California Institute of Technology

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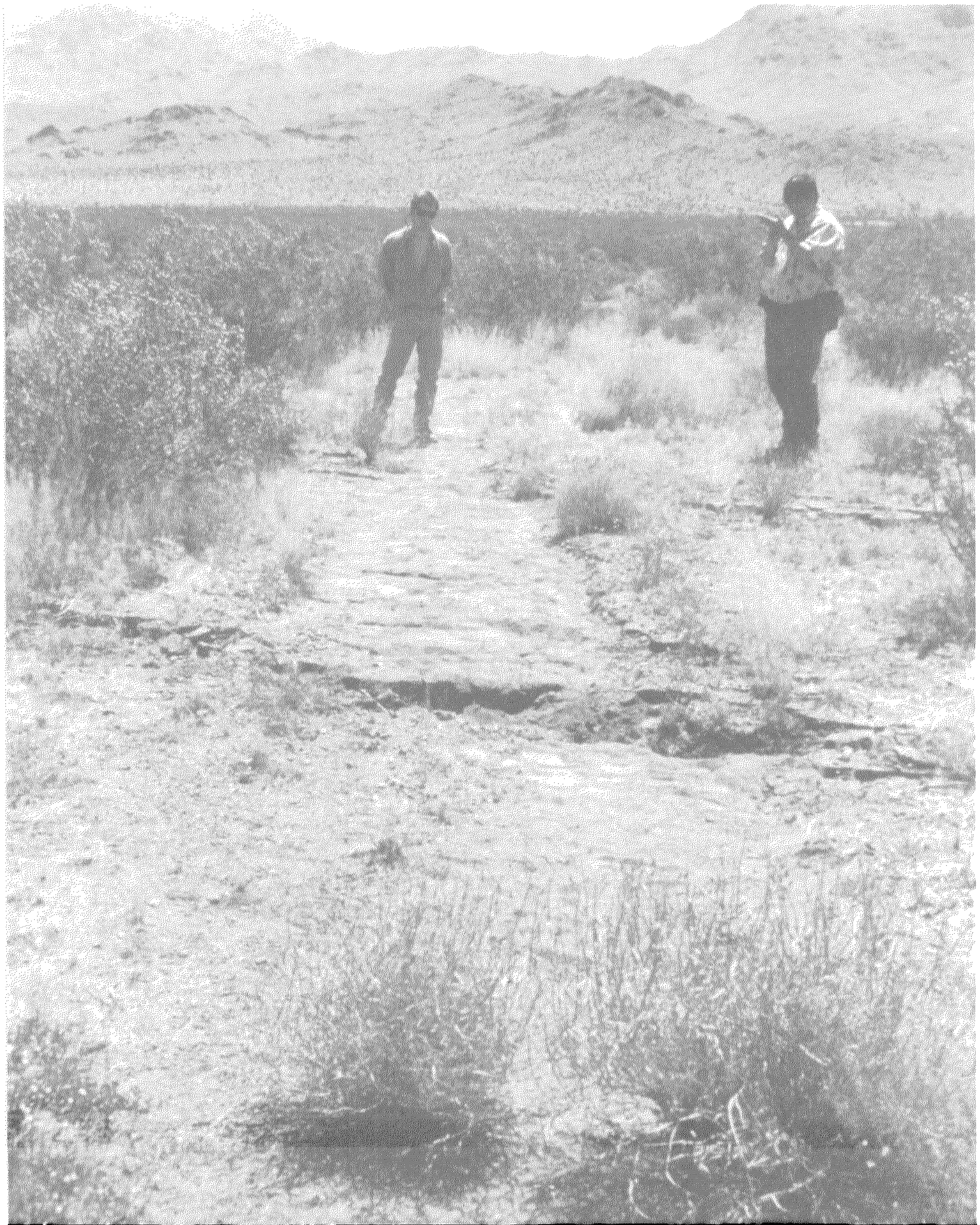
Summer 1992

In this issue



After the magnitude 7.5 Landers earthquake in June just 100 miles east of Los Angeles, Caltech geologists lost no time in getting out in the field. Here Professor of Geology Brian Wernicke (right) and grad student Jim Spotila note a crack in the desert along the northern segment of the fault.

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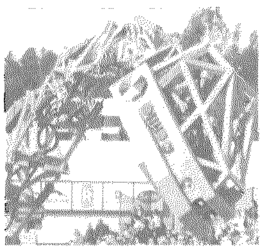

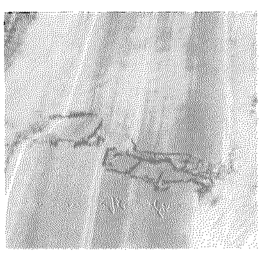

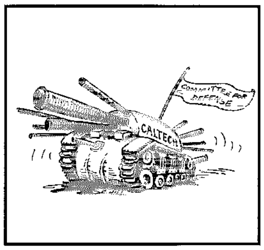

On the cover: A prototype robot tentacle demonstrates its dexterity by grappling a make-believe satellite. In the spirit of international amity, the malfunctioning satellite was hypothesized to be a Soviet one, rescued from orbital oblivion by an American space shuttle crew. Recent events have rendered the Cyrillic initials on the "satellite" obsolete, but the robot tentacle is alive and well at Caltech. Story on page 2.

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Robots That Crawl, Walk, and Slither

200 years ago a dishwasher would have been considered a robot (not to mention a miracle), but it's just a machine to us.

by Joel W. Burdick

Opposite: (from left) Howie Choset, Jim Ostrowski, Greg Chirikjian (PhD '92), and Joel Burdick pose with their robot snake.

What, exactly, *is* a robot? There are a lot of popular notions about what robots are, so let's begin with some definitions. The word *robot* comes from the Czech word *robota*, which connotes obligatory servitude. The word was first used in its current sense by Czech playwright Karel Capek, in his 1917 play *RUR*, which stood for Rossum's Universal Robots. Many of us working in robotics continue this usage implying servitude, and define a robot as a machine that, once programmed, is capable of independent action, and that can be reprogrammed (at least to some extent) to do different tasks. Robotics is just the latest in a long history of engineering's quest to improve mankind's reach and mobility (i.e., to move faster, farther, and higher) and to multiply human ability in order to improve our standard of living. In fact, much of robotics research was originally motivated by the goal of automating factories. That goal hasn't been reached, but it now appears that robots may have greater potential outside of the factory anyway.

