uranus. As a member of the technical staff at JPL and group leader for planetary astronomy, he's part of the Voyager imaging team and, in more down-to-Earth projects, has spent 15 years observing at both visible and infrared wavelengths at Palomar Mountain, Mauna Kea, and Las Campanas. Terrile graduated from the State University of New York at Stony Brook in 1972 and earned his MS (1973) and PhD (1978) at Caltech.


MURRAY
GELL-MANN

Where Are Our Efforts Leading?

A birthday celebration connects topics on the fundamental laws of nature and on international cooperation and environmental conservation—among others.

Paul MacCready (left), creative vehicle inventor, and physicist Valentine Telegdi meet at the conference honoring the 60th birthday of Murray Gell-Mann.

"All my life I've been concerned that human beings learn to understand nature, which includes ourselves, and that we learn how to get along with nature, which includes getting along with one another."

With these words Murray Gell-Mann, Caltech's Robert A. Millikan Professor of Theoretical Physics and the final speaker in a two-day conference celebrating his 60th birthday, summed up the diverse interests that had established the theme of the conference. The topics ranged from elementary particle physics (the field in which Gell-Mann won the Nobel Prize in 1969) and quantum cosmology (one of his current interests), to environmental conservation and biological diversity (he is a lifelong conservationist), and international cooperation and complex systems (some of the areas supported by the John D. and Catherine T. MacArthur Foundation, of which Gell-Mann is a director). However disparate the subjects of discussion may have appeared at the beginning, the links and connections began to come to light as the conference proceeded. As Gell-Mann concluded, "The emergence of a pattern is the special joy of the theorist."

Provost Barclay Kamb opened the conference January 27: "Murray Gell-Mann is vigorously engaged in a search for order and reason in the universe and in nature, from the grand scale of the entire expanding universe to the ultramicroscopic scale of the elementary particles, and with strong attention also to the intermediate scales of our Earth and our lives."

Under the general theme: "Where are our efforts leading?" speakers were asked to reflect on where attempts to meet a particular challenge in science or human affairs currently stand, and also to speculate about how current efforts will look from a future vantage point, and where those attempts will lead in the decades to come. The physicists led off—with topics on the grand scale and the ultramicroscopic scale. (Session chairmen included such renowned physicists as Francis E. Low, Yoichiro Nambu, Yuval Ne'eman, David Pines, Nicholas P. Samios, and Kenneth G. Wilson.)

While the physicists did not shrink from speculating, they were not always in agreement about the future and about the future's assessment of the present. Edward Witten, professor of physics at the Institute for Advanced Study, expressed eloquent confidence that current mysteries are on the brink of solution.

"Our epoch will no doubt be seen as the epoch in which quantum field theory, which was a frail child at birth, full of problems and inconsistencies, came of age, with her frailties and anomalies now seen as signs of strength and beauty, tied up with the natural world. . . . Our epoch will also be seen as a time when quantum field theory, in thus coming of age, has emerged, as perhaps it was not in the past, as a truly fit partner for a faithful match with that other great branch of geometry—Riemannian geometry and general relativity. I hope that our epoch may be seen as an age in which progress in understanding the strong, weak, and electromagnetic interactions led physicists, screaming and kicking though they may have been at first, to become

"It will be seen as an age in which through these gaps in the clouds we've seen our first glimpses of a wonderful new landscape, which is still largely beyond our imagination."

From left above: Francis Low, Valentine Telegdi, and Nicola Khuri stroll toward Beckman Auditorium for the Saturday sessions. Below: James Hartle (left) and Edward Witten look over the conference program.

geometers again. It will be seen as an age in which the serendipitous discovery of dual models and the many great discoveries in string theory that followed in the 1970s and 80s, and I hope beyond, have opened gaps in the clouds and enabled us to begin grappling with problems that rightfully should have been reserved for the 21st century. It will be seen as an age in which through these gaps in the clouds we've seen our first glimpses of a wonderful new landscape, which is still largely beyond our imagination. And I think it will be seen as an age in which the visions, the glimpses that we've gotten through the clouds, go well beyond what we can reach with the available tools and in which the search for better geometric understanding is likely to be one of the great engines of progress."

In agreement with Witten on the significance of geometry was Isadore M. Singer, Institute Professor at M.I.T. In his talk on the liaison between mathematics and physics, Singer predicted that mathematicians and physicists will have to "look to the young people for appropriate attitudes. It's still surprising to me how many older physicists think that the only mathematics relevant to physics is what they learned as a graduate student." Singer emphasized in particular how math and physics are related in the study of space and time, noting Witten's recent introduction of topological quantum field theory. "It's hard to believe that ultimately those insights [into new, exotic space-times] will not have some impact on what happened at the Big Bang or what happens in the large in astrophysics." But his predictions for the rest of the 20th century were not quite so sanguine. "Will it be a golden age? For geometry, yes. We will have understood quantum-mechanically as well as classically the nature of three and four dimensions. Application to elementary particle physics? To be seen."

Not all the speakers peered into the future or assessed our own era. T. D. Lee, University Professor at Columbia and a Nobel laureate, presented an elegant effort of his own, which he dedicated to his long friendship with Gell-Mann and which he described as an example of the "mini-maxi principle"—deducing maximum theory from minimum experimental results—at which Gell-Mann is an acknowledged master. Lee addressed himself to a question of how high temperature superconductivity works—do the electrons pair before a material becomes superconducting, or is the creation of electron pairs and superconductivity a simultaneous event? From a comparison of the lattice architectures of high temperature superconducting materials, Lee deduced the latter.

Harald Fritzsch, professor of theoretical physics at the University of Munich, discussed the mystery of the electron mass—why do masses divide particles neatly into three families, and why is the electron so light? Some theorists postulate the existence of a very massive particle, called the Higgs boson, which interacts with other particles to give them their mass. (Witten referred to the Higgs boson as "one of the keys to astronomy and to life.") But Fritzsch thinks that it is very unlikely that the Higgs particle exists. "Personally I believe that things go in a

Yuval Ne'eman (left) and Isadore Singer enjoy drinks and discussion.

different way—that somehow this Higgs particle is just describing something more dynamical; in other words, little things are going on inside, and then we come to a situation where we have not only the nucleons composed of quarks but also the quarks composed of something else—or at least the Higgs particle composed of something else."

In the future, concluded Fritzsch, "new experiments will tell us which way to proceed—not new theories, but new experiments. Nevertheless I think it will still be a long way to the ultimate goal, namely a complete understanding of the particle physics phenomena. Some theorists, including Murray, believe that they are very close to this goal . . . but I think this is not the case. I believe we shall open another gate at the beginning of the nineties full of surprises, but the end of the road is still far beyond our present horizon."

Valentine L. Telegdi, professor of physics at the Eidgenössische Technische Hochschule in Zurich, spoke on the "shelved atom" as an example of the quantum mechanics of nonobservation—"what happens if you don't do something or don't see something." He also predicted that "the next 20 or 30 years will not be some enormous jump forward in particle physics because the energies that we will be getting are not sufficiently different from what we already get now or in the next year or two. But I think that it will be accompanied on the one hand by this weird mathematics that you heard Professor Singer talk about as the thing all young people should know (at which point I was extremely happy not to be a young person), and on the other hand by some anti-Copenhagen sanity recipes, courtesy of Gell-Mann and Hartle."

These "anti-Copenhagen sanity recipes" had been described earlier in the afternoon in a talk on quantum cosmology—the application of quantum physics to the universe as a whole—by James B. Hartle, professor of physics at UC Santa Barbara. Hartle described his and Gell-Mann's search "for a quantum framework that would enable us to erect a fundamental description of the universe on all scales—from the microscopic scales of the elementary particles out to the largest scales of the realm of the galaxies, from the moment of the Big Bang out to the most distant future that we can contemplate. Such a framework is needed if we accept, as we have every reason to do, that at a basic level the laws of physics are quantum mechanical."

Building such a framework will involve discarding "excess baggage," as in the past the idea of a central Earth and the idea of a fixed geometry, which were the consequence of our particular position in the universe, had to be jettisoned to reach a more general and successful viewpoint. Hartle described the Copenhagen interpretations (Bohr, Heisenberg, et al.), which in various ways took "as fundamental the manifest existence of the classical world that we see all about us." But, he went on, "in retrospect, the Copenhagen idea that a classical world or an observer in the act of measurement occupy a fundamentally distinguished place in quantum theory can be seen to be another case of excess baggage. . . . However, these features of the world are not fundamental. Quantum mechanically, the classical world and observers are but one possibility among many and are unlikely to exist at all in the very early universe. They are . . . approximate features of the late universe, arising from a particular quantum state. The classical reality to which we have all become so attached by evolution is but an approximation in an entirely quantum mechanical world made possible by specific initial conditions." Our classical notion of space-time may be another example of ideas that will have to be discarded, Hartle said.

Hartle concluded by expressing the hope "that in the future this might be seen as the time when scientists began to take seriously the idea that it was important for fundamental physics to consider the universe as a whole and science itself as a unity; the time when they began to take seriously the search for a law of how the universe started; the time when they began to work out the implications of this law for science as a

"The gap between the realities of science and technology and the understanding of those realities by our government leaders is growing ever wider."

whole; and the time when we began to discard the remainder of our excess baggage."

The idea of unifying principles, an inspiration from the physicists, carried over to the second day of the conference, which concerned "the intermediate scales of our Earth and our lives."

Unfortunately, the search for unity has been lacking in much of the approach to social problems. John E. Corbally, president of the John D. and Catherine T. MacArthur Foundation, led off the Saturday sessions, noting that "we social scientists seem to delve ever deeper into more isolated aspects of human behavior. . . . There is no unifying principle. Our consideration of education is primarily a consideration of schooling, and we pay little attention to the environments in which both schooling and education take place in the world today. We tend to ignore the chemistry of the brain and the relationship of birth weight and nutrition to that chemistry. We think of motivation primarily in economic terms and ignore the degree to which motivations related to participation in society might be appropriate. We build new schools, and we ignore the alleys in which a great majority of inner-city learning takes place. It's as if we were studying the paths of bodies through the atmosphere without considering the force of gravity."

Former Caltech President Murph Goldberger (left) and current President Tom Everhart compare notes.

We don't have to worry about our analytical abilities, according to Corbally. But "what seems to be lacking are the synthesists who can put back together in meaningful ways what the analysts so gleefully tear apart."

Anthropologist Robert McCormick Adams, secretary of the Smithsonian Institution and former provost of the University of Chicago, also decried the lack of unity in the social sciences. "The social sciences exist today in a condition of vague, frequently contentious paradigmatic pluralism. . . . Some degree of disarray is obviously healthy and unavoidable . . . but what confronts us at present is far beyond this natural and even desirable level of microspecialization and messiness." Because of this splintering, the "important, problem-oriented issues [of our time] are slipping through our analytical nets."

Adams pointed out that, although both social and natural systems are frequently governed by nonlinear dynamics, it is difficult to encompass them in a unified science (such as chaos theory) because social structure and the flow of events in human history are indeterminate. Chaos in a formal sense is deterministic; it obeys mathematical equations.

Some spheres of social activity are, however, fairly orderly and verge on true determinacy, and Adams stressed the place of "both chaotic and indeterminate behavior in the study of human societies. To do so directs attention to instability, fluctuation, stresses and consequent changes beyond tolerable limits and thus to the modes by which human societies have adapted to these difficult-to-identify but ever-present challenges."

The challenges facing global society and the problems of international cooperation occupy the primary place in the MacArthur Foundation's agenda of concerns, and represent its largest single spending program. James M. Furman, the foundation's executive vice president, described this commitment and emphasized how important it is for institutions to find new ways to look at international cooperation in the years ahead. "I'm afraid that too many universities have changed very little in considering international problems of peace and security. . . . The future of international cooperation is tied in large part to how successfully and how rapidly we can bring about institutional change—change in our own institutions and those of others." It will be necessary, concluded Furman, "to address international cooperation with a perspective and understanding that cuts across the single disciplines, the straitjacketed attitudes reflected in current thinking and practices."

This concept was echoed by Sidney Drell, professor and deputy director of the Stanford Linear Accelerator Center, and until recently codirector of Stanford's Center for International Security and Arms Control, a position he resigned when the university refused to consider for tenure academics working at the center. "The traditional academic structures of many of our

From left: Adele Simmons, incoming president of the MacArthur Foundation, Gell-Mann, Shirley Hufstedler, and Robert Adams applaud the banquet speaker.

great universities are proving highly resistant to the creation of mechanisms for undertaking multidisciplinary work on policy studies in a serious and sustained way," he said. "This applies both to offering resources to support work and to bestowing academic titles, which are the knighthood of the realm, and which are generally reserved for appointment in traditional departments on traditional subjects. I believe strongly in a healthy conservatism in this area in order to maintain rigorous academic standards and to avoid going overboard chasing the latest fashion in policy work. But there comes a point when the process of appointments gets so rigid that innovation is stifled, and the process gets in the way of achieving goals. . . . It is appropriate for universities to uphold the ivory tower from which to peer out over the landscape with widened horizons and a better perspective, the better to anticipate future changes and dangers. But this need not be their exclusive destiny. They can also serve a constructive role in our society by coming down to the ground and entering into the fray of creative, multidisciplinary policy issues challenging today's societies."

Drell and Gell-Mann were charter members of Jason, a group of academic scientists supported by the government to work part time on problems of national importance, particularly the technical ingredients crucial to defense policy decisions. "It was the conviction that we could contribute to sound policy through our technical analyses that motivated our joining Jason and led to further governmental involvements." Looking back on his government work, however, Drell could think of few activities in his life "where the ratio of output to input was so small and the results so frustrating. The gap between the realities of science and technology and the understanding of those realities by our government leaders is growing ever wider. . . ."

The MacArthur Foundation had been crucial to him, Drell said, "in encouraging efforts to work for peace and security through multidisciplinary research and teaching." These kinds of problems involve cultural, behavioral, ethical, and political issues in addition to the technical ones. Such thinking, and a failure of existing institutions to address multidisciplinary issues, led to the founding in 1984 of the Santa Fe Institute, supported financially by the MacArthur Foundation (along with the Department of Energy, the National Science Foundation, Citicorp, and others) and intellectually by Murray Gell-Mann. Another of the day's speakers, George Cowan, gave up his research as a radiochemist at Los Alamos to become president of the Santa Fe Institute because, like Drell, he was "fascinated by what I perceived as a huge and almost unbridgeable gap between facts and policy making."

Cowan interpreted the arena of policy making as encompassing more than security and nuclear war and emphasized that "it's increasingly likely that an exponential erosion of the basic resources essential to human life over a period of relatively few decades will produce catastrophic damage to the structure of modern society. The threat of war may well recede and be overtaken in priority of concern by immediate

Two Nobelists, Abdus Salam and Murray Gell-Mann, discuss a point—of physics or Third World policies.

"The threat of war may well recede and be overtaken in priority of concern by immediate dangers."

dangers." The factors that threaten to produce such a catastrophe, Cowan said, are nearly all related to exponential population growth.

Shirley Hufstedler, Caltech trustee and former secretary of education under President Carter, also emphasized the population problem. "No country, including our own, can manage its economy or maintain sustainable development without addressing . . . the population issues. But that means we must address the issues of women and girls," said Hufstedler. She cited numerous statistics reflecting the soaring birth rate, lack of education, and abysmal reproductive health care of women in poor countries. Family planning does not lack adequate technology; but there needs to be a "distribution of that technology in ways that are culturally acceptable to the women and girls who need it. . . . We should not comfort ourselves that we know how to approach the issues effectively until we do the hard, grass-roots work of understanding the complex systems that have created and maintained those sets of behaviors."

Education, although it does not provide an exact correlation with fertility, is still one of the best indicators for success of population-control programs, said Hufstedler. "The amount of education that girls and women receive influences all their life opportunities. . . . It influences the age of marriage, control over childbearing, paid employment, and access to family planning and health care. Because it is the childbearing aspect of these women that is the most significant in terms of the impact of education, I say that it is even more important to educate these girls and women than their male counterparts."

Abdus Salam, Nobel Prize-winning physicist, and director of the International Center for Theoretical Physics in Trieste, also upheld education as the solution to problems of the Third World —but education in science and technology. The only factor that distinguishes the North from the South, he believes, is "the mastery, the utilization of science and technology." For example, he stated that in his native Pakistan there is a total of 46 PhDs in 19 universities. (Hufstedler's figures noted that only 17 percent of Pakistan's school-age girls are enrolled in school, and that women bear an average of seven children.)