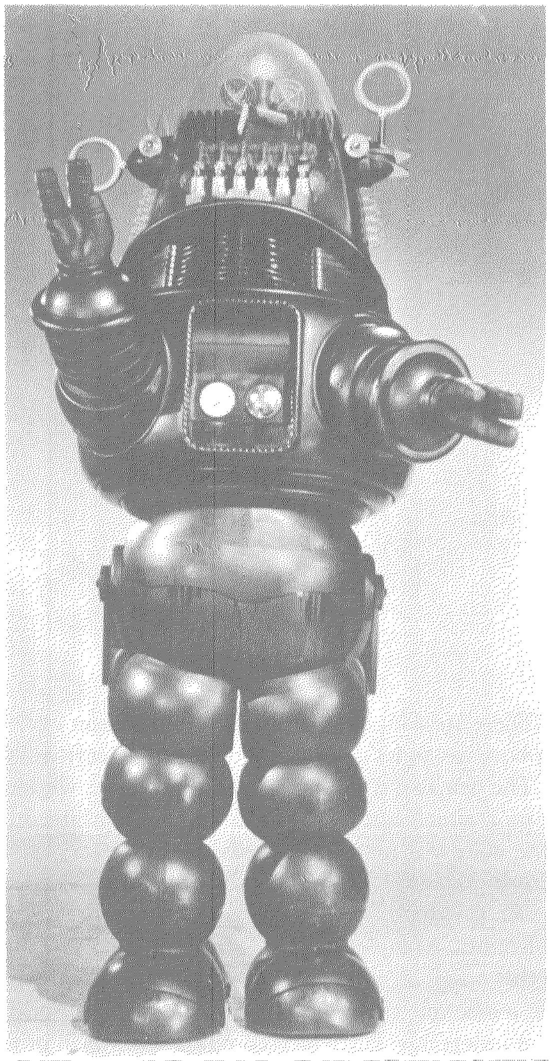
The word robot is really a metaphor for the next generation of automated machines. Once a certain level of automation becomes widespread, we no longer call it robotic. For example, 200 years ago a dishwasher would have been considered a robot (not to mention a miracle), but it's just a machine to us. Today's robots are essentially complicated electromechanical systems that are controlled by computers. This makes robotics research almost a branch of computer science. Hence, much of robotics research centers on developing computer algorithms—mathematical expressions or computer codes that take inputs from sensors, refer back to the assigned task, and output an action—that will enable robots to accomplish what we want them to do. Not only must the algorithms do complex things, but they must compute very quickly. A vision algorithm to detect falling boulders isn't much use if the robot is crushed before the computation finishes.

In addition to the quest for enhanced productivity, another grand theme of modern engineering is the drive to build increasingly large and complex systems in order to satisfy societal needs. Unfortunately, recent events such as the near-collapse of AT&T's phone system show that we're not very good at it yet. One reason robotics hasn't gotten as far as early enthusiasts had hoped is that we've underestimated the complexity of building "intelligent" robots. Most of the robots that people envision in science fiction are really of the complexity of the national phone system. Take Gog, one of my favorite science-fiction robots, from the 1954 movie of the same name. It could not only play tennis, it could also build nuclear bombs. And, unfortunately, a programming glitch caused it to almost destroy the world. A lot of engineers like me are interested in new approaches for designing and operating complex systems. Robotics provides us a convenient way to study such systems without using quite as much hardware as the phone company.

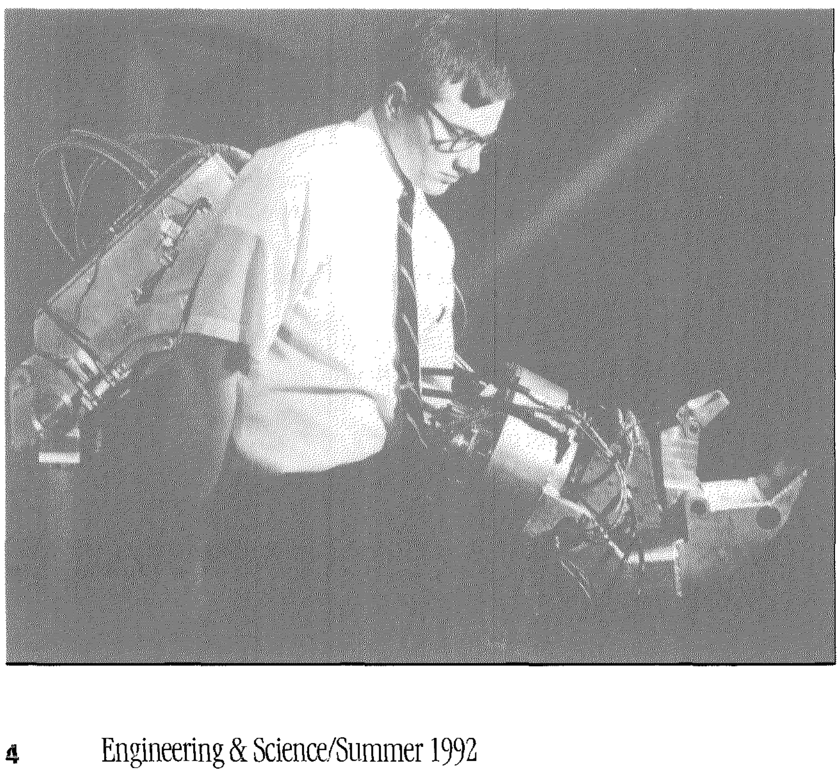
Mankind has been interested in building mechanical servants for a long time, but modern robotics dates from about 1960, when the first computer-controlled factory robot was installed. Its computer was quite crude by today's standards, but it *was* reprogrammable. By then, digi-

Right: Robbie the Robot (from the 1956 movie *Forbidden Planet*) is perhaps the archetypal science-fiction robot.

Below: The Hardiman project, developed by the General Electric Company for the Army and Navy in the late 1960s, never got much farther than this prototype arm. Its descendants live on in Hollywood, however, as in the "power loader" Sigourney Weaver wore in *Aliens* (opposite page).



Still from *Forbidden Planet* Courtesy of Turner Entertainment Co. and the Academy of Motion Picture Arts and Sciences.

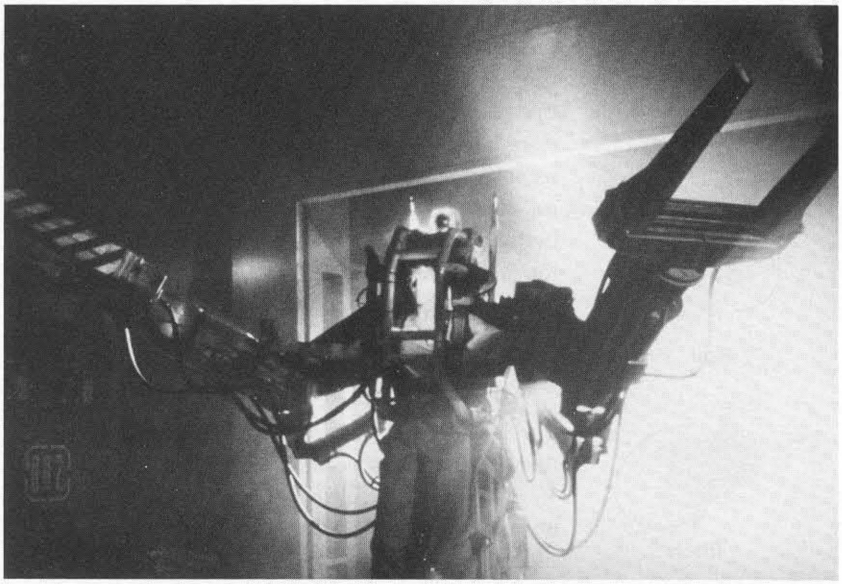


tal computers had been around long enough for people to begin thinking about smart machines for industrial automation. It made sense to remove people from assembly lines because such jobs are boring, dangerous, or costly. The year 1960 also saw the beginning of commercial nuclear power. The nuclear industry had a different vision for robotics. They wanted to build mechanical proxies so that humans wouldn't need to enter highly radioactive, dangerous, or inaccessible areas. Such robots weren't necessarily smart, as they would follow the motions of a human operator.