Salam suggested some steps developed countries could take to improve the situation: earmark 10 percent of aid funds for science and technology; support requests (especially to university publishers) for scientific literature; and, through the United Nations, support international centers for science such as the one he directs in Italy.

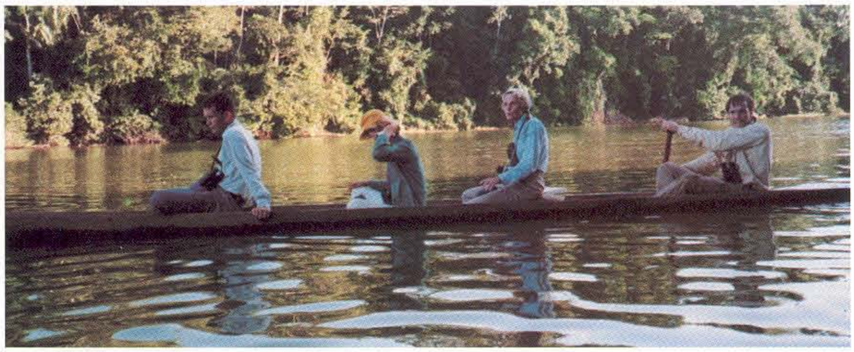
Science and technology also have a role to play in environmental conservation, according to James Gustave Speth. "Environmental protection must become an affirmative process of redesigning transportation, manufacturing, energy, and housing, so that all of these sectors are more closed and isolated from their impacts on the natural environment. This transformation will challenge science and technology in ways that we can only dimly perceive today." Speth, one of the leaders of the international conservation movement, was formerly chairman of the President's Council on Environmental Quality,

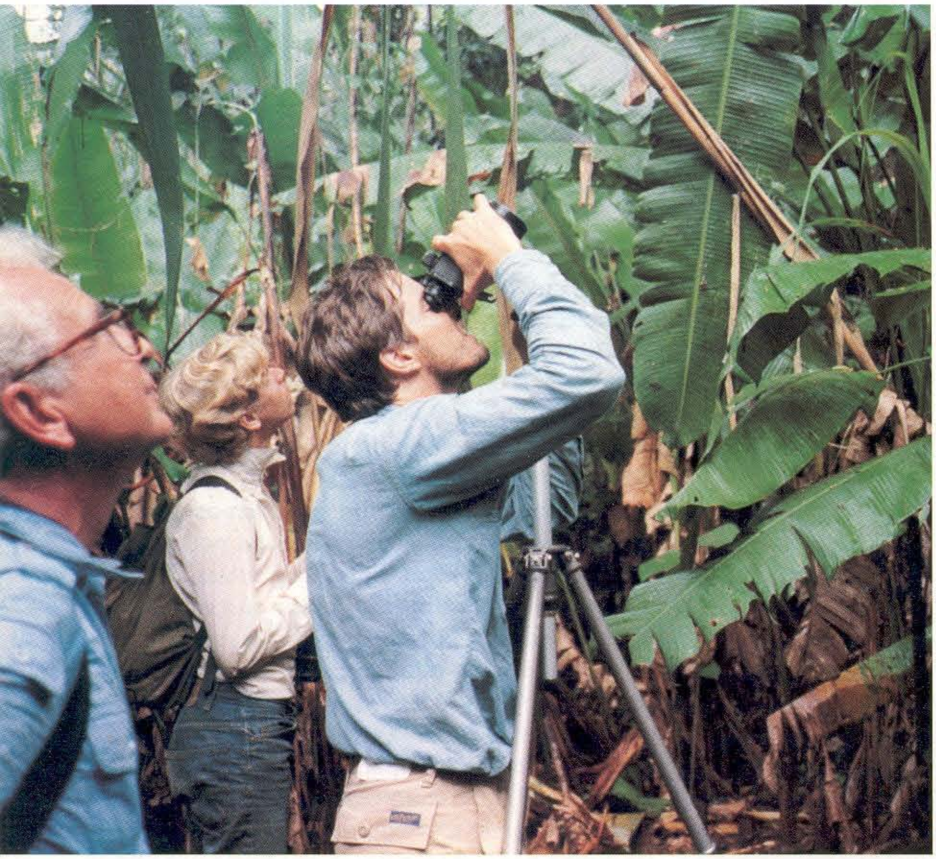
What was once a forest north of Antsirabe in Madagascar is now barren, eroded land, the result of burning. Settlers from Southeast Asia brought the tradition of clearing the land with fire, which is sustainable in an area with more rain and more soil but not here. Timbering (here in the Ranomafana area of Madagascar) is also a danger to survival of the rain forests.

and he is now president of the World Resources Institute, which he and Gell-Mann had worked to "shape and define" together in 1981-82. Another interdisciplinary undertaking supported by the MacArthur Foundation, the World Resources Institute taps the expertise of biologists, physicists, chemists, economists, bankers, businessmen, journalists, former government officials, and experts in environmental policy and Third World development, among others.

Speth was hopeful that "a new and more international environmental agenda is emerging" as political leaders begin to pay attention to these issues. And political leaders are starting to pay attention because this new agenda "affects international economic and political goals—expanding international trade and markets, promoting Third World economic development, and insuring long-term political stability in the world." Speth suggested making conservation a priority mission of international cooperation in the 1990s—an international environmental decade—to deliver a sustained planet as a gift to the new century.

One of the problems Speth noted is that the major debtor countries are also tropical countries and the principal sites of vast global deforestation. He emphasized the importance of a "planetary bargain" that would couple debt relief and wise stewardship of tropical forests. One magnificent and well-preserved area was described by Charles A. Munn, who also had a partial solution to offer for other places. Munn, an associate research zoologist with Wildlife Conservation International, has spent 12 years studying animals in the tropical forests of the Peruvian





A group of tourists (top) explore Peru's Manu National Park by boat. The "world's foremost nature tourist" (above, left) observes birds with Charles Munn in Manu. On the facing page, a cebus monkey, one of the park's inhabitants, forages for a meal.

Amazon, and he brought along slides and a film (giant otters fishing, macaws nesting) of the inhabitants of Manu National Park, where he works. Munn described tropical forests as covering 7 percent of the land surface of the globe but probably housing more than 95 percent of all species of life. "Half of the world's tropical forests have been destroyed just in the last few decades, and the rate of destruction has been increasing."

Munn's suggestion for a solution to the dual problems of vanishing tropical forests and Third World poverty was nature tourism, an undertaking he has promoted in Peru. "Nature tourism is the fastest growing segment of the international tourism market . . . and it could provide more income and employment sustainably for more local people than any other form of economic development." Nature tourism also fosters a two-way education "about the aesthetic and economic value of wilderness and nature. Both tourists and local tour operators experience nature together, sharing viewpoints from vastly different cultures. . . . It should teach both to be better stewards of the natural world." Munn thought his topic particularly appropriate for the occasion "because Murray himself is without doubt the world's foremost nature tourist."

"Murray is a man with his head in the sky and his feet in the mud," was how Peter Seligmann described the same phenomenon. But Seligmann, president of Conservation International, was not as sanguine about solutions to Third World problems. "Creating an inviolate park in a region of the world where social and

"Half of the world's tropical forests have been destroyed in the last few decades, and the rate of destruction has been increasing."

economic crises are acute is foolish. We need solutions to these complex problems, and the solutions have not yet been found. . . . The confluence of today's global problems demands a more strategic, a more experimental philosophy —one that seeks to integrate the elements of an interactive system in which biological diversity and ecological processes are maintained and legitimate human needs are met, and the knowledge of the interdependence of human and natural processes is deepened. This is ecosystem conservation—a philosophy of regional development that unites place and process."

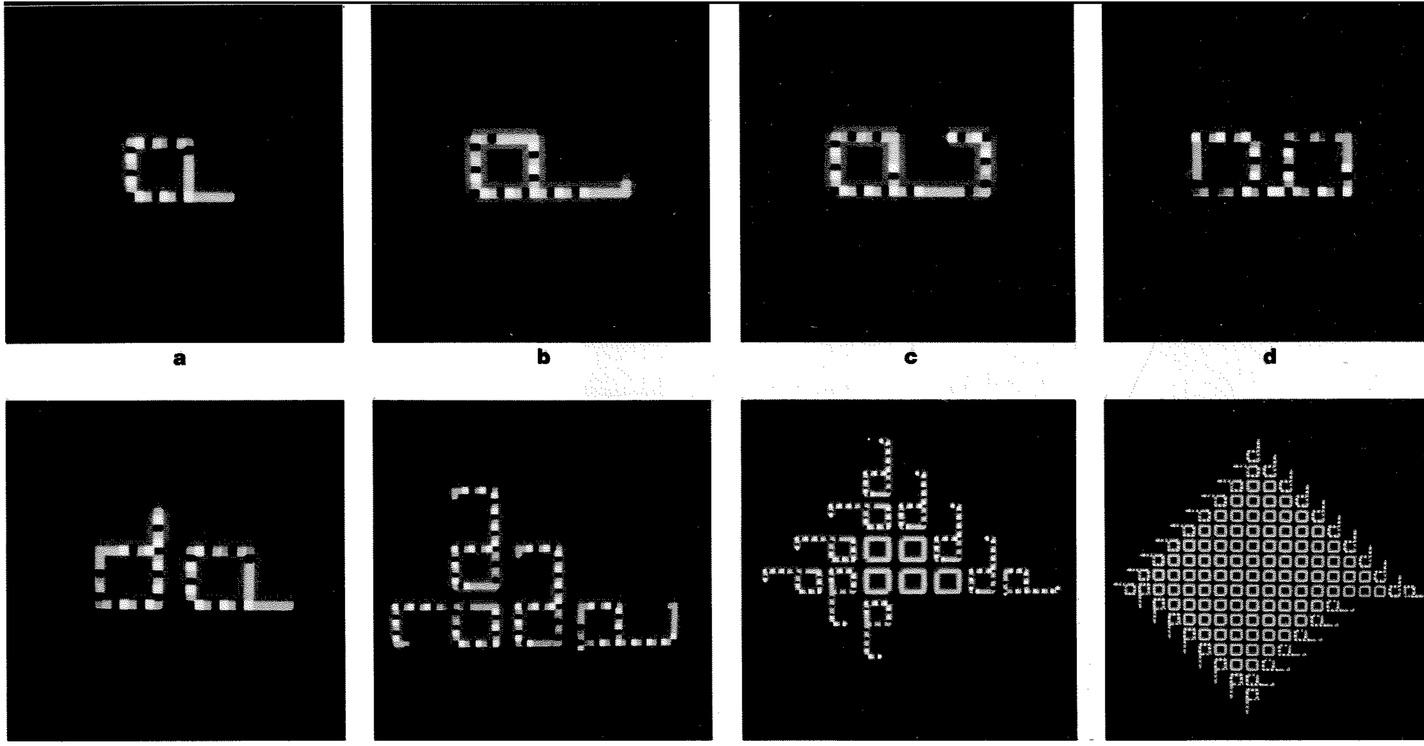
George Cowan also emphasized complex interactions such as those discussed by the conservationists. "If we wish to be effective, we must better understand the coupling between facts, policy making, and human behavior. . . . All of these components and our potential interventions are strongly interactive and influence the behavior of the system as a whole in ways that can't be predicted from intensive research on the individual parts." The decision to found the Santa Fe Institute "to nurture research in the sciences of complexity was stimulated by the obviously growing need for a broader and more coordinated approach to the real problems of society. . . . On questions of global security and conditions necessary for a sustainable world, it's evident that we're dealing with almost the ultimate example of complexity."

Such complex systems are usually nonlinear, said Cowan, and must be examined in their entirety to see their essential properties. Numerical simulation on powerful computers is providing a sort of "intermediate laboratory midway between theory and actual experiment. And in addition, a mathematics of nonlinear dynamics is emerging that is strengthening the theoretical treatment of complexity."

Among the young scientists who have started to create the new sciences of complexity is J. Doyne Farmer, group leader in the theoretical division at Los Alamos National Laboratory and an external professor at the Santa Fe Institute. Farmer described the field of complex systems as one in which "the emphasis is on the nonlinear interactions of simple things . . . on the emergent properties when simple things interact and generate complex behavior."

The most important problem facing scientists in the next 50-100 years, said Farmer, will be understanding "the inexorable tendency for the formation of structure and organization in nature." And one particular approach to that problem is the study of artificial life—"man-made systems that exhibit behaviors characteristic of living systems. . . . It's a pattern in space-time that involves things changing in time—a pattern rather than a material entity in and of itself." The motivation for doing this, said Farmer, is that "if we can actually construct life then we have a hard measure of whether or not we understand something about it. . . . One of the central questions in artificial life is understanding what *is* life."

Farmer showed slides of several computer-generated models (cellular automata) capable of self-reproduction, the formation of colonies, and other remarkably complex behaviors—including



a b c d

e f g h

Chris Langton, postdoctoral fellow at Los Alamos, developed this cellular automaton model of self-reproduction. Signals propagating around the "Adam" loop (a) cause the short arm to grow and curl back on itself (b, c, d), producing an offspring loop (e). Each loop then goes on to produce further offspring, which also reproduce (f). This process continues indefinitely, resulting in an expanding colony of loops (g, h), consisting of a "living" reproductive fringe surrounding a growing "dead" core, as in the growth of a coral.

one designed to model "in a very metaphorical way" the behavior of an ant (antomaton). But these just mimic life. "Ultimately the challenges that we face are to produce artificial organisms that spontaneously emerge with no predefined fitness function; that can display the ability of evolution to innovate as well as just optimize; to have genuinely emergent properties that have functional interactions with their environments; that exhibit automatic design without predefined goals; where we see the emergence of organisms with identities. . . ."

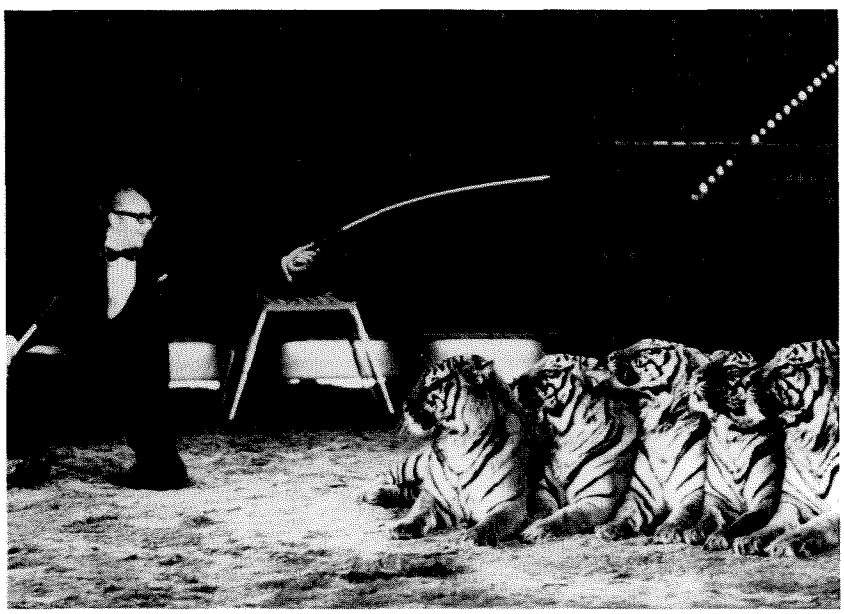
Supercomputers will achieve the hardware equivalent of human intelligence by the year 2000, said Farmer, and PCs by 2025. "I think what we're about to see is the ability to make Lamarckian changes in hardware, wherein a conscious organism can actually change the hardware in which another living organism resides. . . . I think that in 100 years we will no longer have a monopoly on intelligence." While he viewed this as a very dangerous thing, he did not consider it bad, but rather "something that could possibly be beautiful," by creating biological diversity. The creation of artificial life, concluded Farmer, is "an inevitability that we can only hope to shape."

A more familiar complex system, the human mind, was discussed by Mardi Horowitz, director of the Program on Conscious and Unconscious Processes at UC San Francisco, another interdisciplinary research facility supported by the MacArthur Foundation. Horowitz discussed the unconscious control of conscious experience related to intrusive thoughts. "What becomes conscious seems to be a concatenation of multiple values and hierarchies decided by an unconscious and very clever control process." This involves schemas (defined roughly by "you can't teach old dogs new tricks"). Using as an example the process of grief, Horowitz described the "reschematization" process of recovery. "It takes time to change the inner cognitive map." Learning more about unconscious thought processes and schemas is important, claimed Horowitz, in understanding values (such as those that lead to the difficulty in changing population growth standards) and how they are transferred between generations.

Horowitz also touched on creativity and suggested the sort of unconscious schemas that make up creative thought. Paul B. MacCready, president of AeroVironment, Inc., also spoke on creativity and thinking skills. MacCready is known for building "peculiar" low-powered vehicles—from the 1977 human-pedaled airplane, the *Gossamer Condor*, to last year's solar-powered *Sunraycer* automobile—"all impractical, but unusual and interesting and valuable as catalysts and symbols to stretch minds," he said. MacCready strongly advocated programs that "give the tools . . . to perceive openly, to operate from a broad perspective and healthy skepticism, and to process information creatively." He claimed to be "a fair pessimist about civilization's future," agreeing with Farmer that surviving life may well be not carbon-based at all—but rather silicon- or gallium-arsenide-based.

John H. Schwarz, professor of theoretical physics and co-organizer of the conference,

Taming tigers — requirement for a Renaissance man.



attempted in its waning moments to portray Gell-Mann's accomplishments by listing (just for fun) all the physics terms he had introduced—from "quarks" to "strangeness" to "gluons." But MacCready, who had also attempted to describe Gell-Mann's contributions, concluded that, "Murray Gell-Mann can only be characterized by two days of talks by friends from around the world." □ — *JD*

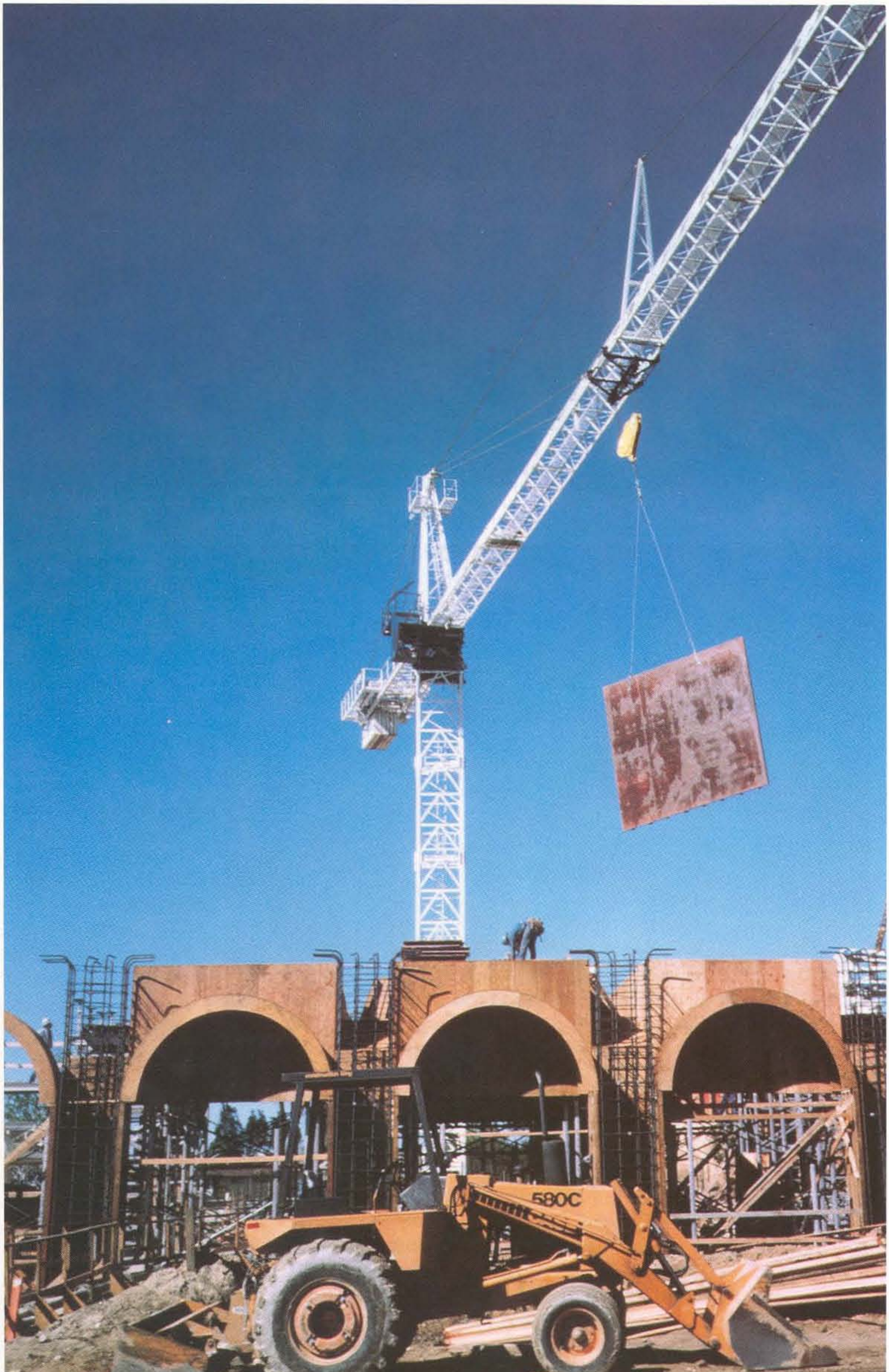
The conference proceedings will be published by Cambridge University Press.

Most of the participants couldn't resist taking the occasion of "celebrating 60 years of Murray Gell-Mann" to make some good-natured fun of his well-known extracurricular interests—languages and birds in particular—and of the occasion itself. Telegdi pointed out that since Gell-Mann's birthday is in September, the conference must really be commemorating the 60th anniversary of his conception. Nicholas Samios, director of the Brookhaven National Laboratory, remarked that it was characteristic of Gell-Mann to reach 60 faster than anyone else. And Nobel laureate Kenneth Wilson, professor of physics at Ohio State, speculated that Gell-Mann's early start in physics was due to his childhood realization that he had been born 10 billion years too late to observe the Big Bang and didn't want to miss anything more.

Although birds belonged perhaps more aptly to the second day of the conference, tales of Swiss birds, Israeli birds, etc., crept into the physics sessions as well; Telegdi entitled his talk "Is Quantum Mechanics for the Birds?"

Gell-Mann's rigorous attention to correct pronunciation (in many languages) came in for some ribbing. Corbally confessed to always waiting until Gell-Mann left the room before attempting to pronounce any foreign word. Seligmann informed the guest of honor that "my father tells me I *am* pronouncing my last name correctly." And more than one speaker described being suddenly hailed at some foreign airport in impeccable idiomatic Mandarin (or Hebrew, or . . .) with the subsequent discovery that the hailer was, of course, Murray Gell-Mann. But Marvin Goldberger, director of the Institute for Advanced Study and former president of Caltech, recalled stories of less-than-dazzled Chinatown waiters and unimpressed fishermen on the Isle of Skye (where Gell-Mann attempted some Gaelic). At the closing banquet Goldberger delivered his birthday greetings in Fang, a Bantu language spoken in western equatorial Africa, and Nicola Khuri, professor of physics at Rockefeller University, opened his remarks in Kurdish.

Telegdi offered a dubious etymology of the honoree's name, and showed some doctored slides of Gell-Mann as the true Renaissance man—as orchestra conductor, chef, acrobat, fencer, and tamer of tigers.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Beckman Institute Becomes Concrete

The Institute will be supporting potential home-run hitters.

Workers assemble the forms for the Beckman Institute's east facade. The arches open onto the central courtyard.

Once a gleam in the eye, then a hole in the ground, the Beckman Institute is rapidly rising in the northwest corner of campus. The official dedication is slated for October 1989, and the real dedication for several months later, when the interior is finished and the building is habitable. Even now, the prospective inhabitants are packing their bags, at least mentally, in preparation for the move-in.

Research in the Beckman Institute, in its standard press-release description, "will focus on the invention of methods, instrumentation, and materials that hold the promise of opening new avenues for fundamental research in chemistry, biology, and related sciences . . . an environment that will promote the initiation and early development of research that may be deemed too innovative for more conventional funding." In other words, the Institute will be supporting potential home-run hitters, whose research could cause far-reaching changes if it doesn't strike out.

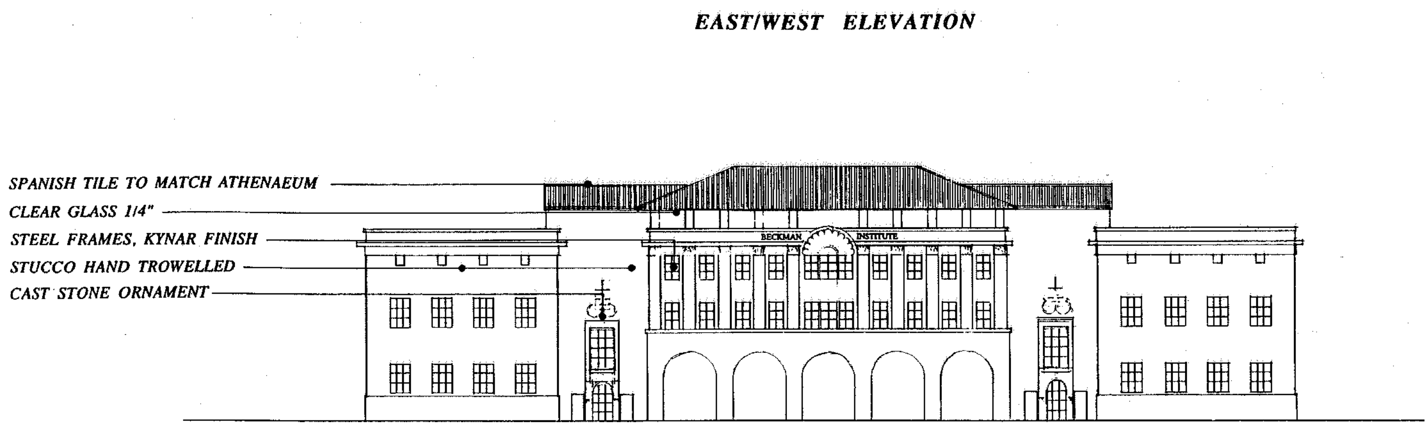
The Institute is the brainchild of Life Trustee and Chairman Emeritus Arnold O. Beckman, whose \$50 million pledge sparked the project. The pledge includes an endowment fund that will provide seed money to get promising research off the ground. According to Harry Gray, the Beckman Professor of Chemistry and Director of the Beckman Institute, "This guaranteed base supports a project's most critical activities, and, by sharing the risk, will make it easier to attract outside funds."

The Institute will even have a farm team of sorts, a research grant program to fund small-scale preliminary work in the researcher's own lab. A grant will only last a year or two, just long enough to see how things go. When time's up, says Gray, "If it works, we'll stop funding it 'cause somebody else will. If it doesn't work, we'll stop funding it anyway!"

Research space at the Institute is divvied up into "resource centers" based on proposals the faculty submitted in early 1988. Each focuses on developing a particular area of technology. Part of each center's mission is to make the instruments or methods it develops available to the campus community, including undergraduates, in a walk-in, "user-friendly" facility. The Institute's starting lineup includes four centers, and a fifth may be approved soon. Final capacity will probably be seven or eight.

Three (two and two-thirds, actually) centers merge biology and chemistry. Bowles Professor of Biology Leroy Hood's Center for the Development of an Integrated Protein and Nucleic Acid Biotechnology will continue his group's automation of the analytic and synthetic techniques basic to molecular biology and genetics. Professor of Chemistry Jesse Beauchamp's Center for High-Performance Mass Spectrometry is working on a different approach to one of the same problems that would give biotechnologists a whole new set of tools. And two of the three principal investigators in the Structure and Spectroscopy Center (Gray and Professor of Chemical Physics and Biophysical Chemistry Sunney Chan) are looking at the chemical means to biological ends: how biomolecules move chemicals and energy.

The other occupants are doing straight chemistry. Shell Distinguished Professor and Professor



"We'd rather seed something new that looks exciting than keep propping up something that isn't working."

of Chemistry John Bercaw, the third collaborator in the Structure and Spectroscopy Center, is looking at catalytic processes. The Materials Resource Center will include Professor of Chemistry Robert Grubbs and Associate Professor of Chemistry Nathan Lewis, who will be exploring ways to make new solid-state materials with unusual properties, and Professor of Chemistry John Baldeschwieler, who will be setting up a scanning-tunneling and atomic-force microscopy facility to look at their creations.

The centers will vary in size and longevity. Beauchamp's will have four or five people; Hood's may eventually have as many as 30. In theory, everyone is a transient—doing a specific piece of work and moving on. According to Gray, "The larger centers, like Hood's center and the materials science center, will probably be there for a long time, but will emphasize different themes. People—perhaps even principal investigators—will come and go, but the fields are so broad that there is going to be something interesting to do for a long time. A smaller center, like Beauchamp's, is more narrowly focused on a certain problem, so either he will be successful and stay on, or be unsuccessful and quit."

Funding mechanisms will vary, too. Hood's center, for example, will live entirely on "soft money"—outside funds. "In fact," says Gray, "all successful centers will have a substantial amount of external support. The very high-risk centers will rely more on hard money to get started, but those that don't attract external funding after the first two or three years will certainly die. And we'd rather seed something new that looks exciting than keep propping up something that isn't working."

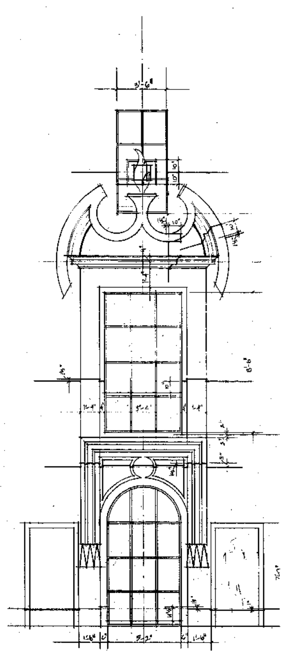
The resource centers will also attract outside collaborators, who might stay for six months or a year while they work on a particular problem. A Visiting Scholars' Center, complete with offices, conference rooms, and a lounge, will take up part of the third and fourth floors.

The building will also house some things not part of the Beckman Institute proper: additional space for computation and neural systems laboratories, various kinds of biology, materials science and applied physics, and the Caltech Archives.

While the above sounds simple, logical, and straightforward, it didn't come easily. The ideal Institute's mission had been defined very broadly, with the details to be penciled in later. But someone had to pick up that pencil before the real Institute could open for business. The first decision was to organize into resource centers. Others quickly followed: how would the centers operate? Who would occupy them? How much space and money would each one get, and where, exactly, would it go? All these questions fell to an executive committee to answer.

The committee's first project was drawing up a charter stating exactly what the Institute's mission was, and how to go about it. The Institute's novel approach to research meant that the usual rules didn't quite fit. But the new rules had to meet everyone's notion of how Caltech should operate. Jay Labinger, the Beckman Institute's administrator, helped Gray keep things on track, "basically making my life bearable," Gray says. It took a year and a half of

The Institute's novel approach to research meant the usual rules didn't quite fit.



monthly meetings to hammer out a charter. Recalls Labinger, "The most difficult part was getting all the committee members in one room at the same time. You'd find out there's only one day when everyone's free, and it's not till the middle of next month. So we did a lot of work by memo. That charter went through I hate to think how many iterations. Harry and I would circulate a draft to the committee, and people would make all kinds of changes, and this kept going until everyone was happy. And then we took our revised semi-final version to the chemistry and biology divisions, who made changes, so we took it back and rewrote it again. Then it went to the administration, who had their own concerns, of course, and it finally converged into something everyone could agree on. But everything else really flows from that document."

What flowed from that document was step two: selecting the resource centers and allotting them space and money. These two tasks took about six months each. Says Labinger, "We had to cycle several times between the committee's reading of what each proposer really needed, as opposed to what they asked for, and what we could afford to give them. Space, for example: not only how much space, but where. Certain operations should really go in the subbasement, things that need to be shielded from vibrations. And some centers should be next to each other to foster interactions—Hood's and Beauchamp's, for example: their programs are quite different, but their goals are pretty much the same. And we didn't want to give away the whole building in the first round, locking ourselves in. But the leftover space had to be usable—not a closet here, a lab there, and an office somewhere else. And indeed, we have at least three good-sized contiguous areas left.

"And the budget is pretty much the same. The first few years are complicated, because you have heavy equipment purchases as well as salaries and operating expenses. Do we actually want to spend some of our capital on equipment? If we do, it's an investment in the Institute, but it takes dollars out of your endowment, so you have less income in later years. We have to decide all these things."