The early history of robotics is filled with ideas that either never panned out, or became evolutionary dead ends because of limitations in technology. One was General Electric's Hardiman, which was like those "power loaders" in *Aliens*—a machine you wore that increased your strength so you could lift heavy cargo. Hardiman was never completed, as the computers of the day weren't up to the task of controlling it, but there have been recent efforts at the University of Minnesota and the University of California at Berkeley to revive the concept. Some other dreams from the early days, such as multi-armed robots and robots with flexible torsos—things people never dreamed would be as hard to animate as they are—are also being revived, now that computer technology has become vastly more sophisticated. In general, from 1960 to 1966, people were just experimenting with building different kinds of machines; there was no clear vision of what the significant problems of robotics are.

The golden age of U.S. robotics research

From 1960 to 1966, people were just experimenting with building different kinds of machines; there was no clear vision of what the significant problems of robotics are.



began around 1967–68. It was an exciting time of incredibly rapid advances—an explosion in robotic capabilities. Scientists and engineers were getting a clearer idea of the important technical problems, and developing the basic analytical and technological tools to solve them. Many students who earned their PhDs in robotics research immediately founded companies to transform their research into actual products, making the delay between laboratory research and industrial application very short.

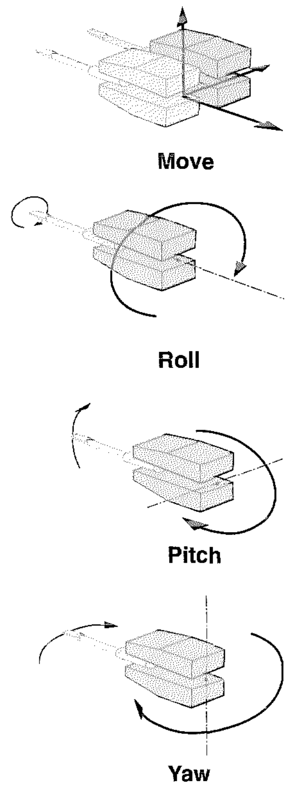
The late 1970s and early 1980s saw an expansion in industrial robotics, and many corporations started experimenting with factory automation. Some applications, such as welding and spray painting in the automobile industry, proved successful. Others did not. There were some grand failures, such as the toilet manufacturer whose robots kept crushing the fixtures, and many inconclusive efforts that proved too costly to continue. There are several reasons why these efforts failed. In part, U.S. manufacturers didn't understand the capabilities and limitations of robots. The problem was often not in the robot, but in poor management techniques and poor manufacturing processes that couldn't be fixed by the magic bullet of robotics.

There were some grand failures, such as the toilet manufacturer whose robots kept crushing the fixtures.

These sometimes naive and invariably expensive forays into automation were often driven by the overhype that predominated in the robotics industry during the late 1970s and early 1980s. In 1990, there was a great article in the *Los Angeles Times* entitled "Prediction Has Become Robotic," which pointed out that ever since the 1930s it's been predicted that ten years from now we're going to have robots in the home doing all sorts of things for us. Ten years go by and nothing happens. Then the hype begins again. In a typical example, the Quasar Company announced in 1978 that within two years it would be offering a $4,000 robot that would cook for you, mow your lawn, and vacuum your rug. We haven't seen it yet.

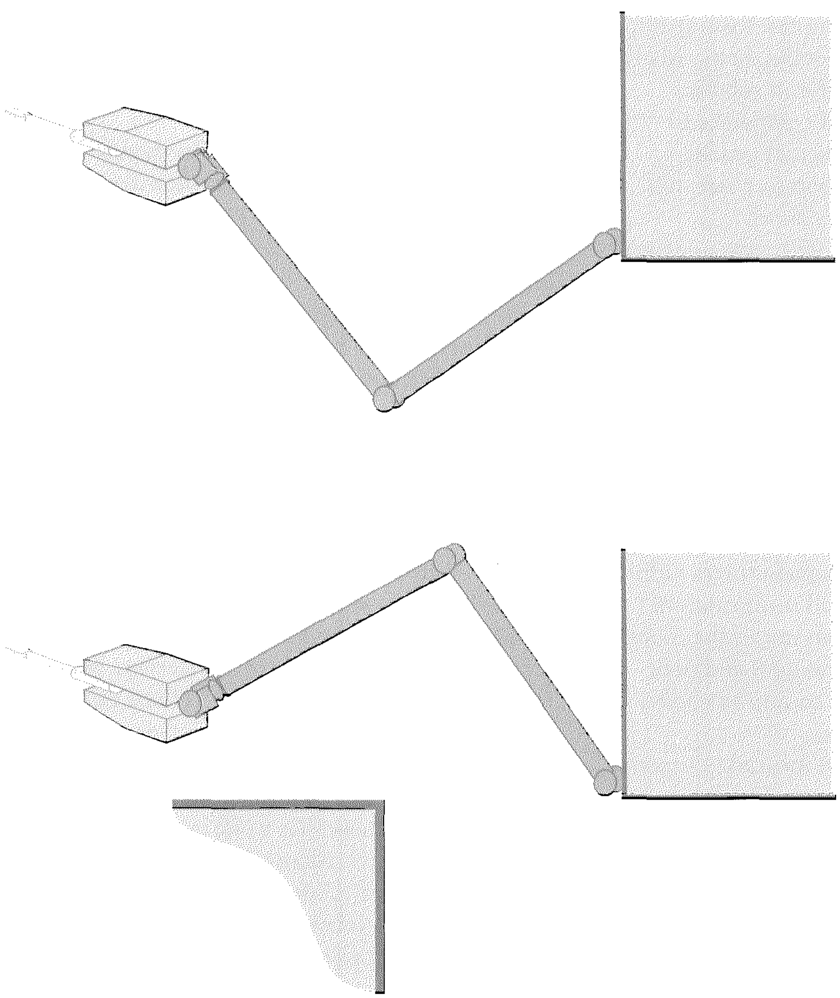
Because of the overhype and the dismal results of many experiments, American industry turned sour on robotics in the mid-1980s. The U.S. robotics industry started declining in 1987, and only recently has it begun to grow again. Back in 1979 people were predicting that the U.S. robotics industry would be a $4-billion-a-year industry by 1990. It's not, although Japan's is. Japan has about five times as many robots installed (about ten times as many per capita) as we do now.

The almost-exclusive focus on industrial automation had some negative effects on the rest of the field. One was that when the robotics industry didn't grow, funding for robotics research fell off. The other was that the preoccupation with industrial automation limited our vision of what robotics might do outside of the factory. Manufacturing is only about one-third of our gross domestic product. There are many other economically and scientifically important areas where robotics can have an impact: robots that explore other planets; robots that work in nuclear plants or toxic-waste sites; robots that work in the service industry; and robots that assist in medical procedures. The robotics community is now pursuing these applications. However, the activity level has been small until recently, because of



Right: A robot arm needs six degrees of freedom in order to position an object: one for each of the three dimensions of space and the three different kinds of rotation.

Below: Extra degrees of freedom allow the arm to avoid obstacles.



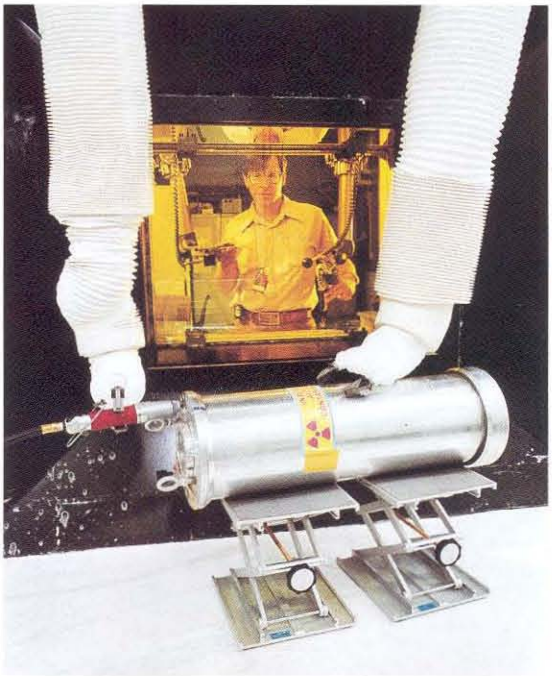
the earlier fixation on industrial automation.

As an academic, I can also claim that robotics research is useful in and of itself, beyond automation, medicine, and the other possible applications. Algorithms developed for robotics have recently found uses in other areas. For example, robotics algorithms developed at JPL are now being used by computational chemists at Caltech for molecular-dynamics simulations. And the next generation of air-traffic-control computers will be based on research into how robots could cooperate in a factory without hitting each other.

As for my own research, I study "dexterous multifunctional robots." By "dexterous" I mean nimble robots that can move in complicated ways. And by "multifunctional" I don't mean our friend Gog, who could fix a toaster in the morning, play tennis in the afternoon, and build a nuclear bomb at night. I mean that when we humans grab something we normally use our hands. But if need be, we can use other parts of our bodies—for example, slamming the refrigerator door shut with our hip while we have the mustard and mayonnaise jars in our hands, the baloney package in our teeth, the loaf of bread on one forearm, and the head of lettuce pressed between our other arm and our chest. While current robots may be mechanically capable of performing such maneuvers, they cannot figure out how to do it automatically, and thus require laborious, explicit programming by humans.

A lot of my research is related to a simple concept called redundancy. In Great Britain, if you're redundant you're unemployed, and in systems engineering redundancy means building backup systems. In robotics it takes on a different meaning. Most robot arms are built with six joints, because in order to grab some object, position it in three dimensions, and control its orientation in roll, pitch, and yaw, the arm needs to move in six directions—it needs six degrees of freedom. Adding extra joints to the robot makes it "kinematically redundant." Now, if both ends of the arm are stationary—because it's holding something in position, say—these extra degrees of freedom allow the rest of the arm to move internally. It can swing to avoid obstacles or to optimize mechanical properties, such as the force it's applying in some direction.

If adding a few degrees of freedom to a robot makes it more dexterous, what if we add a *lot*—hundreds, maybe thousands? Rather than looking like the typical robot arm, these things will look like snakes, and that's the slither part of my title. We call such robots "hyperredundant," a word coined by one of my first graduate students, Gregory Chirikjian (PhD '92), when he started



Above: Intelsat VI, stranded in a useless low orbit when its booster rocket failed, was plucked from space by (from left) Richard Hieb, Thomas Akers, and Pierre Thuot aboard the shuttle *Endeavour*. The satellite had to be retrieved by hand after unsuccessful attempts to grab it with a specially designed capture bar nearly sent it spinning out of reach. A robot tentacle that could wrap itself around the satellite to grip it might have had better luck. With Akers and Thuot keeping a firm grip on the satellite, Hieb was finally able to attach the capture bar so that the satellite could be stowed in the cargo bay while a new booster was attached.

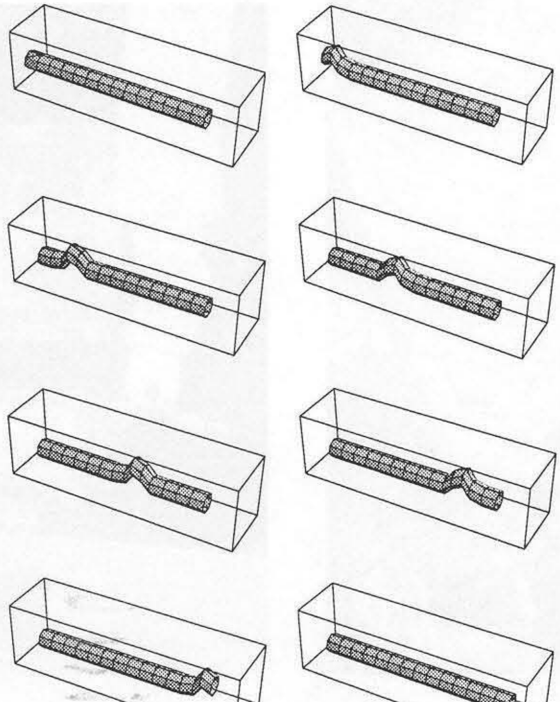
Right: The nuclear-power industry uses robot arms, operated by remote control, to manipulate "hot" radioactive materials inside shielded rooms.

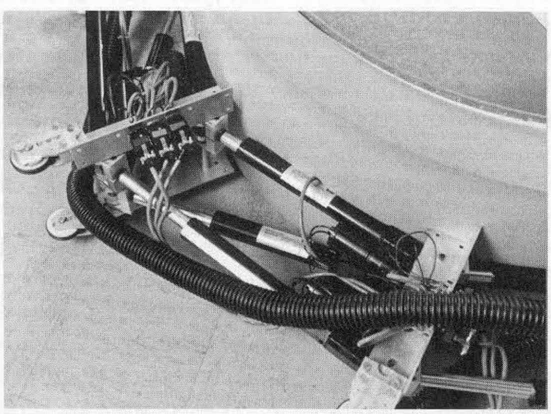
working on them just after I came to Caltech in 1988. These robots are not useful for industrial automation. But just as biology has evolved snakelike animals for certain niches, snakelike robots could be quite useful in some areas. In the nuclear industry, for example, they could crawl around inside reactor cores, which are very complicated spaces containing lots of obstacles. Or imagine that you want to retrieve a satellite in orbit. If you don't grab it properly, it can go spinning off into infinity. This almost happened on the Intelsat VI rescue mission in May 1992. But a tentacle could wrap around the satellite in a firm grip. And the Department of Energy has huge underground tanks—at Hanford, Washington, among other places—full of all kinds of nasty, unidentified toxins that have accumulated over the years. Robot snakes could go in and sample these materials and perhaps aid in their cleanup. More important, we are currently working on snakelike robots for medical applications.