The committee will continue making these decisions over the years as resource centers come and go. Except for Gray, Labinger, and the biology and chemistry division chairmen, who serve *ex officio*, the members serve three-year terms expiring at staggered intervals, guaranteeing fresh viewpoints. This past fall, Giuseppe Attardi, the Steele Professor of Molecular Biology, replaced Professor of Biology John Abelson. The other members are: Hood; Grubbs; Bren Professor of Chemistry Peter Dervan; Chandler Professor of Cell Biology Eric Davidson; Chandler Professor of Chemical Biology, Emeritus, Norman Davidson, acting chairman of the Division of Biology; and Professor of Chemistry Fred Anson, chairman of the Division of Chemistry and Chemical Engineering. Members who do not have research going on in the Beckman Institute, such as Eric Davidson, bring valuable perspective to the committee, while the internal members, such as Hood, provide feedback on how decisions are working out in practice.

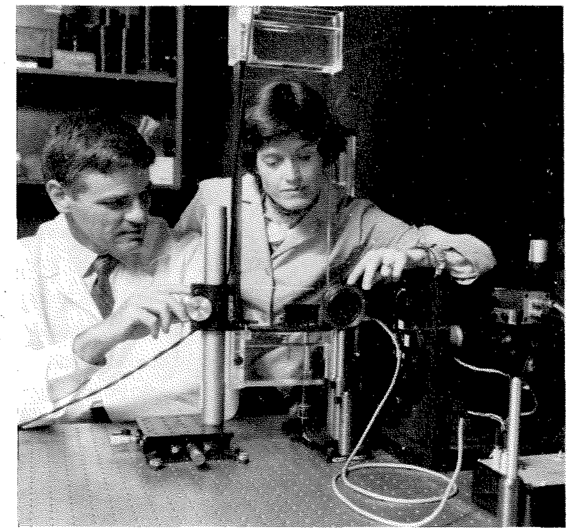
Lee Hood's Center for the Development of an Integrated Protein and Nucleic Acid Biotechnology will be the largest resource center by far, occupying the lion's share of the second floor. It's so large, in fact, that the National Science Foundation (NSF), which is providing most of the center's funds, requested that Hood step down as chairman of the Division of Biology in order to give it his full attention. It'll probably also be the longest-lived of the Institute's determinedly transient occupants. The NSF is funding the center as one of eleven Science and Technology Centers nationwide. (Caltech also has a half-share, along with Rice University, in the Center for Research on Parallel Computation, to be on Rice's campus in Houston, Texas.) The NSF has the option to continue funding successful centers for eleven years.

"The NSF grant relates to everything we'll be doing in the Beckman Institute, but it doesn't pay for everything," Hood explains. "Our work is divided into two components: one that develops new techniques and one that sets up a means to apply these techniques and make them available to the Caltech community, and, as outside companies get interested in producing the machines, to all scientists. The NSF grant essentially pays for the developmental component."

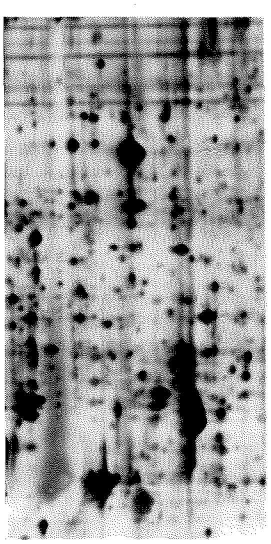
Once a rugged, "user-friendly" machine is produced, the applications team, led by Members of the Professional Staff Suzanna Horvath and David Teplow, work out the procedures the biological community will actually use.

The developmental effort falls into five subgroups. One, headed by Senior Research Fellow Michael Harrington, will be refining two-dimensional gel electrophoresis, a technique for separating complex mixtures of proteins. Another will improve ways to find the amino acid sequences of the minuscule amounts of protein 2-D gel electrophoresis isolates. New equipment to sequence and map genes is being developed by Senior Research Fellow Robert Kaiser's team. All of these projects need specialized instruments,

Right: Hood and Member of the Professional Staff Jane Sanders with the prototype DNA sequencing machine.
Below: Part of a typical 2-D electrophoresis gel (actual size). Standard gels are 20 × 16 centimeters.



A single microdroplet containing about 5,000 cells' worth of protein can yield several thousand spots.



which Charles Spence's group makes to order. And better computer systems to handle and store sequence data are being evaluated by Tim Hunkapiller, a graduate student, and scientists at Caltech's Jet Propulsion Laboratory (JPL).

Before you can even *begin* studying a protein, you have to isolate it—usually from a messy, complex mixture of other very similar molecules. To make matters worse, the most interesting proteins are often the rarest—perhaps one molecule in 100,000. One promising separation method, two-dimensional gel electrophoresis, sorts proteins in one direction by their net electric charge, then in another direction by their mass. An electric field applied to the "gel"—a sheet of polyacrylamide—makes the proteins move. A single microdroplet containing about 5,000 cells' worth of protein can yield several thousand spots on the gel, spots as small as 100 picograms (100 trillionths of a gram) of an individual protein. Although the method's extraordinary sensitivity has gained it wide acceptance since Patrick O'Farrell introduced it in 1975, it isn't used nearly as much as it could be. Reproducibility is a problem—even identical samples prepared by one person often come out a bit differently. The two separations use different gels, and a small alignment error during transfer—sandwiching the gels face-to-face and blotting the spots from one to the other—is almost unavoidable. Harrington's group is trying to develop a machine that will do the whole process in one step on a single gel. The other problem is that the technique *is* so good at separating components. Comparing gels from, say, cultures of normal and diseased cells should reveal missing or aberrant proteins as mismatched spots—a simple and powerful way to find the culprit. But the sheer number of spots, even if they stay put, makes it hard to say for sure that one spot appears (or doesn't appear) on both gels. So Harrington's group is collaborating with Jerry Solomon's image-enhancement and analysis team at JPL, "basically taking the algorithms developed for the Voyager missions and turning them from stars to molecules," as Hood puts it.

Once an interesting spot has been found, researchers need to be able to pluck it off the gel and determine part of its amino acid sequence. (The sample's usually so small that it gets used up before the complete sequence can be found.) Fortunately, a small portion of the sequence contains sufficient information to make a DNA probe that will seek out and bind to the protein's gene. Then the gene can be cloned—making millions of identical copies of itself—and its location on its parent chromosome, as well as its entire sequence, can be determined. Finding a protein's sequence is tiresome but straightforward: a well-known set of chemical reactions clips the first amino acid off of one end of the molecule (the so-called N-terminus), the freed amino acid is identified, and the process is repeated. But even small proteins are hundreds of amino acids long. It's grindingly slow manual labor, taking perhaps six hours per amino acid, but in 1967 a scientist named Edman designed some fancy electronically controlled plumbing that works automatically and much faster than a graduate student. Since then, Hood's group has

The central courtyard

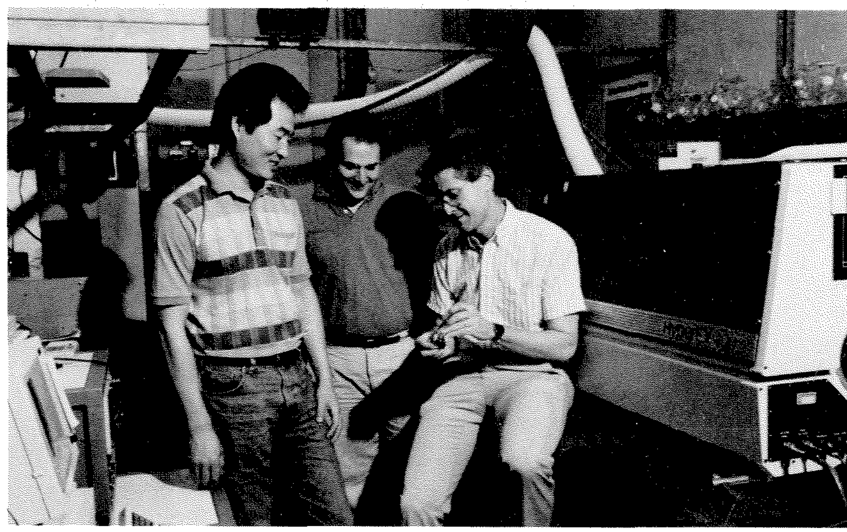
The most interesting proteins are often the rarest.

been refining the technology, making it faster and more sensitive. The latest equipment can sequence 10 picomoles of protein, and next year's model will be 100 to 1,000 times as sensitive. It will use fluorescent labels that, once attached to their respective amino acids, can be read off by a laser scanner similar to the bar code reader at a supermarket checkstand.

Kaiser's subgroup is working on a similar problem: analyzing the sequence of "letters" that make up the gene's coded instructions. They partially automated this chore in 1986, and are now working on a fully automatic design. The DNA to be analyzed is grafted into a bacteriophage, which churns out mass quantities of the stuff—a standard genetic engineering trick. But in this case, the bacteriophage lives in four flasks, one for each letter in the DNA alphabet. The nutrient soup in each flask contains all four letters (organic chemicals called nucleotides, actually), but a small proportion of one letter is defective—lacking a hydroxyl group needed to keep the chain growing. Instead, the letter carries a fluorescent dye, say, green for A, red for C, orange for G, and yellow for T. When a defective letter joins the growing DNA chain, growth stops. Since a defective G, for example, can wind up anywhere there's a G in the original DNA, at least one strand will end at each G. All four flasks, taken together, yield a set of strands ending with color-coded tags at every position in the original DNA sequence. Electrophoretically sorting the strands by length gives a laser-readable sequence of fluorescent bands whose colors match the letter sequence of the original DNA.

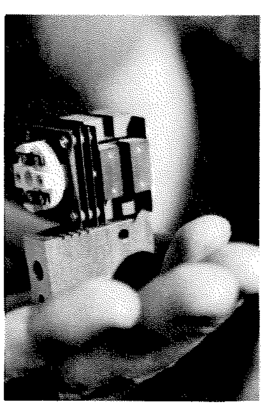
Sequence data from DNA or protein scanners can be computerized. Several sequence databases already exist, and the volume of information will grow exponentially as the sequencers become more powerful and in more general use. Sequencing the human genome (all the DNA in one set of human chromosomes—the biological equivalent of the Quest for the Holy Grail) would generate a string of data three billion items long. How does one store that much data accessibly? More important, how does one analyze it? The whole point of doing the work is to be able to look for similar sequences in different guises. Hunkapiller's team is looking at three approaches. In one, custom-built coprocessors or "superchips" could handle the computationally intensive parts of a pattern-recognition program. A program written directly in silicon, as it were, runs much faster than a similar program in a conventional computer that has to keep asking a memory chip what to do next. The other two approaches involve using parallel processors such as the Caltech/JPL Hypercube, which attacks massive problems by doling little bits out to interconnected small computers, or neural networks, whose unique design allows them to not only recognize patterns but discover them. JPL will collaborate on this project, and Hood hopes to pick the brains of the Computation and Neural Systems program too, which should be easy, since CNS will get space upstairs from him. The collaboration may even extend as far as Rice University, the other half of the Parallel Computation Research Center.

"This is a self-contained, modular attack on



Right: Graduate students Seung Koo Shin (left) and Dave Dearden with Beauchamp (holding sample cell) in the FT-ICR lab. The magnet is in the left rear; part of the laser setup is on the right. Below: The sample cell.

The entire assembly, sans magnets, is smaller than a pack of cigarettes.



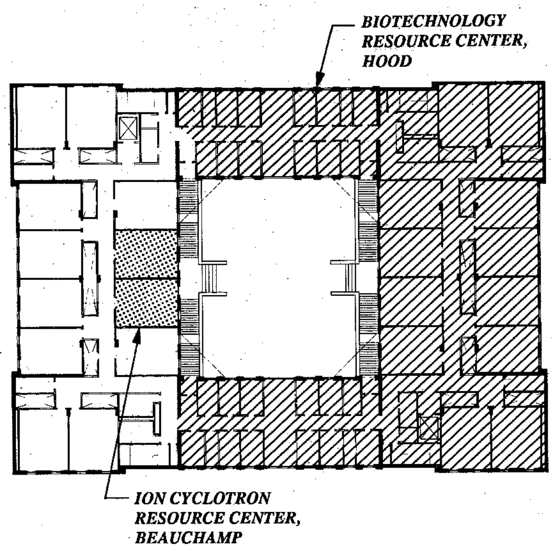
many of the fundamental problems of analyzing genes and proteins," says Hood. "It's already led to two applied facilities the Caltech community can use—one for synthesizing proteins and genes to order, which is four or five years old now, and more recently one to sequence proteins. In the not-too-distant future I hope to have a third one set up to sequence DNA at very fast rates. Then we'll be ready to undertake some really challenging projects, such as sequencing all human T-cell receptor genes." T-cell receptors are a critical part of the immune system. Their almost infinite variability, encoded in some 6 million letters of DNA, is crucial in the body's ability to recognize countless foreign and potentially dangerous substances. The most ambitious sequencing project to date, it would be a good dry run for various proposed attempts to sequence the human genome.

The smallest center, and the one with the most narrowly defined scope, is no less ambitious in its way. To be located just around the corner from Hood, Jack Beauchamp's group hopes to refine Fourier Transform Ion Cyclotron Resonance Spectroscopy (FT-ICR) to the point where it can detect a single ion. FT-ICR now detects as few as ten ions, a sensitivity Beauchamp will try to better by using superconducting magnets and by developing improved signal-processing techniques. Current equipment in Beauchamp's lab can handle molecular weights of up to about 1,000 atomic mass units (AMU). Beauchamp wants to reach 50,000 AMU, large enough to study small enzymes. The group will also try to improve an FT-ICR method for determining amino acid sequences in biological molecules. If they succeed, sequences could be run much faster and on much less material than is now possible.

FT-ICR identifies charged molecules by their mass-to-charge ratio. Charged particles, or ions, in a magnetic field travel in circles in a plane perpendicular to the field. At room temperature and typical field strengths (about 160,000 times stronger than the earth's magnetic field as felt in Pasadena), the circles are less than a millimeter in diameter. "Trapping electrodes" keep the ions from drifting along the field, and complete a three-dimensional electromagnetic "bottle." (The entire assembly, sans magnets, is smaller than a pack of cigarettes.) A trapped ion orbits at a characteristic frequency—its cyclotron frequency—proportional to the magnetic field strength and inversely proportional to the ion's mass. This frequency is generally in the radio frequency (RF) range. Applying an RF electric field at right angles to the magnetic field excites the ions, making them emit a signal picked up by electrodes at right angles to both fields. This signal contains a frequency corresponding to each ionic mass and is analyzed by a computer. The ions themselves stay in orbit indefinitely and can be redetected any time you please. Beauchamp notes, "About the only thing that can happen to the ion is it might react with a stray gas molecule, or it might diffuse to the wall of the sample cell and be neutralized."

Beauchamp's scheme to sequence proteins depends on getting them ionized, orbiting, and reacting with the right gas molecules. "We've had 20 years of experience with gas-phase reactions of ions," he says, "and we think we can design reactions that'll remove one amino acid at a

SECOND FLOOR PLAN



Gray's group has demonstrated that electrons can, in fact, leap across 20 atoms—a considerable distance—in less than one millionth of a second.

time." (Beauchamp's approach, incidentally, works on the so-called C-terminus, the opposite end of the protein from Edman's reactions.) With the endmost amino acid gone, an RF pulse would remeasure the mass, and the amount lost would fingerprint the missing amino acid. As the whirling ion continued to shed amino acids, its entire sequence could be read off.

This approach, if successful, would be about ten billion times more sensitive than current sequencing techniques, which require 10 to 100 picomoles of sample (roughly a quadrillion molecules). "But this comparison is misleading," says Beauchamp, "because those techniques work with the entire sample. We're only counting the molecules we can get airborne. Right now, that's fewer than one in a million."

Getting the molecules airborne is like lifting an elaborate sand castle—large and heavy, but very fragile. "You have to heat the sample incredibly fast—in nanoseconds (billionths of a second)—to vaporize the molecules before they're destroyed," Beauchamp observes. "If you heat the sample slowly, it'll fry itself." The group uses a pulsed, high-power laser to heat the sample. If Beauchamp can get the laser-vaporization process optimized, and put together a scheme of highly selective chemical reactions that will cleave one amino acid from the protein, he "can see this becoming a major focus in my group in ten years. We'll be able to study a tissue specimen by scanning a pinpoint laser over it and mapping molecules such as neurotransmitters. The collaboration with biology will be fascinating."

Three stories below, in the subbasement, Harry Gray will be using a laser spectroscopy lab to study electron transfer in proteins, a process fundamental to life. Whenever living cells store or use energy, electrons are transferred between molecules. Chemists used to think these transfers could only happen between two molecules in extremely close contact—rubbing up against each other, as it were. Gray's group has demonstrated that electrons can, in fact, leap across 20 atoms or more—a considerable distance—in less than one millionth of a second. These findings will affect such seemingly unrelated efforts as computer chip miniaturization, fuel cell development, and creating an artificial process that mimics photosynthesis, the method plants use to gather energy from sunlight.