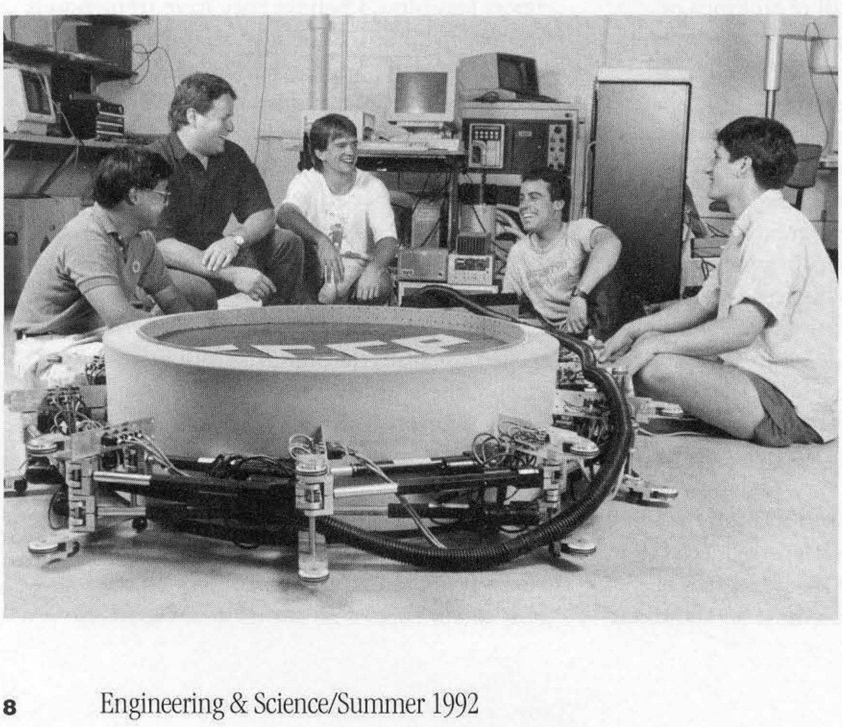
Snakelike robots have been around for about 25 years, though little real progress has been made with them. The "father" of snake robots is Shigeo Hirosi, of the Tokyo Institute of Technology, who built the world's first serious working one in the mid-1970s. While impressive in their audacity—these robots were a great leap beyond what anyone else had done—his robots couldn't maneuver with any accuracy or speed. Hirosi is still at it, and his robots are very well engineered and work reasonably nicely, but most of the other researchers' prototypes are collecting dust. Hyperredundant robots have so many degrees of freedom that traditional algorithms for coordinating their motions are useless. The algorithms just take too long to compute. Some compute an entire gesture and then execute it, which means the robot sits and thinks for perhaps half an hour, then makes one rapid movement, and then goes catatonic again while it figures out its next move. The others calculate motion incrementally, so that the snake moves continually, but in glacial slow motion. Thus, no one has been able to figure out how to make robot snakes do anything useful. This daunting complexity has kept hyperredundant robots confined to the laboratory, and has discouraged most people from working in the robotic-snake field.

One of my long-term goals is to make these robots feasible—I believe they have tremendous promise in a number of areas that current robot technology can't approach. Our initial focus was to develop a set of building blocks. These building blocks, called primitives, are simple low-level operations, such as extending the snake to its full length in order for it to begin grasping something. Primitives are more complex operations than moving a single joint, but less complex than executing a complete task such as grappling a satellite. We had to develop the analytical tools needed to create the algorithms that would execute these primitives realistically.

For example, consider how such machines might get around. In Greg's thesis work, we developed a mathematical framework for precisely and efficiently controlling these complicated machines' locomotion. In nature, inchworms, earthworms, slugs, and snakes (which are analogous to our robots) all use different kinds of







Top: The slug mode of traveling-wave locomotion.

Middle: Each of Snakey's ten segments consists of three actuators, or pistons—two parallel and one diagonal per segment—that, acting together, move the segment in two dimensions.

Bottom: (From left) I-Ming Chen, Brett Slatkin, Ostrowski, Choset, Chirikjian.

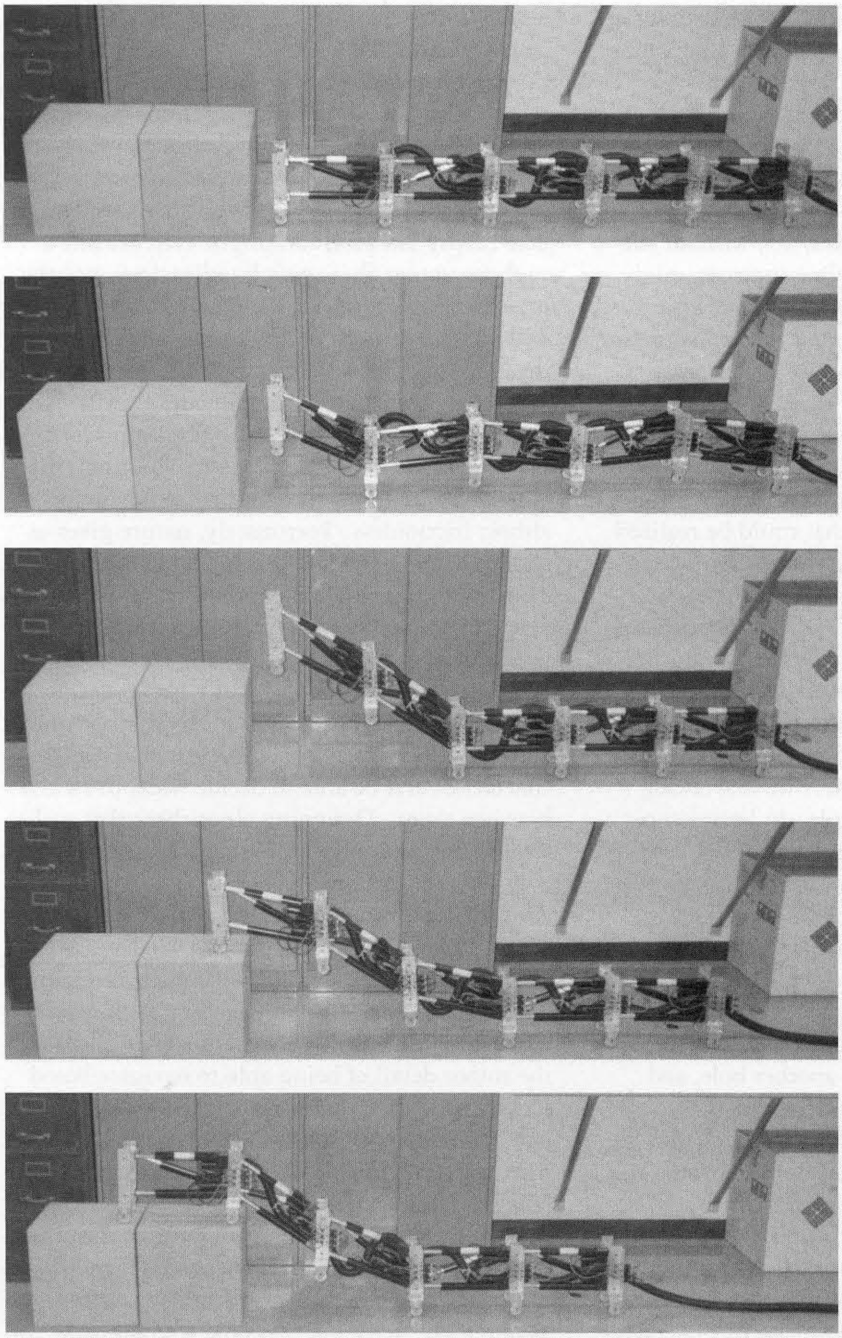
waves for locomotion. Inchworms use a form of movement analogous to a standing wave that resonates through the body. Earthworms move with an extensional wave that travels down the length of the body. Slugs use a vertical traveling wave, like when you snap a rope lying on the ground. And snakes use several motions. While stalking, they often use a "creeping gait" in which the abdominal muscles and scales move in a rhythmic wavelike pattern. Greg has found that there's an underlying set of equations that generates every kind of wave-like locomotion seen in nature, as well as some we haven't seen yet. Even the sidewinder, which moves forward by looping its body sideways, can be described exactly. But that's just half the battle. Once we know the mathematics of how the snake as a whole moves, we still have to determine the mathematics of how and when each muscle or actuator in the snake must move. This is the level of detail required to implement explicit algorithms to control robotic motion.