Gray's experiments use myoglobin, a protein related to the hemoglobin that carries oxygen in the blood. Myoglobin occurs in muscle cells, where it acts as a temporary oxygen storehouse. Buried within the myoglobin molecule is an iron atom, which acts as an electron launching pad. If a palladium or zinc atom is substituted for the iron, a pulse of laser light can launch the electron. The landing site is a ruthenium-ammonia complex that Gray's group attaches to the molecule's surface. The ruthenium can go in one of four spots where a histidine, one of the amino acids from which proteins are built, projects from the myoglobin's surface. Each site is a different distance from the iron, allowing transfer rates to be studied over a range of 13 to 22 angstroms. (An angstrom is one ten-billionth of a meter.) The amount of energy needed to make the reaction happen can be studied by modifying the takeoff and landing points—by substituting palladium for zinc at the launch, for example, or pyridine for ammonia at the splashdown.

Electron transfer also requires a very specific alignment of atoms along its path. Another series of experiments studies how altering that alignment affects the transfer rate. These experiments use altered forms of another protein, cytochrome c, where an amino acid at a particular point in the molecule is replaced with a different amino acid, a process called "site-specific mutagenesis." Since each amino acid has a different shape, changing one near the path alters the atomic alignments along the path. "We're trying to understand the rules governing these pathways," says Gray.

But there are many paths an electron could take through a protein's complex structure. In another approach to the same problem, Gray is building much simpler molecules with a single specific path designed into them. The path leads from an iridium atom, the electron source, to an electron acceptor. While an electron's flight time through a protein is around a millionth of a second, flights through these smaller molecules take only a few trillionths of a second. "To measure events that fast," says Gray, "takes some pretty fancy lasers."

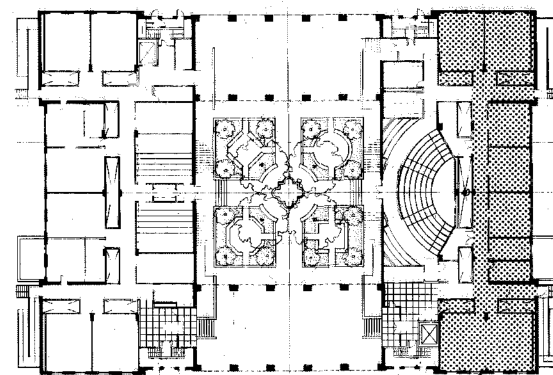
At the moment, Gray and Sunney Chan, the laser center's other user, must go elsewhere to look at their molecules. Both go to the Brookhaven National Laboratory in Upton, New York. Chan also goes to UCLA, New Mexico, and Michigan State. Chan remarks, "The events Harry looks at are a lot faster than mine, but we aren't really set up to do time-resolved spectroscopy of biological molecules in general. Having the laser center right here will give us a lot more flexibility in what we can do."

The catalysts work so quickly, like a conjuror palming cards, that you can't see what's going on.

Chan works with "biological machines." These molecules work against the tendency of things to spread themselves as evenly as possible, like a bagful of marbles spilled on a smooth floor. A chemical concentrated on one side of a permeable membrane, like a cell wall, will diffuse through it until the concentrations on both sides equalize—the state with the least potential energy. Chan's "machines" span the membrane, using the energy released as one chemical equilibrates to pump another in the opposite direction, against its concentration gradient. Cytochrome c oxidase, for example, is found in muscle cells, where it uses electrons going "downhill" to pump protons "uphill." Lactose permease, found in the membrane of *E. coli*, the microbiologist's pet bacterium, uses protons going downhill to accumulate lactose, a sugar used as fuel, inside the cell. Other machines pump wastes back out.

Chan uses lasers to watch his machines work. "These machines actually have moving parts," he explains, "and if we want to understand how the chemistry takes place, we have to watch the parts move." A loop of protein called an α-helix, for example, might partially uncoil and then coil up again as it pumps an ion along. Chan's group tracks these motions by stimulating the molecule with a pulse of laser light and recording the light the molecule emits in response.

"Very few people are working on these molecules because they are so big and complicated," says Chan. "There are probably only half a dozen groups in the world in this field, and our laboratory is probably the leader. The chemists haven't gotten around to synthesizing them yet, or trying to model their actions, because they are so big. But in ten years' time, chemists will be making them, so we're trying to learn the chemical principles they work on, the rules we need to remember when we want to design one of these machines." And the machines wouldn't have to



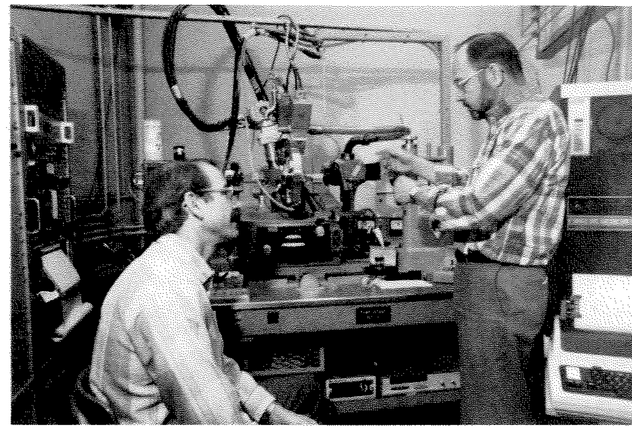
GROUND FLOOR PLAN

be designed just for biological functions, either, but could be designed for industrial processes, fuel cells, and chemical sensors.

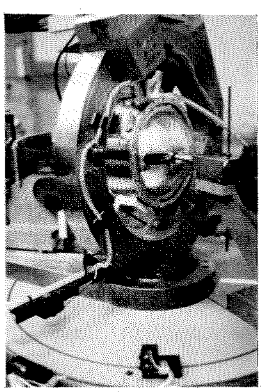
John Bercaw, on the other hand, will be using the x-ray crystallography facility—two stories up on the ground floor—to look at small molecules with molecular weights in the hundred-AMU range. Bercaw's molecules are organometallics—containing both a metal ion and carbon-based constituents. He is trying to work out the mechanisms behind some industrially important catalytic processes.

Take Ziegler-Natta olefin polymerization, for example—millions of tons of polyethylene and polypropylene are made this way every year. But no one knows exactly how the process works, not even Karl Ziegler and Giulio Natta, who shared the Nobel prize in 1963. The trouble is the catalysts work so quickly, like a conjuror palming cards, that you can't see what's going on. Says Bercaw, "We've made some molecules, scandium derivatives mostly, that are terrible catalysts because they work very slowly. But that allows us to study how the reaction mechanism works step by step. They're also very clean—they are selective, and they don't make side products."

Bercaw and his coworkers are also looking at the basics behind hydrocarbon oxidation—turning methane (CH_4) into methanol (CH_3OH), for example. It's the same approach: "We've made molecules that undergo very clean transformations that could be catalytic steps. I should point out that we haven't found a catalyst. Nobody really has found one that's practical, not like the Ziegler-Natta system. We're trying to do some basic science that might help us dis-



Right: Bercaw (seated) and Schaefer in the x-ray lab. The diffractometer behind them is one of three in the world that can cool a sample to 22 K, greatly reducing atomic motions that can blur crystal structures. Beckman Institute money will upgrade the computer system and other components.
Below: The sample chamber. The x-ray source is on the right, the detector on the left. The sample itself is no larger than a flyspeck.



cover a way to oxidize hydrocarbons very selectively." And if they can select a particular hydrogen atom from the dozens in a large hydrocarbon molecule, remove that atom, and replace it with an oxygen atom, presumably they'll be able to work backwards as well. "This could spin off to other processes. Hydrodesulfurization—removing sulfur—is practiced big time by the petroleum industry, desulfurizing crude oil."

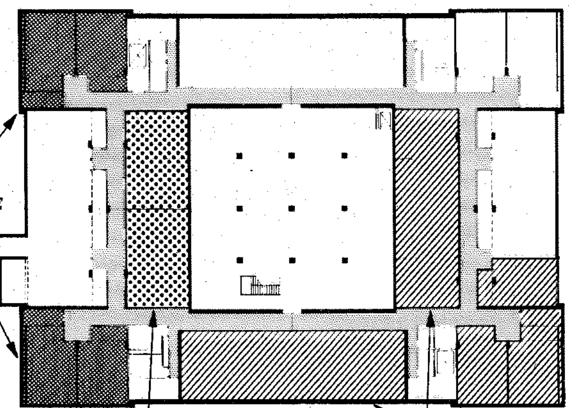
So they try whole families of molecules, an atom different here or there, like a shoe salesman proffering ten pairs of sandals to an indecisive customer. And when they find one that works right, "we dig in and really study it carefully. We investigate the catalyst's structure, and the product's and the starting material's, how they rearrange from one to the other, and how the reaction rates change as we make variations. Structure has a lot to do with function, and most of our structural information comes from x-ray crystallography. But the synthetic work, the kinetic studies, and the other analytical work will all be done elsewhere."

(The x-ray crystallography facility, incidentally, will be moved lock, stock, and Cu K α sources from the Noyes Lab subbasement. Senior Research Associate William Schaefer, its director, is ecstatic. "I get an office with a window for the first time since 1968!")

Bob Grubbs and Nate Lewis's facility, the Molecular Materials Resource Center, will share the Institute's subbasement with the laser labs. Grubbs is an organic chemist with a flair for making polymers (*E&S*, summer 1988). Lewis is an inorganic chemist who traffics in semiconductors. Together, they will beget hybrid organic/inorganic materials, while working separately on novel materials in their own fields of expertise. Their combined group may eventually include 20 people. "We're basically building properties into new materials from the molecular level up," says Grubbs, "rather than starting with the bulk material and working down."

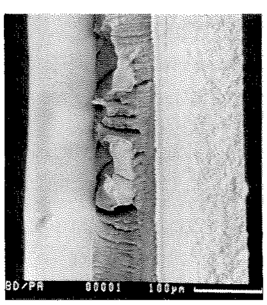
Grubbs can make polymers that can conduct electricity even though they don't contain any metal atoms. (A polymer is a very large molecule made up of hundreds of small molecules called monomers.) The method uses liquid ingredients, so the polymer can be cast into any shape or poured onto any unreactive surface. Conductivity depends on composition, which is easy to control with Grubbs's techniques. Grubbs and Lewis have already made organic diodes and capacitors from alternating films of polybutadiene, an insulator, and polyacetylene doped with iodine, a conductor. The two groups will collaborate in applying polymer films to semiconductor devices and exploring the novel types of switching functions, sensing applications, and other electronic uses that these new materials might make feasible.

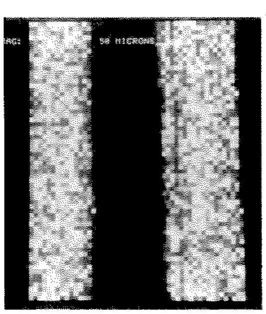
"To put this in perspective," Lewis explains, "to make a Schottky barrier, for example, which is a conductor-semiconductor junction used in integrated circuits, you take a metal—gold or platinum or copper—and deposit it on top of the silicon or gallium arsenide semiconductor. You can do this by evaporation—you just boil the metal—or by bombarding the silicon with a beam of metal ions." It's a brute-force, but effective, way to make electrical contact. Different metals have various "work functions," and the



SUB-BASEMENT FLOOR PLAN

'What happens when you mix cerium and uranium in a superlattice?'



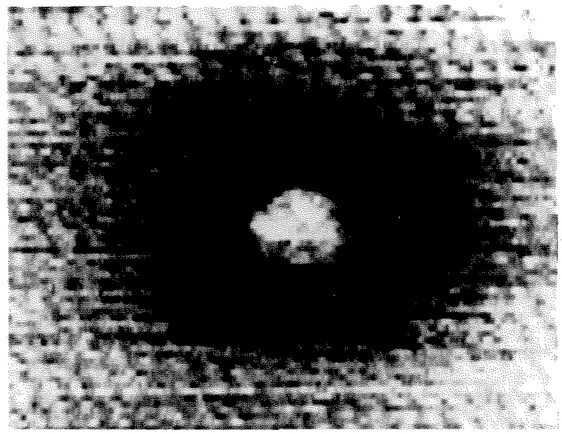


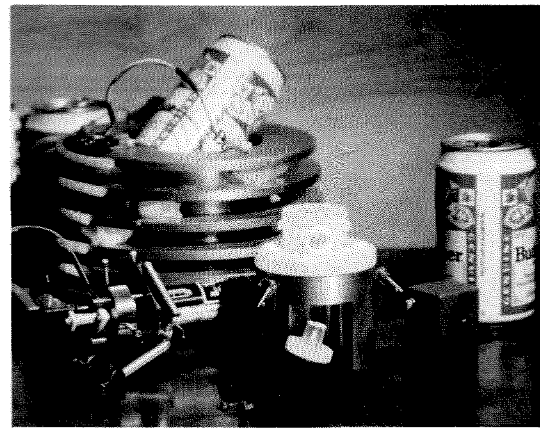
junction's properties should vary predictably with the metal. But things often don't work so nicely, presumably because the less-than-elegant assembly method mucks up the interface. "The metal may be diffusing into the semiconductor, or alloying with it, because the metal's very hot. But now Bob Grubbs comes along with a process capable of making a series of polymers with different work functions, and these polymers can be gently coated onto my pieces of silicon at room temperature. So people in my group started to wonder how these devices would behave, how the charge would move from one layer to the other, and what would happen at the boundary between an organic and an inorganic conductor. This project naturally brings together the organic chemist and the inorganic chemist, who normally wouldn't be talking together about this type of work. And that's what's unique about the Beckman Institute."

Grubbs can sprinkle different monomers through his polymers at will. The final molecule may have any number of regions of any desired size and composition. In principle, it's possible to make an insulating polymer with conducting regions small enough to behave as "quantum dots"—regions so small (20 to 100 angstroms across) that the electrons inside them can only move in specific ways. It might also be possible to make organic "superlattices"—ultra-thin-layer composites of two materials where each layer is only a few atoms thick. Although the superlattice's bulk composition is 50 percent A and 50 percent B, its properties aren't six of one and half a dozen of the other. Instead, the superlattice has "emergent properties"—entirely new behaviors derived from electronic states of the composite that are not merely the sum of the components' electronic states. (Grubbs' polymers aren't limited to electronic applications. Other projects have included creating a fluid that might be injected into the lenses of cataract patients' eyes as an alternative to hard plastic implants.)

On the other side of the street, Lewis is also interested in making exotic new inorganic materials. The semiconductor industry has spawned a sophisticated technology for making solids to order, techniques like molecular-beam epitaxy and metal-organic vapor epitaxy. But the machinery's expensive, and monopolized by the semiconductor industry, Lewis says, so, "If your garden-variety chemist says, 'Gee, what happens when you mix cerium and uranium in a superlattice?' no one's going to let him borrow their machine, which is dedicated to growing compounds the electronics industry needs, to find out. Yet these machines could make odd combinations of elements that are dissimilar enough to do really interesting things nobody's seen or predicted. So we want to put some of these machines in Beckman, where anyone can come in with an idea for a new material and make it, without having to build an instrument from the ground up. It will be a resource for the Caltech community. I'd also like to study how these machines actually make materials, the processes involved, and see if they could be improved."