We also want our snake to operate in very tight corners, so Greg's been coming up with some very interesting obstacle-avoidance algorithms. Again, traditional algorithms, when applied to snakes, take so long they never compute. Greg's algorithms compute in real time—as fast as the machine can move—and can even handle moving obstacles.

In order to demonstrate our analyses, we've built a hyperredundant robot named Snakey. Snakey is properly called a "variable-geometry truss structure." Each of Snakey's segments is like the span of a bridge between two piers. The segment's trusses are actuators—pistons—that we can make longer and shorter so that Snakey as a whole will slither around. This design is quite different from what's found in nature. We've chosen it for its strength. Others have built snake robots with actual spinal columns, but those robots are too wimpy to do anything useful.

From basic functions like locomotion and obstacle avoidance, we can build more complex functions. Snakey can grasp and manipulate things like a tentacle would. Imagine you've grabbed a satellite, and you want to reorient it so you can work on a particular part of it. The obstacle-avoidance methodology curves the tentacle around the satellite to embrace it, and the locomotion algorithms "walk" along its surface. This reorients the satellite, turning it beneath the tentacle a little bit at a time. If we know the object's geometry, the algorithm automatically figures out how to move all 30 of Snakey's actuators. We can even break Snakey into two tentacles of five segments each, and have them

Snakey can avoid obstacles by going around or (in this case) over them. Only five segments were used in this demonstration in order to keep Snakey's length comfortably less than the width of the lab.



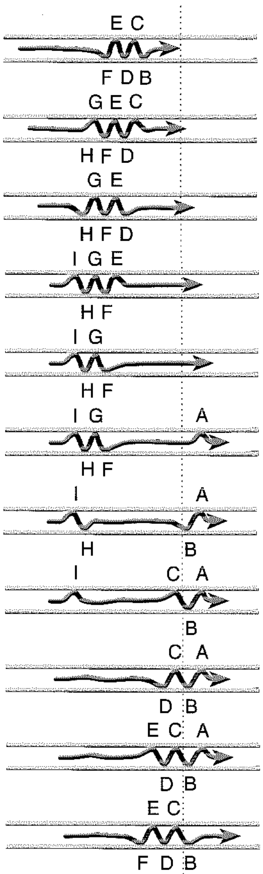
cooperate to manipulate an object.

Snakey is so dexterous that it can curl up on itself. Traditional robots can't. It's also so big that it doesn't always all fit in our lab. It can actually stretch (unlike real snakes) from its minimum length of about 12 feet out to about 18 feet. Then we have to open the door and let it stick out in the hall, where it bumps against the far wall. It can do all the different kinds of snake locomotion. It can do the earthworm movement. And when we turn it on its side, so that it moves in the vertical plane, then we can do the inchworm standing-wave locomotion, using wheels that only turn in one direction so that the machine will move forward. Furthermore, we can make these complicated motions fairly precisely, so that Snakey goes where we want it to go.

Right now we have to tell Snakey where the obstacles are. It doesn't have enough on-board sensors to automatically detect objects and move based on that data only. This is one focus of our current research (with graduate student Howie Choset and visiting scientist Nobuaki Takanashi from NEC corporation, Japan). We hope to be able to demonstrate motion based strictly on sensor input in the near future.

We're now going beyond demonstrating algorithms to thinking about making these snakelike robots do practical things. We are currently helping JPL build a small snake-robot that will be carried around on the end of a larger traditional robot arm. This robot will peer around inside the complicated structure of the future space station to inspect for cracks, micrometeoroid damage, and so on. And, depending on up-

A snake in a confined space, such as a pipe, naturally adopts the "concertina" mode of locomotion. The letters mark parts of the snake's body that are held motionless, pressed against the pipe, while the rest of the body is thrust forward or drawn in to be held against the pipe in turn.



coming budget constraints, we hope to start a project next year with JPL and the Kennedy Space Center to make a snakelike robot to service the space shuttle on the launch pad. In order to flip switches, remove dust covers, and rearrange thermal blankets in a fully loaded space shuttle cargo bay, humans must currently dangle from a gantrylike device called the Payload Ground Handling Mechanism (PGHM). Because each payload combination is different, NASA has to build special fixtures, at a cost of a million dollars per mission, to enable people to reach into the packed shuttle bay from the PGHM. A dexterous snakelike robot would be able to thread itself through the labyrinthine bay to do these simple tasks without special handholds or safety harnesses. Caltech will be developing all the algorithms for this robot.

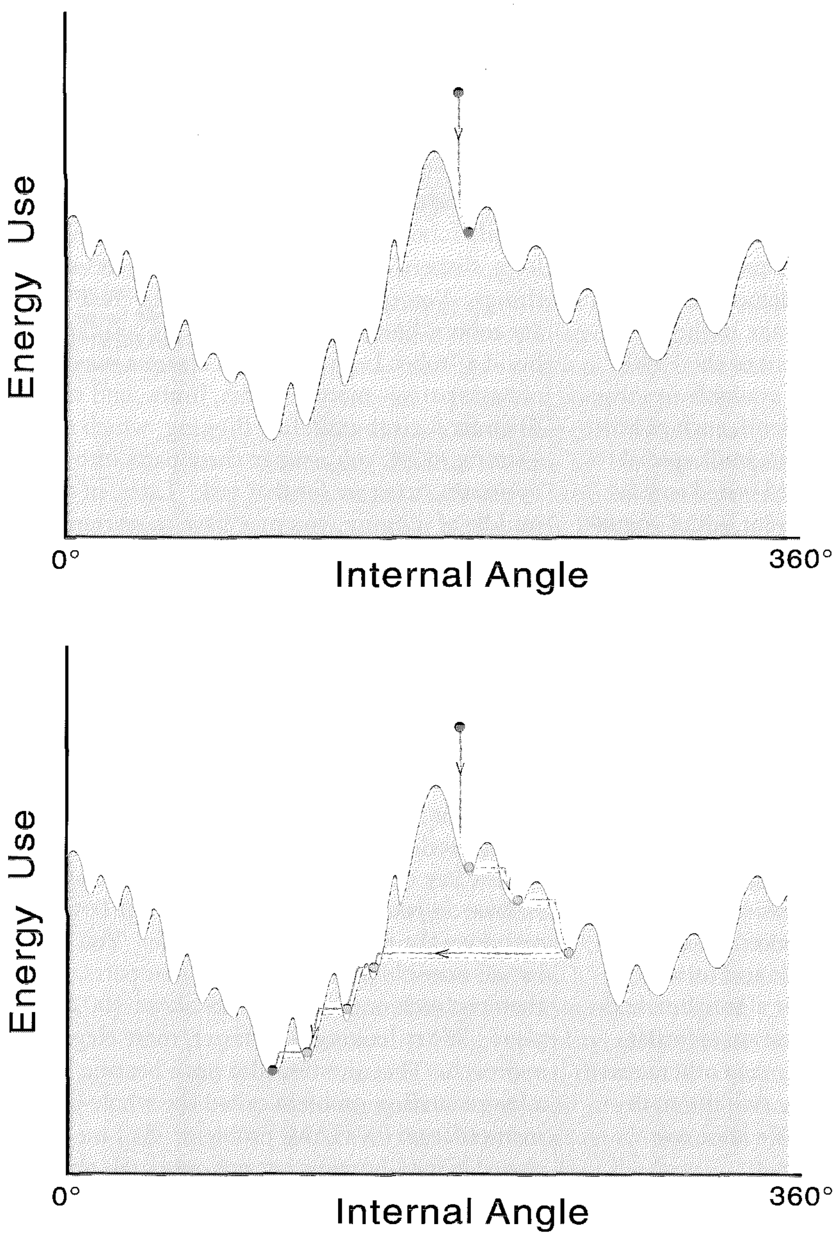
But I'm most excited about applying these robots to medicine. Of the 21 million surgeries performed yearly in the U.S., surgeons have estimated that about 8 million could be done with minimally invasive techniques, i.e., without slitting somebody wide open. One common minimally invasive procedure is arthroscopic knee surgery. Presently, only about a million surgeries per year are performed this way. The average traditional surgery puts you in the hospital for about eight days. The equivalent minimally invasive surgery requires, on average, a four-day hospital stay. The potential savings in hospital costs and lost productivity that could be realized by the complete adoption of minimally invasive surgery amounts to about three-fourths of one percent of the GNP. There are two main ways in which the number of minimally invasive surgeries will increase. Training more surgeons to do them will put us at around three million. But getting to eight million will require a big leap in technology, and that's where we're working.