The Molecular Materials Resource Center will also offer a facility for scanning-tunneling and atomic-force microscopy, which Balde-



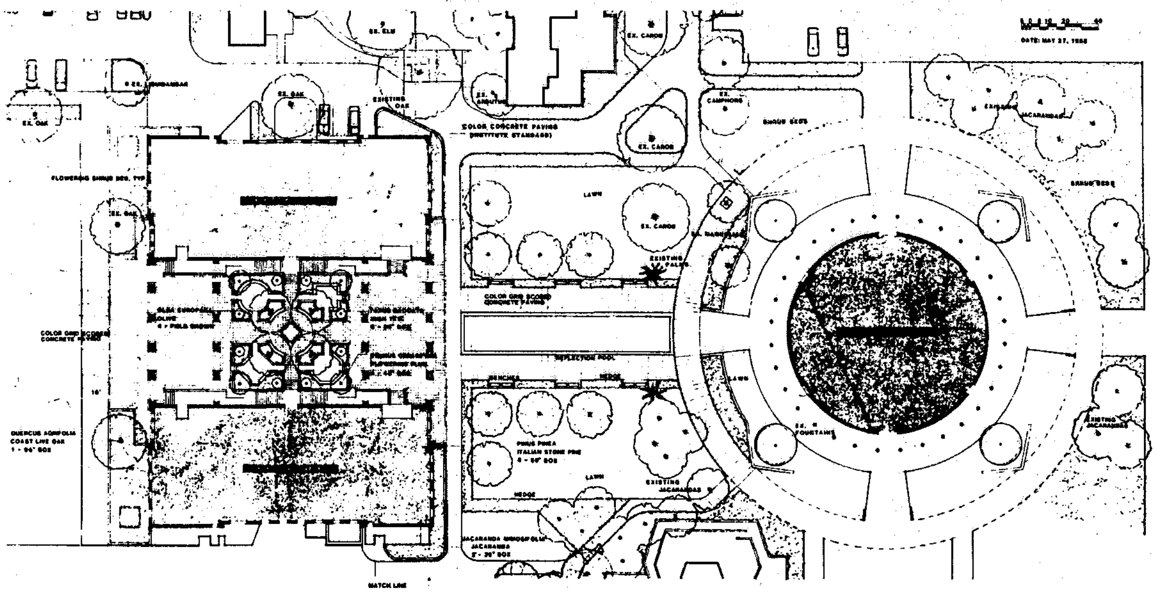


Far right: Not a can crusher, but the heart of a scanning tunneling microscope (STM). Right: STM image of a "blot" on the surface of a layered molybdenum disulfide semiconductor. The blot is roughly 10 angstroms in diameter, easily readable by STM. Opposite: Cross-sectional electron micrograph (above) and energy-dispersive spectrogram (below) of a nonmetallic capacitor—polybutadiene sandwiched in polyacetylene. Each layer is about 100 microns thick. The spectrogram shows iodine dopant as white spots.

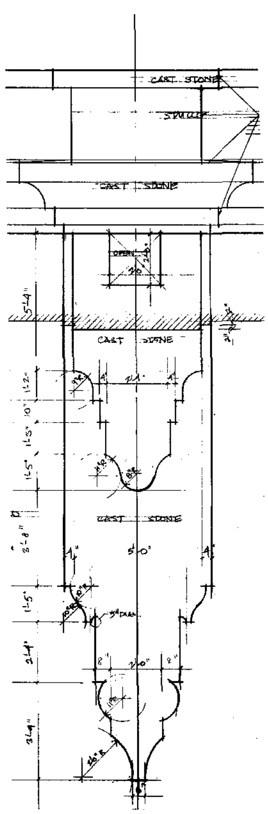
schwieler will administer. Both techniques measure atomic-scale forces between a solid surface (or even a single molecule) and a scanning, atom-sized probe, creating a three-dimensional picture of the solid so detailed that you can see individual atoms on the surface. The atomic-scale resolution makes these techniques ideal for looking at the resource center's new materials, which have been engineered from the atomic level on up, and other researchers on campus are eager to apply this technology to their own work. Baldeschwieler hopes to expand the biological applications in particular. It should be possible to look at a single protein molecule in a water solution, for example, and see the convoluted, three-dimensionally folded shape the protein assumes to do its job—a dainty shape that's distorted or lost when the protein is concentrated, purified, freeze-dried, crystallized, or otherwise manhandled by the techniques normally used to determine molecular structures. And there's the possibility of making ultracompact data systems. The probe could be used to create a tiny blot—only a few atoms in diameter—on a clean, smooth semiconductor surface. The same probe, scanning the crystal later, could read the blot as a digit of binary code—a blot is "1," and no blot is "0." "If we can figure out a way to make and read these blots reproducibly, we could increase the storage density on a memory chip by a factor of a million," says Baldeschwieler. "And we think we know how to make them."

But before anybody makes anything in the Beckman Institute, the building has to be built, preferably to a plan that meets the evanescent occupants' changing needs. "Dave Morrisroe (vice president for business and finance and treasurer) went to great lengths to be sure we got outstanding architects and contractors for this project," says Gray. Schaefer, the x-ray crystallographer, is the liaison between the architect, the contractors, and the Caltech community. Gray calls him the Beckman Institute's "acting director" in acknowledgment of his day-to-day responsibilities. Schaefer is certainly experienced—he helped convert Mead Laboratory into a showplace teaching lab, and has supervised the rehabilitation of other chemistry buildings. "So when the plans for this building became a reality," Schaefer says, "Harry asked me to help out. It takes an awful lot of time, but it's fun. It's my contribution." Schaefer spends his time worrying about details so the principal investigators don't have to. Details of the lab setup—what utilities are provided and where—and details of the decor—the color of the seats in the auditorium and the tiles in the courtyard. Even whether the U in "BECKMAN INSTITUTE" is rendered as a U or a V. "The architect's designer, Tim Vreeland, is specifically trying for the look of the old campus," says Schaefer, "the South Houses, and the Athenaeum. But it's not clear that it should be a V just because of that, and most of us are modern enough to think a V looks kind of silly. What do *you* think?"

Although the building will recall the old campus, changing times and economics means there will be no elaborate embellishments like the stonework crabs and sunflowers on Kerckhoff, or the Tree of Life on North Mudd.



Landscape plan: Beckman Institute on the left; Beckman Auditorium on the right.



"Vreeland put in some nice details, though," says Schaefer. "Like the big reflecting pool between the building and the Beckman Auditorium. He showed us a design for the decorative tile at the bottom of the pool, and it immediately recalled the double helix of DNA. And there'll be an abstract sculpture in the courtyard. Harry suggested that since the building relates to biology and both organic and inorganic chemistry, how about using a model of ferritin, an iron-containing protein? Its structure had recently been determined, but the only thing he could remember was that it had 4-3-2 symmetry. So I designed this geometric solid with the same 4-3-2 symmetry, and the 24 points on the solid represent the 24 subunits on the ferritin molecule. Of course, it doesn't look anything like the protein itself. We've thought about a plaque explaining it, but it seems to me that if you don't put a plaque up, it would be an awfully good question to ask during freshman initiations."

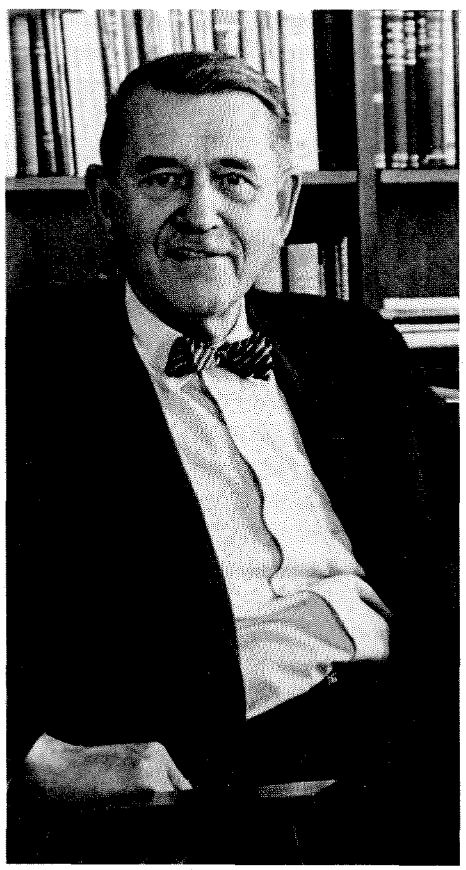
The main architect, A. C. Martin, and the lab designers, McClellan & Copenhagen, have both worked with Caltech before. They began by interviewing everyone who was known to be moving into the building, resulting in a bound volume two inches thick from which McClellan & Copenhagen derived their lab designs. These detailed layouts, with fume hoods and workstations, chilled water lines and compressed air outlets, and major pieces of lab equipment all drawn to scale, go to A. C. Martin for translation into working drawings. Says Schaefer, "I have to check all these things, make notes on them, and go back and forth when they don't match. Then there's a four-hour meeting once a week with both sets of architects, the Turner Construction people, and Physical Plant to discuss what's going on. Physical Plant has a lot of responsibilities, too—there are all kinds of permits you have to get, plans and documents that have to be filed with all these different agencies, logistics to think about—Bob Fort (director, Physical Plant) and Mike McCallan (manager, Engineering and Estimating) have gone way out of their way to make sure this project gets done right and on schedule. (Gray agrees, "Bob and Mike deserve a special vote of thanks.")

"You have to think of everything. The doorway sizes were based on the lab equipment. We worried about hallway width. Corners. Down in the subbasement, in the laser lab, they wanted these Newport optical benches—six- by twelve-foot tables two feet thick. How do you get them down there? The architects added an areaway alongside the building, so you could drop them down the areaway. Then Tom McClellan made a small model to be sure you could get them around the corner once you got them in the hallway. The laser lab doors are double doors, like in the Noyes Laboratory of Chemical Physics. A lot of what's going on here comes from our experience with Noyes. Noyes was designed by the late Holmes Sturdivant, a professor here for many years. He was a master of detail who spent enormous amounts of time worrying about these things. We've benefited a lot from him."

As we all will from the Beckman Institute.□—*DS*

Obituaries

Frederick C. Lindvall 1903–1989



Frederick C. Lindvall, professor of engineering, emeritus, died January 17, 1989. He had been a member of the Caltech faculty since 1930, and was chairman of the Division of Engineering and Applied Science from 1945 to 1969. He became emeritus in 1970. At a memorial service on March 13, Lindvall's life and his varied interests in engineering, education, and music (and gastronomy) were eulogized by Donald E. Hudson, professor of mechanical engineering and applied mechanics, emeritus; J. Harold Wayland, professor of engineering science, emeritus; Robert Zurbach, former president of The Associates; and Ruben Mettler, chairman of the board of trustees. Rosalyn Tureck played Bach's Chromatic Fantasy and Fugue.

Fred Lindvall was a man of many dimensions—including his long and dedicated association with Caltech, his national prominence in engineering education and the engineering profession, his wide range of engineering research interests, his many cultural and civic interests, and his love for family and friends.

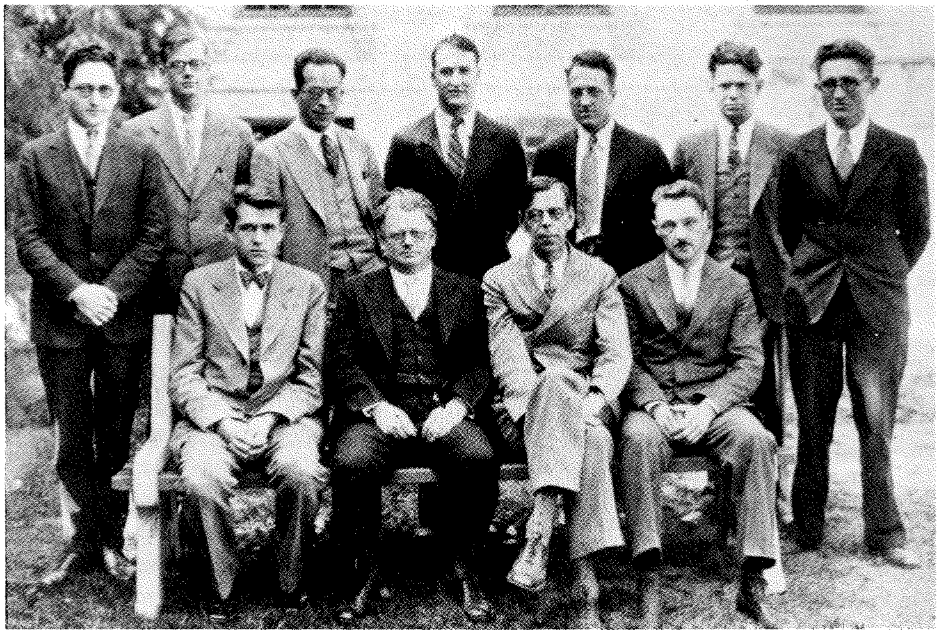
In this context, it is my privilege today to speak as one of Fred's former students, and thus focus on his role as a teacher, an academic advisor, and a personal friend. I had the good fortune, as a Caltech graduate student and PhD candidate in the late 1940s, to have Fred as my principal thesis advisor. His broad knowledge of engineering and of the world outside Caltech, his teaching style, and his active encouragement made a strong impact on me. At that time he was in the early years of his long service as chairman of the Division of Engineering and Applied Science. It was an exciting time for Caltech, and for engineering in general, and Fred was in the middle of the action.

He encouraged graduate students to spread their wings—academically and professionally. He emphasized applied science and applied mathematics as the underpinning of modern engineering, and encouraged us to take as many courses as possible in other departments and divisions at Caltech. My first acquaintance with concepts such as interdisciplinary research, system engineering, and management of technology came from Fred. He made it seem very natural for an electrical engineer to do a thesis in aeronautics, and have an examination committee consisting of professors from a wide range of disciplines, especially in physics and mathematics.

One day he suggested that I become an instructor in applied mechanics, to *teach* a course that I had just completed myself a year earlier—initially this was an unnerving experience and later a real joy. I recall my surprise when I learned that I was expected to build from scratch with my own hands the experimental apparatus needed to do my thesis research, including several racks of electronic instrumentation, a sophisticated wind-tunnel probe, and an elementary blow-down wind tunnel to demonstrate the experimental concept before I could apply for time in a regular wind tunnel in Guggenheim.

Although Fred emphasized quantitative analysis, he made it clear that, in practice, engineering (and especially engineering design) is a *decision-making* process that can lead by many different paths to an effective solution, but with no exactly right or exactly wrong answers. He made clear the difference between *analysis* and *synthesis*.

To this day, I don't need to consult



In this 1932 photo of Caltech's electrical engineering faculty, Lindvall sits at left, next to Royal Sorensen.

a Caltech catalog to remember the advanced engineering course that Fred personally pioneered and taught—EE 226—in which he demonstrated these points. More than any other course I took at Caltech, it made a lasting impression on me. Fred assigned general problems of a practical nature that we as students had never encountered before, often with a due date one or two months later, so that there was plenty of time to think about the problems and how to approach them. The student was left on his own, and was to determine (and later defend) his underlying assumptions, his approximations, his methods, and the validity of his chosen solution. The fact that the course had an EE label had no constraining influence on Fred's problem selection. I can recall problems that introduced us to long narrow bridges (such as the famous Tacoma Narrows bridge), to an earthfill dam in a canyon with a particular geology, to high voltage transmission lines, to rocket motors, and to analog computers. The key task was to take the problems all the way to final design solutions, supported by quantitative analysis.

What made this so exciting was that, as graduate students, we had just been introduced in our candidacy courses to the "magic" of Laplace transforms, the incredible scope and beauty of Maxwell's equations, the power of vector analysis, and the mysteries and uncertainties of fluid mechanics. Fred's course helped us *begin* to understand how practical engineering solutions could be developed from such abstract theories and analytical techniques, if we could add enough common sense and engineering judgment. After several years of drinking out of an intellectual fire hose, we were finally able to sip and taste some of the water.

In just a few years after receiving my PhD degree, I found myself as the project leader of a team designing and developing a new integrated electronic navigation and fire-control system for jet fighter planes. Then a few years later I was in a similar situation as engineering project leader for a rocket-propelled, inertially guided, long-range ballistic missile that was also to be used as a launch vehicle for spacecraft. I can say without hesitation that Fred's engineering philosophy, his lasting influence, and his teaching were pivotal to the success of those projects.

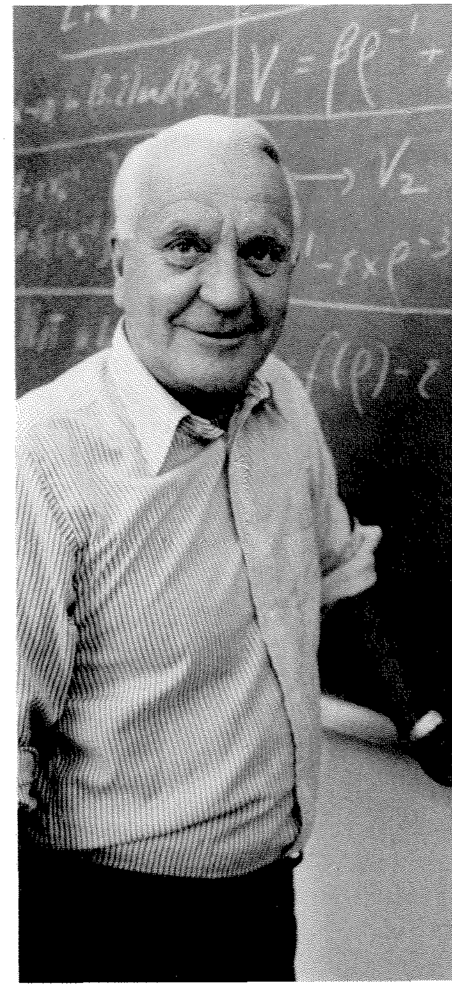
In closing, I wish to salute and honor him as a giant of the engineering profession, one of Caltech's finest, a superb teacher, and a trusted advisor and friend. We will all miss him.