Let me give you an example. In laparoscopic gall-bladder removal, they poke a hole in your abdomen, stick in a hose, and fill you up with carbon dioxide until you look like a balloon. With the abdominal cavity inflated, the organs aren't all squashed against each other, so the doctors have more maneuvering room, and they're better able to see what they're doing. Then they insert a TV camera through another hole, and they come in with long, scissorlike tools through adjacent holes, snip your gall bladder off, and drag it out through one of the holes. Instead of a six-inch scar, and four weeks out of work, you have a bunch of eight-millimeter holes, and you are back to work in about four days. But there are lots of places in the human body that surgeons can't get to with current laparoscopic technology. In order to get to these deeper parts, we need long, thin, articulated, actively controlled devices—e.g., small hyperredundant robots.

I'm working with Dr. Warren Grundfest, of Cedars-Sinai Medical Center, and one of my graduate students, Brett Slatkin, to develop surgical robot technology. Right now we're working on a gastrointestinal robot—a robot "tapeworm" that crawls through your intestinal tract. Available endoscopes (which are long, semiflexible tubes containing a fiber-optic bundle for inspection and laser surgery) can't get to about 70–80 percent of your GI tract because both ends of it have sharp bends that are really hard (and very painful!) to get around. If you want to get beyond these bends, where the endoscope can't go, you have to start cutting. We're working on a tiny robot that can crawl through your intestine and negotiate those turns. It will not only reach the entire intestinal tract, but will also be less painful to the patient. It will have a TV camera to inspect the intestinal lining, possibly have a small arm to take biopsy samples, and might even act like a tugboat to tow fiber-optic bundles deep into the intestine for laser surgery. We think this device will ultimately eliminate about half a million invasive surgeries a year in the U.S. alone.

Our problem is that the human intestine is very hard to get a foothold in. It changes its diameter by a factor of four over very short lengths. It's elastic. It's squishy. And it's very slippery—almost frictionless. Fortunately, nature gives us some clues. There's a mode of snake locomotion, called the concertina mode, that snakes use in very constrained places. We've used our mathematical analyses to design algorithms to replicate that motion. But to successfully navigate the human intestine, the gastrointestinal robot must have mastered a number of gaits, including the concertina, and be able to decide when to switch between them. Designing algorithms that make that decision automatically is one incarnation of a very complex problem that I'll return to later. And there are other challenges to overcome before actual deployment of this robot. We have to shrink everything down to 8–10 millimeters in diameter, and pack in two TV cameras, a bunch of sensors, and a little robot arm. Then there's the minor detail of being able to navigate based strictly on sensory input rather than needing to have a detailed up-front model of the environment we're slithering through. These challenges will keep us busy for years to come.

I want to briefly summarize some of the other research efforts in my group that are related to the theme of dexterous and redundant robots. While there aren't many people who do snake ro-



A stylized graph of energy use versus internal angle for a robot arm. Top: A typical minimization algorithm drops a marble on the slope, where it rolls downhill and gets caught in the nearest valley. Bottom: TRUST's marble "tunnels" through the graph each time it gets stuck, until it reaches the lowest valley of all.

botics, there are a fair number who study legged locomotion—how robots can be made to walk. They'll tell you they're trying to develop machines that can maneuver over very rough terrain. That's a bunch of baloney. Like us, the people working in legged robotic locomotion do it for fun. The research in this field is divided into two areas, which are analogous to the conscious and unconscious motions that humans use to walk. There's an oscillatory, unconscious motion that you use when you're not thinking about walking—a natural rhythm that propels you forward and keeps you balanced. And there's a more irregular, planned motion, as when you're walking and suddenly realize you've forgotten your glass of milk, and you have to turn around and go back to get it. We're studying the rhythmic gaits. It's a real challenge to develop algorithms that mimic the smooth, stable, balanced stride that we use unconsciously.

Many algorithms have been proposed by other researchers, and many have been implemented in real walking robots. However, these efforts have often led to jerky or bouncy gaits. You wouldn't want to ride these machines, the way they lurch and sway. We've analyzed some of these algorithms to try to understand why they're so rough. As an example, there's a famous hopping algorithm by Mark Raibert (formerly of JPL, and now at MIT). When he tried to make his robots hop higher and higher, they didn't. They started limping. We found out why. For you physicists, it turns out to be a period-doubling bifurcation leading to chaotic motion. My grad student Jim Ostrowski is now trying to use our analytical tools to develop a more rigorous framework for designing running algorithms, like the one we've come up with for snakelike locomotion.

I now want to discuss a less glamorous concept, but one that's very important to me as a systems engineer. We often use a redundant robot's extra degrees of freedom to optimize some mechanical property—to maximize the force the robot exerts in some direction, or perhaps to minimize the energy the robot uses to move. It helps to think of this graphically. In the case of minimizing energy, the horizontal (x) axis represents the robot arm's internal angle, and the vertical (y) axis corresponds to the robot's energy use. We can then plot a curve that shows the energy use for a given internal arm angle. The lowest point on the curve corresponds to the internal arm configuration with lowest energy use. Typically, this curve has many little valleys, or local minima. We often want to find the global minimum—the lowest point anywhere—rather than getting stuck in one of the local minima. This global optimization problem has been extensively studied. Most algorithms make an initial guess about the best value of x, and then drop a marble, as it were, on the graph at that point and let the marble roll down the hill. The marble gets stuck in the nearest valley, which is almost always a local minimum. My grad student Bedri Cetin and I have collaborated with Jacob Barhen at JPL to develop a new algorithm that borrows an idea from quantum mechanics. When the marble gets stuck, it "tunnels" through the hillside to find a deeper valley, rolls down that hill, and continues to tunnel and roll, tunnel and roll until it finds the bottom. We call our algorithm TRUST, for Terminal Repeller Unconstrained Sub-energy Tunneling. It's substantially faster than well-known global optimization algorithms in standard benchmark tests.