Ruben F. Mettler
Chairman, Caltech Board of Trustees
Retired Chairman and
Chief Executive Officer, TRW Inc.

Paco A. Lagerstrom 1914–1989

On February 2, Paco A. Lagerstrom, professor of applied mathematics, emeritus, collapsed on the street, and died without regaining consciousness on February 16, a few days before his 75th birthday. With him Caltech lost an unusual personality whose importance to the Institute, the students, and his colleagues was not realized by many but was much appreciated by those who knew him closely and managed to penetrate, at least a little, the wall he chose to erect around himself. I considered him a sometimes difficult but utterly reliable and honest close friend, with whom I debated and from whom I learned for almost 45 years. Indeed, in the last few weeks of his life he tried to teach me gauge theory!

Paco's scientific career began at the University of Stockholm where he studied logic within the faculty of philosophy. He came to this country in the late thirties and completed a PhD in pure mathematics with a thesis in topology under Bochner at Princeton in 1942. He finished when contributions to the war effort were expected even from pure mathematicians and worked first as an instructor at Princeton and then at Bell Aircraft in Niagara Falls, if I remember correctly, in flight test evaluation. I was told that during a severe blizzard only a single employee appeared at the closed plant: Paco on skis!



At about this time a very competent and active research group was established at the Douglas Santa Monica plant, led first by Francis Clauser and later by Harold Luskin. Paco joined this group in 1945, at a time when the excitement for supersonic and space flight had begun. He contributed to both. In particular he was a member of the team which put together the first (and positive) proposal for a U.S. satellite—this in the mid-forties, some 10 years before Sputnik. The report, now known as RAND #1, was originally secret and hence did not have the general impact it deserved. Needless to say, the recommendation to launch a U.S. satellite was not followed at the time.

Paco's work on supersonic wing theory made a profound impression on me because of the unusual way he proceeded. I was at the time a consultant to the group at Douglas and noticed Paco doodling with a picture of a narrow delta wing in supersonic flight. He realized that the problem was topologically a torus; this was sufficient for him to obtain the solution immediately in terms of elliptic functions. I successfully conveyed my enthusiasm to Clark Millikan; Paco joined GALCIT as research associate in 1946, and his career at Caltech began. He advanced to professor of aeronautics in 1952 and when, after Clark Millikan's death, the applied mathematics option was started, he became professor of applied mathematics in 1967.

Paco was never a highly rated classroom teacher. He lacked smoothness of presentation and the ability for an easy, jocular manner, but his deep understanding of the material he taught was always evident. He had however a profound impact on students through personal contact and tutoring, certainly on his own research students, a number of whom became prominent in academia and industry. In addition, he was sought out and spent much time in discussions with a large number of graduate and undergraduate students from various options. In this way Paco exerted a major influence on the direction and progress of numerous research projects. He had a deep knowledge of mathematics; whenever a proper, congenial interface was provided, he could be equally effective in solving engineering problems. This was the case in his days as research engineer and later as consultant to Douglas and as an active member of the GALCIT facility.

Paco's approach to linearized wing theory, on the basis of the acoustic wave equation, did not become very popular. To me it is a beautiful and very useful way to obtain subsonic and supersonic wing theory, steady or unsteady, from a single point of view. His "Laminar Flow Theory" in the *Princeton Handbook of High Speed Aerodynamics and Jet Propulsion* is a classic in the field. In addition to his and his students' set of publications, he still managed to finish his monograph on singular perturbation theory, which appeared just a few months before his death, another lasting contribution to the state of the art.

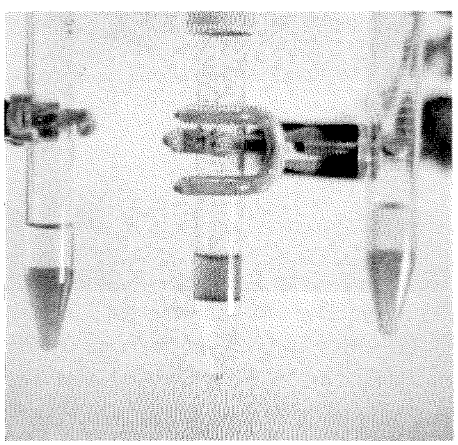
In recent years Paco felt, I believe correctly, left out and not appreciated at Caltech, a condition to which he himself of course contributed by his unorthodox, rigid approach and lack of smooth manners. I have always felt that one essential attribute of a successful academic group is the ability to appreciate and support gifted oddballs. One can only hope that Paco Lagerstrom's experience does not indicate that this virtue has been totally lost at Caltech in this time of smooth entrepreneurs.

Paco strove to be the perfect, somewhat Victorian, gentleman. He spoke at least five languages, read and translated poetry, and took pride in his knowledge of good wine and food. His love for and knowledge of music was well known. He served for many years on the board of the Coleman Chamber Music Association and was its president in 1958-60. His contributions to the programs at Caltech are substantial and well documented. He will be sorely missed there as well as by his friends in many phases of human activity.

Hans W. Liepmann
Theodore von Kármán Professor of Aeronautics, Emeritus

Lab Notes

Remove the hook, and voilà! Pure protein.



Left: Copperless PEG and salt water—the protein (dark layer) stays down in the salt water. Center: PEG-copper and salt water—the protein moves up into the PEG layer. Right: PEG-copper and mild acid—the protein moves back out of the PEG layer.

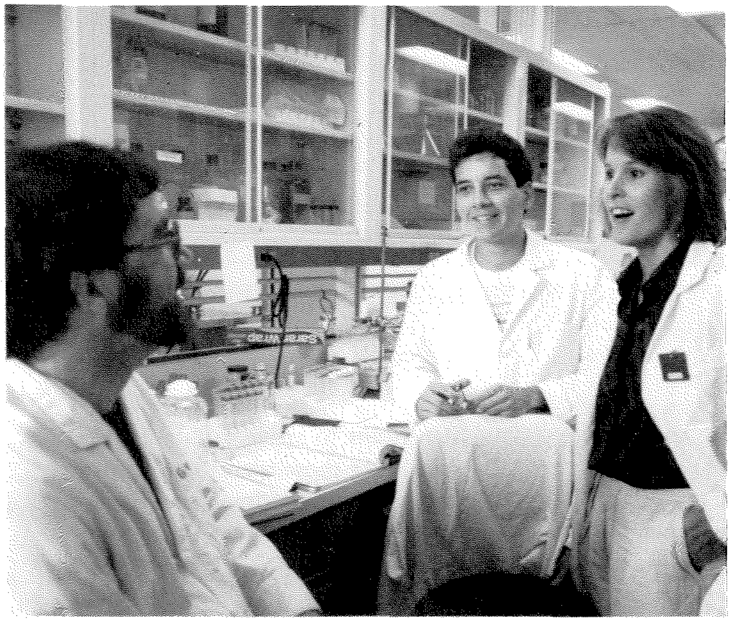
Hooked on Proteins

Picture a manufacturing plant making a hundred different models of industrial sewing machines, say, for export. The assembly line madly cranks out finished sewing machines, which pile up inside the doorless factory. Eventually a burst of sound blasts the factory's corrugated metal walls loose from their rivets, and a torrent of water washes the sewing machines out to sea in a tangle of smashed production equipment and bent structural steel. If you were a buyer of sewing machines with the zigzag option, retrieving your consignment wouldn't be easy. Yet this is about what happens when genetically engineered cells that mass-produce a particular protein ship out their product. The cells are burst open (lysed), and the protein is extracted from a vat full of cellular wreckage including hundreds of different proteins. The purification process is usually messy, requiring a number of steps and a variety of nasty solvents.

Assistant Professor of Chemical Engineering Frances Arnold is working on better ways to separate out the protein. To catch the protein, Arnold has designed a "hook" attached to a water-soluble polymer molecule. Add the polymer and some salt to the cell/protein solution, shake it once or twice to mix everything thoroughly, and let it sit for a moment. The polymer, with the protein in tow, bubbles up through the water to form a distinct, easy-to-separate layer on top. Once the polymer is safely in a separate container, remove the hook, and voilà! Pure protein.

The hook is actually a copper ion attached (chelated) to a derivative of polyethylene glycol (PEG). "The idea of using an affinity ligand attached to a polymer is not new," Arnold says. "What's new is that we use metals." The group began the work this past summer, when senior Ed Naranjo helped synthesize the PEG-copper polymer as a Summer Undergraduate Research Fellowship project.

If pure PEG is added to a protein solution containing a high concentration of a salt such as sodium sulfate, the PEG and salt instantly separate into two different phases. Proteins generally remain in the salt water, but if a few of the PEG molecules have copper ions attached to them, a protein like hemoglobin goes into the PEG phase by a factor of 200 to 1. And the separation is reversible—drop the pH of the solution from neutral to slightly acidic, and the protein returns to the saltwater layer. Merely dissolving ionic copper in the solution doesn't have the same effect,



From left: Wuenschell, Naranjo, and Arnold.

"When you're working on physical properties that nature hasn't paid much heed to, there's lots of room for improvement."

because the copper ions distribute themselves evenly between the two phases.

The protein's main copper-grabber is an amino acid called histidine. (Amino acids are the beads that, when strung together, make proteins. The amino acids interact with each other to give the protein its three-dimensional shape.) Histidine's structure consists of a ring of five atoms dangling from the amino-acid backbone. If the histidine is on the protein's surface, a nitrogen atom in the ring is positioned just right to stick to a passing metal atom. The attraction is just a passing fancy, though—the copper can be shoved aside by a hydrogen ion. So in a mildly acidic solution, where hydrogen ions abound, the histidines let go of the coppers, and the protein separates from the polymer.

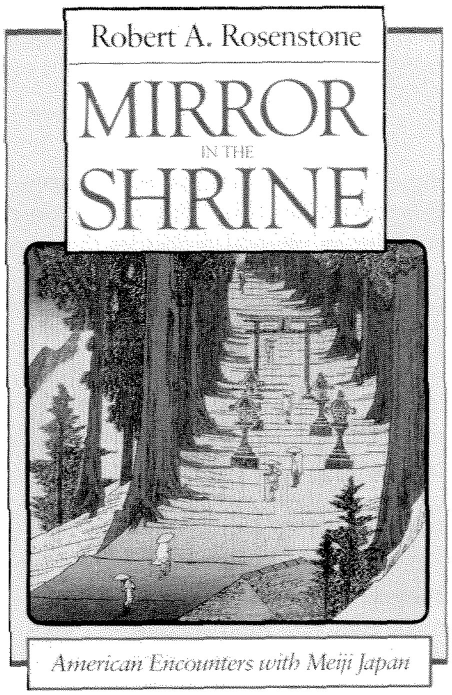
Arnold's group has shown that the more histidines there are on the protein's surface, the more efficiently it is drawn into the polymer-copper layer. Hemoglobin—which has between 20 and 26 histidines per molecule, depending on the species from which it came—will migrate completely into the polymer layer. But only a small number of the molecules in a sample of yeast cytochrome c, which has only two histidines per molecule, will cross over into the polymer layer. "By adjusting the relative volumes of the PEG and saltwater phases," says Arnold, "we can recover most of the hemoglobin—with a high degree of purity—from a mixture of cell debris and other proteins with fewer histidines."

But histidine is a fairly rare amino acid, and many useful proteins have no histidines on their surfaces at all. And while changing one or two amino acids in a molecule is no big deal, it would be impractical to try to make a protein with few histidines, like insulin, suddenly sprout 20 or 26 histidines on its surface. Arnold is investigating other, more efficient ways to make a protein's surface bind to metals. One method creates a metal-chelating site through protein engineering, substituting different amino acids at one or two positions in the molecule's original amino acid sequence. When the protein kinks into its natural shape, cleverly chosen substitutions will align to clutch a metal atom like a lobster claw pinching an unwary finger.

Robert Todd, a graduate student in Arnold's group, is constructing cytochrome c mutants containing different arrangements of histidines, aided by Professor of Organic Chemistry John Richards's group. "I think this kind of application of protein engineering is going to be very useful," says Arnold. "When you're trying to alter a protein's catalytic activity, its biological function, you're working against a very tight ceiling. Nature has had five billion years to optimize function. But when you're working on physical properties that nature hasn't paid much heed to, there's lots of room for improvement. Furthermore, you're working on the protein's surface, far from its active site, where it's a lot easier to make one or two substitutions without disrupting the biological activity."

Arnold and Research Fellow Gerry Wuenschell, who helped develop the PEG-copper separation technique, have applied for a patent on it. "The technique uses very mild conditions," says Arnold. "And it's an extremely low-cost way to separate proteins. Polyethylene glycol is marvelously inexpensive, and salt, well . . . I hope that this technique will be used industrially. Purifying hemoglobin, for example—when you make blood substitutes from hemoglobin, you get a residue of virus particles and other contaminants as part of the process. And you don't want that going into the patient." Arnold plans to explore other separation methods using protein-metal interactions, while at the same time making this process more selective. This means designing new polymer chelates that will recognize amino acids other than histidine or that will pluck out a histidine only if it is surrounded by other specific amino acids.□—*DS*

Books



Harvard University Press, 1988
$25.00
315 pages

Robert Rosenstone has written a wonderful historical account of the encounters of three late 19th-century Americans with Meiji Japan: William Elliot Griffis, Edward S. Morse, and Lafcadio Hearn. One was a committed minister turned teacher, another a natural scientist who became a leading expert on Japanese mollusks and pottery. The last was a journalist and romantic writer who settled in Japan, married a Japanese woman, and wrote 10 volumes which in their day were considered the best writings on Japan by an American.

This is no ordinary historical work. Rosenstone's new book deliberately questions many of the things that in the usual genres of historical representation we take for granted: Where to begin, and where to end. What words can do, and what they cannot. Why knowledge about the past, and knowledge about the present, cannot be properly separated. At times *The Mirror in the Shrine* reads more like a modernist novel than a narrative history.

Though unconventional, this is narrative history at its very best. The narrative is simultaneously gripping and unsettling in ways that depict, even embody, critical questions that a handful of historians are beginning to ask with increasing insistence and rigor. We gentle readers are not allowed to imagine an omniscient narrator who, however much the footnotes of normal histories may reveal a struggle against silences (in the historical record) and noises (in previous historical accounts), can tell us the whole story. Here we have fragments, questions, many stories. But what stories they are!

Imagine yourself one of the first Americans to arrive in Japan, a few years after those islands had emerged out of the self-enclosed feudalism of more than two centuries of Tokugawa rule. Perhaps you have just recently finished a year of theological studies at Rutgers Seminary, started a comfortable life in a Methodist church in New York, been jilted by a young love. And you get the offer of a lifetime. You are asked to become a teacher of natural science in Fukui, Japan, at what seems an extravagant salary. Although you would rather travel as a missionary, you know that missionizing is not allowed in Meiji Japan. If you were Griffis, you would take the offer, find yourself in a part of this strange new land where you are a solitary Westerner. You might equate the teaching of Western science with the mission of Christian religion. You might even find yourself so drawn to exotic mysteries that you are tempted by your beautiful, young, Japanese servant girl, whom you suddenly and inexplicably dismiss.

If you were a historian trying to piece together a coherent account of Griffis's journey, you would feel frustrated at the reticences of the record, the limits of words. The past might seem a steadily shifting montage of images and words and questions. You endlessly rearrange the montage to fill in gaps, but gaps only get bigger. The historian stares at microfilm reels and computer screens, tempted to bring order to chaos. But then other forms of chaos intervene —memories, perhaps, of one's own landing in Japan, one's own cultural, intellectual, personal dislocation. Remembering does not end this book, but begins it on every page.

Encounters imply changes. No

Letters

change seems as dramatic as that undergone by Edward Morse. An obsessive collector of shells, he personifies the confidence of Victorian science. Without any of the aesthetic predispositions and sensitivities of a Lafcadio Hearn, Morse sees beauty in classification tables and new specimens. Initially far more resistant to change than Hearn, who went to Japan for mysterious experience, Morse in fact undergoes greater change than either Hearn or Griffis. He notes that the Japanese have in many respects worked out better ways of living than Westerners. He extends his interest from mollusks to pots, though he confines his aesthetic wanderings by familiar modes of classification, carefully (scientifically) organizing pottery by age, region, and style. Before long, Morse is studying the tea ceremony, and shortly thereafter, Japanese singing, perhaps the most foreign (for him) aesthetic of all. He writes, "It is by taking actual lessons in tea ceremony and singing that I may learn many things from the Japanese standpoint." More than a new ethnographic science is at work here. Morse has entered into radically new forms of experience.

Hearn too changes. He immediately recognizes the beauty of Japanese ways. However prefigured this recognition is by his desire to get away from the known and find the exotic instead, Matsue, where he first stays, seems magical. Soon Japan becomes steadily less exotic, and his subsequent move to the southern island of Kyushu marks the alienating familiarization of his new country. By then he has a Japanese wife, who cares for him and stays by his side, and gives him the family that is his one constant buffer against the multiplicity of worlds that increasingly challenge the harmony of his literary imagination. Hearn remains restless, content only at home and in words. But the words reveal little about the man; the biographer once again comes up against the limits of knowledge, the silence of sources.

It is ironic that a book whose words flow so well finds words so limiting. This is partly because the biographer is suspicious of surfaces, and seeks out the contradictions and reticences of his subjects, perhaps also of his own self. Partly this is because the biographer—here I should say critical historian—is all too aware of how his own words shape, frame, and give meaning to words of other texts in other times. Though it may seem to some that facts are made to look too much like fiction, and fiction too much like history, this is because the book has succeeded in drawing us in, not just to some distant past, but to present imperatives of the past as it lives on. In Rosenstone's book it lives on with special power, style, and imagination.

Nicholas B. Dirks
Associate Professor of History and Anthropology
University of Michigan

EDITOR:

I am writing regarding the article "High Temperature Superconductivity" by David L. Goodstein (Winter 1989, Vol. 52, No. 2). On page 12 of that article Prof. Goodstein discussed nuclear fusion and stated ". . . magnetic confinement is no longer the system of choice. As a matter of fact, I don't think there is a major research group in the world working on magnetic confinement. It's just not the way the problem is being approached these days."

From this statement it appears that Prof. Goodstein was unaware of the state of affairs in the fusion research field. On speaking to him I found that he really meant to say "magnetic mirror confinement" rather than "magnetic confinement." Magnetic *mirrors* are confinement devices that have indeed been shelved, but the term magnetic confinement includes tokamaks, stellarators, reverse field pinches, field reversed theta pinches, and several other concepts all of which are being pursued vigorously. It is important to correct the misleading impression left by Prof. Goodstein's statement, and so I would like to summarize here the true status of magnetic confinement research.

First of all, magnetic confinement *is* one of the two systems under consideration (the other is inertial confinement), and there are many major research groups around the world working on magnetic confinement. The U.S. spends about $350 million annually on magnetic confinement, and Japan, Euratom, and the Soviet Union are all spending similar sums. Superconductivity is of potential relevance to magnetic confinement and, in fact, both Japan and the Soviet Union have built tokamaks with superconducting coils.

Second, Prof. Goodstein wrote that "nuclear fusion, the promise of limitless energy from seawater or something, has been just around the corner since World War II and is still just around the corner," implying that there has been negligible progress in this field. Although there have indeed been instances of optimism, in general the scientists involved have realized that fusion research, being one of the most challenging technical problems addressed by man, would take both a long time and much effort before success would be achieved. There has actually been enormous progress. To appreciate this, let me briefly restate the requirements for generating useful energy from nuclear fusion (called "break-even"): One must (i) heat a deuterium-tritium plasma to temperatures over 100 million degrees Kelvin, while (ii) simultaneously confining the plasma so that the heat does not leak out. The critical parameter for requirement (ii) turns out to be the product of the plasma density times the energy confinement time, and a working fusion reactor would require this product to exceed 10^{14} particle seconds/cubic centimeter. In the 1950s the best plasma temperatures obtained were about 1 million degrees and the confinement parameter was about 10^{9}–10^{10}; in the 1960s these improved to 5 million degrees and 10^{10}–10^{11}; and in the 1970s 50 million degrees and 10^{12}. Now, in the 1980s the Princeton TFTR tokamak has achieved ion plasma temperatures of over 100 million degrees (for comparison, the temperature of the core of the sun is 15 million degrees) and confinement parameters a few times 10^{13}.

These parameters correspond to being within about a factor of four of break-even (these experiments have all been done in deuterium plasmas; tritium injection is being temporarily postponed because of the careful handling required, and because it is more important to put the limited resources available into further improving the plasma). Similar results have been obtained on the European JET tokamak. The world fusion community is now designing the next generation of machines, which will operate well into the break-even regime. The U.S. program is suffering somewhat because of funding limitations caused by the current deficit problem, and it seems possible that the lead established here might be taken over by the Japanese (who are going full speed ahead) or the Europeans (who have been quite good at coordinating their resources to build JET).

Paul M. Bellan
Associate Professor of Applied Physics

E&S *welcomes letters from readers in response to material appearing in the magazine. We will publish relevant letters as space permits, but reserve the right to edit for length and clarity. Letters should be sent to* E&S, *Caltech 1-71, Pasadena, CA 91125.*

EDITOR:

Paul Bellan is exactly right about my goof. I deserve a double reverse theta pinch for saying such a thing. Furthermore, Paul isn't the only plasma physicist to object to me about that one. There were times when my phone heated up to well over 10^{8} kelvins (Paul is wrong about calling 10^{8} kelvins "100 million *degrees* Kelvin").

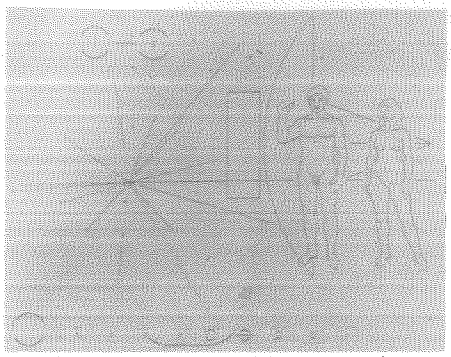
On the other hand, nobody has reached me to object to any of the other outrageous assertions in the article. I take this to be a good sign.

David L. Goodstein
Vice Provost
Professor of Physics and Applied Physics

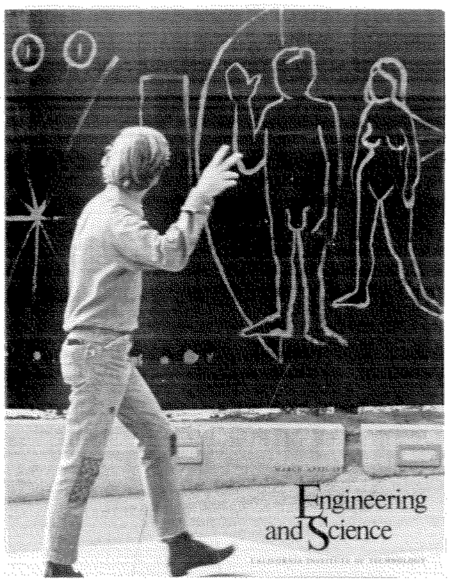
EDITOR:

Thomas Carroll's letter in the Winter 1989 issue brought back memories of the late 60s and early 70s on campus. Tom writes that he is proud to have been the cordial undergraduate who appeared on the cover of *Engineering & Science*, volume 35, number 5, March-April 1972. Caltech should also be proud—for staying calm during those turbulent years. The cover photo shows a student facing away from the camera, waving the peace sign to the two human figures on the space-bound Pioneer 10 plaque that someone had caricatured on a construction wall near Beckman Auditorium. Tom writes fondly of Floyd Clark and the photo session, but that's not the whole story.

You see, Sarah Ingersoll, my wife, had painted those figures several months earlier, and I'm proud to have been her accomplice. This confession still leaves



Random Walk



unidentified one more important person— the Caltech security guard who allowed us to complete our project. The wall was made of pure redwood and had no other graffiti on it. We planned a quick attack and a quick retreat after dark, but the guard arrived just as the naked figures began to appear. While Sarah painted and our children played underfoot, I began a frantic explanation of Pioneer 10 and the plaque. The guard remained silent. He revealed nothing about the rules he was operating under or whether he bought my story or not. A small crowd gathered. But then nothing happened; Sarah completed the painting and everyone drifted away. The guard did his job well. I hope he sees this letter.

Andrew P. Ingersoll
Professor of Planetary Science

Honors and Awards

Fred Anson, professor of chemistry and chairman of the Division of Chemistry and Chemical Engineering, has won the 1989 American Chemical Society Award in the Division of Analytical Chemistry for his achievements in pure and applied chemistry.

Professor of Chemistry John Baldeschwieler, has received the 1988 Richard C. Tolman Medal from the Southern California Section of the American Chemical Society in recognition of his broad accomplishments in chemistry and his extensive public service.

Assistant Professor of Cosmochemistry and Planetary Science Geoffrey Blake is one of 91 Sloan Fellows for 1989. The Alfred P. Sloan Foundation selects outstanding young scholars from a nationwide pool of applicants.

Bren Professor of Chemistry Peter Dervan has received the 1988 Harrison Howe Award from the Rochester Section of the American Chemical Society for his work in DNA sequence recognition and mechanistic organic chemistry.

Harry Gray, Beckman Professor of Chemistry and director of the Beckman Institute, and Steven Koonin, professor of theoretical physics, have been elected Fellows of the American Association for the Advancement of Science (AAAS), an honor bestowed on AAAS members "whose efforts on behalf of science . . . are scientifically or socially distinguished."

Leroy Hood, Bowles Professor of Biology, has been awarded an $800,000 grant from the L. K. Whittier Foundation to develop a gene analyzer that will automate DNA-based diagnostic techniques.

George Housner, Braun Professor of Engineering, Emeritus, has been named the first recipient of the Earthquake Engineering Research Institute's George W. Housner Medal. The medal was established in his honor to recognize advances in earthquake safety.

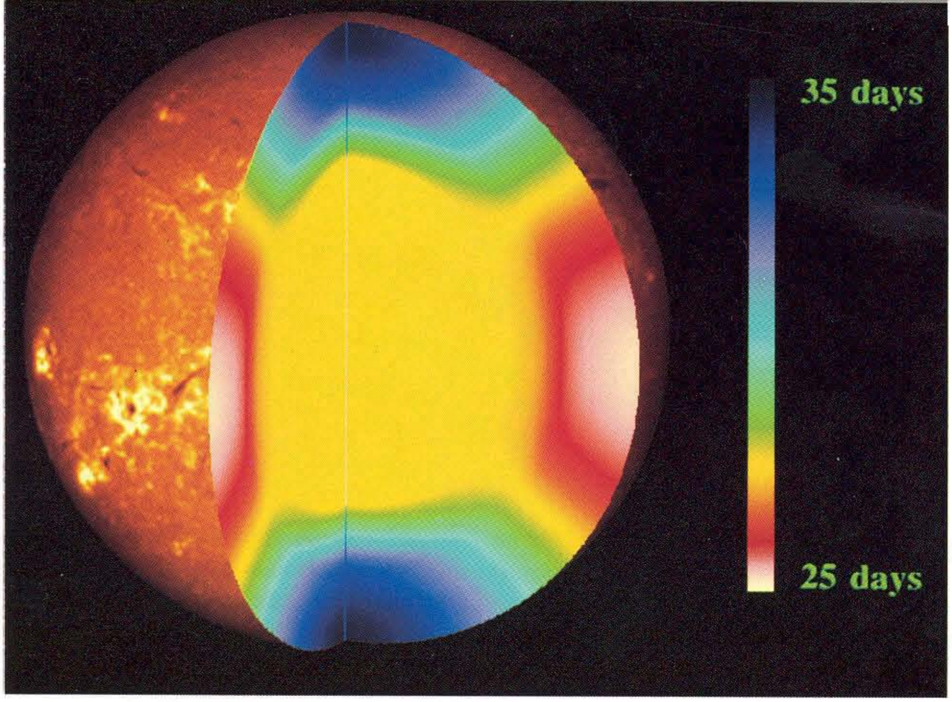
Christoph Koch, assistant professor of computation and neural systems, has been awarded a James S. McDonnell Foundation grant of $150,000 for the next four years.

Edward Lewis, Morgan Professor of Biology, Emeritus, is a co-recipient of the 1989 Wolf Prize in Medicine for his four decades of pioneering research in molecular biology and genetics.

Assistant Professor of Chemistry Daniel Weitekamp has been named a Dreyfus Teacher-Scholar for 1988. The Camille and Henry Dreyfus Foundation awards about a dozen of these $50,000 grants annually to exceptional young faculty members nationwide.

Ahmed Zewail, professor of chemical physics, won the 1989 King Faisal International Prize in Science for his ultrafast laser chemistry work.

Two faculty members, along with 42 other international scientists, have been elected Foreign Members of the USSR Academy of Sciences. They are Roger Sperry, Nobel laureate and Board of Trustees Professor of Psychobiology, Emeritus, and Professor of Geology Peter Wyllie.



The sun's interior rotation has been measured for the first time by Assistant Professor of Astrophysics Ken Libbrecht, using data from Caltech's Big Bear Solar Observatory and a technique called "helioseismology" that uses waves on the sun's surface to probe its depths. The surface rotation varies from every 36 days at the poles to every 25 days at the equator. Libbrecht found that these rates extend inward some 130,000 miles—about 16 earth diameters—30% of the way to the center. Lower down, the sun appears to rotate rigidly once every 27 days, but the data only extends 260,000 miles into the sun. The false-color interior shows rotations, while the "skin" was taken from an unrelated photo.

Professorships

Four faculty members have been named to chaired professorships—two old and two new—and another new chair has been established.

John M. Allman was selected by the board of trustees as the second Hixon Professor of Psychobiology, succeeding Nobel laureate Roger Sperry, who held the chair for 30 years and is now Board of Trustees Professor of Psychobiology, Emeritus. Allman, whose research involves the cortical areas of the brain that are responsible for processing visual information, has been a member of the Caltech faculty since 1974 and professor of biology since 1984.

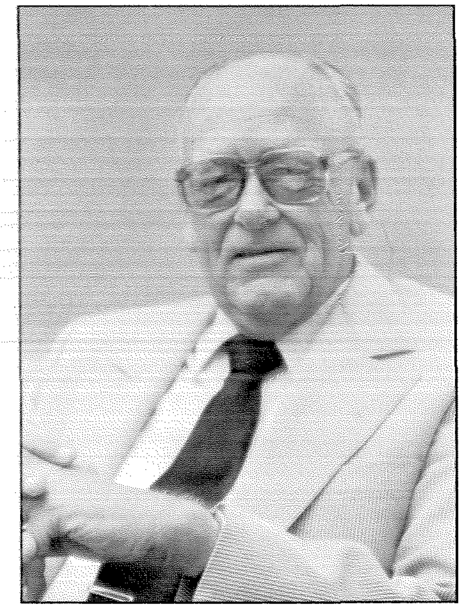
Roger D. Blandford, announced as the Richard Chace Tolman Professor of Theoretical Astrophysics, will be the second occupant of the Tolman chair. The first was Nobel laureate Richard Feynman, who was the Tolman Professor of Theoretical Physics from 1959 until his death in 1988. Blandford has brought new insights to such cosmic phenomena as pulsars, cosmic jets, and black holes, and is currently developing theoretical models that attempt to explain the birth of quasars. He joined the faculty in 1976 and has been a full professor since 1979.

Of the two new professorships recently established, William L. Johnson has been named the Ruben and Donna Mettler Professor of Engineering & Applied Science. This chair was endowed by two donations of $750,000 from the TRW Foundation and from the Mettlers. Ruben Mettler, a Caltech alumnus, serves as chairman of the Caltech board of trustees and is the retired chairman and chief executive officer of TRW Inc. Johnson, who earned his doctorate at Caltech and has been a member of the Caltech faculty since 1977, works in the area of materials science and solid state physics, including the study of superconducting materials, electronic structure of metals, rapidly quenched materials, and disordered and amorphous solids.

Hiroo Kanamori was selected to be the first holder of the John E. and Hazel Smits Professorship, which was established from bequests from their estates. Smits was a member of The Caltech Associates and a leader in the southern California hospital community. Kanamori's research focuses on the causes of earthquakes, and his interests also include tsunamis, volcanoes, and the structure of the Earth's crust and mantle. He has been professor of geophysics at Caltech since 1972.

A professorship in physics honoring Richard P. Feynman has been established by a $1.5 million gift from Michael Scott, BS '65, the first president of Apple Computer. Scott, who vividly remembers his first day in Feynman's freshman physics class, wished in particular to recognize Feynman's genius as a teacher.

VOLUNTEERING AT CALTECH



Stan Holditch '48 currently serves as Alumni Fund Chair.

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- It's fun.

If you are interested in volunteering at Caltech and would like more information, please write or call:

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