More important, TRUST is analog, rather than digital, in nature. That is, the algorithm doesn't break the problem up into ones and zeros and solve it by discrete computation, but rather uses continuous mathematics. Consequently, we can build analog circuits to implement TRUST, and the answer emerges as a voltage in the circuit. This approach is reminiscent of the 1940s, when digital computers weren't available to solve complicated mathematical problems, such as how to lob an artillery shell. Engineers built special-purpose computers that were hard-wired to solve one particular problem. These went out of vogue in the 1960s as reprogrammable digital computers became powerful, because you didn't have to build a new computer for each new problem. But now we can easily and cheaply design and fabricate special-purpose analog computers on a chip, thanks to Carver Mead (BS '56, MS '57, PhD '60, Moore Professor of Computer Science), who has been pioneering this technology right here at Caltech. With proper algorithm design, these special-purpose chips can be much faster than digital computers, because the program is built right into the circuitry rather than encoded in a set of instructions that the computer has to read and then execute. Bedri has built and tested two of the three chips we need for our algorithm, and the third is under way. Optimization is important not only in robotics, but in many other areas of engineering, such as telephone switching, or the optimal design of bridges. We hope our algorithm will find widespread use.

Another robotic application of global optimization is grasping. Imagine your robot is trying to pick up a moon rock. The robot takes the rock's image with its TV camera, makes a mathematical representation of the rock's surface, and has to figure out where the best points are on that surface to grab it. Humans typically use an antipodal-point grasp, gripping the object at opposite points on its surface, like the north and south poles of the globe. Mathematically speaking, the object's surface normals—that is, lines drawn perpendicular to the surface—are antiparallel at the grasped points. This is one of the most stable grasps possible, and one that requires the least amount of friction, which is very important if you're grabbing an unknown object that might be slippery. So the problem is to find the antiparallel normals of a very complex shape automatically. By posing this as a global optimization problem and taking advantage of our algorithms, we can solve it quite rapidly.

And finally, my grad student I-Ming Chen is working on modular and self-configuring robotic systems. Suppose that you're a NASA engineer, and you want robots to build a base on the moon. You need strong robots to dig holes, nimble robots to put parts together, walking or otherwise mobile robots to transport things, and perhaps a long, slithery robot to peek into holes and inspect things. You can build and launch all these different robots, but that's expensive. Or you can build a "robot Lego set." You create a bunch of basic parts—motors, joints, limbs, and such. Then for a given task, like digging, which takes a strong robot, you arrange these parts into the optimum structure for that task. Later, in the middle of digging, you may have to rearrange the parts in a different way to do something else. This idea is potentially useful not only on the moon, but at any remote site where you can't afford to bring in a lot of hardware but you need to do a wide variety of things—such as in an underground toxic-waste tank, say. This is another wrinkle on the concept of redundancy, more like the engineering notion in which redundant subsystems improve the capability and reliability of the whole system.

The key question that I-Ming is working on is, how do you automatically figure out how to rearrange the parts for a specific task? You could list all possible combinations of your parts, and then test each one. That'll take about 100,000 years. We're looking for a faster, more elegant approach. This question also has a bearing on a long-standing problem called the whole-arm manipulation (WHAM) problem. As I mentioned before, humans can not only grab objects in their hand, but can use many other parts of their body for complex maneuvers and manipulations. We currently don't have a systematic way to enable robots to automatically plan such complex actions. Algorithmically, the WHAM problem has much in common with the modular

I will not predict the future of robotics. It's been predicted to death already and everybody has been wrong.

Even the Rose Parade is getting into the act. The General Motors float for 1992 featured a hyperredundant neck.

robot rearrangement problem. In both cases, the robot's planning algorithms must automatically determine how to coordinate the system's resources—the robot's various surfaces in the WHAM case—to solve a complex problem.

Robotics is a lot harder than we originally thought. Back in the late 1970s, Marvin Minsky, often called the father of artificial intelligence, predicted that by the early 1990s we'd have machines that were smarter than human beings and just as capable. He was clearly wrong. One of the reasons robotics is so hard is that truly intelligent, flexible robots are going to be complex systems beyond the capability of one person to create. The breakthrough will come when all of the building blocks developed by individual researchers, such as vision, tactile sensing, locomotion, manipulation, and machine intelligence, can be put into a unified framework—a Grand Unified Robotics Field Theory. We're working on some modest pieces of this unification—the WHAM problem is an aspect, as is the GI robot's deciding when to use which mode of locomotion.

Just as Minsky mispredicted the pace of advances in robotic capability, earlier researchers and futurists mispredicted the areas in which robotics may have its greatest impact. My personal opinion is that the robotics revolution, if it ever comes, will happen outside of the factory. Robots can be more than tools for increasing our productivity and standard of living. They may also play a role in solving some of our most vexing societal problems, such as the massive costs of medical care and toxic-waste cleanup. Developing robotic technology for these other applications may ultimately improve our ability to automate factories as well.

In conclusion, I will not predict the future of robotics. It's been predicted to death already and everybody has been wrong. Most of these predictions foundered because they assumed a lot of things would come together in a way that never materialized. Our research, however, is self-contained—we can move ahead regardless of what others do or don't do. But in the meantime, it seems that the more things change. . . . There was an item in the *New York Times* on August 13, announcing that the Matsushita Electric Industrial Company is developing a robot "that vacuums a room automatically and puts itself away." That's all it does, however. Maybe this one will actually work. □

Assistant Professor of Mechanical Engineering Joel W. Burdick came to Caltech in 1988 as the ink was still drying on his PhD in mechanical engineering from Stanford. Burdick earned his BS from Duke in 1981, and his MS from Stanford in 1982. Since his arrival, Burdick has won several awards reserved for young faculty of great promise, including the Office of Naval Research Young Investigator Award, the National Science Foundation Presidential Young Investigator Award, and the Richard P. Feynman–Hughes Fellowship. The latter recognizes faculty who combine innovative research with outstanding teaching. Burdick also won an ASCIT Excellence in Undergraduate Teaching Award in 1990. This article is adapted from a recent Watson Lecture.

Double Fault: The Landers Earthquake

The Landers quake . . . which fortunately struck in the sparsely populated desert 100 miles east of Los Angeles, occurred in a tectonic setting luckier for scientists too.

This fence near Landers was offset in two places, neatly shifted a few feet by separate traces of the first segment of the fault.

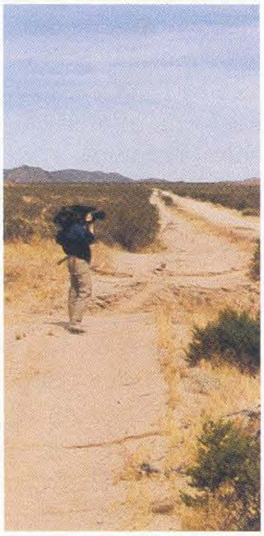
The magnitude 7.5 Landers earthquake that shook up southern California on June 28 overturned a "prediction" *E&S* made in the Winter 1990 issue: "Loma Prieta may . . . become California's best-studied earthquake, at least until the Big One hits." Landers was not the Big One, yet it suddenly presented Caltech seismologists and geologists with a spectacular experiment right in their own back yard. And no time was lost in going to work on it.

Unlike the Loma Prieta temblor, which had a significant amount of vertical displacement, the Landers quake occurred on a strike-slip fault, in which the two sides of the fault slide past each other horizontally—right-lateral slip in which opposite sides of the fault seem to move to the right—with only very slight vertical movement. But while the 7.1 Loma Prieta earthquake in October 1989 killed 62 people and caused extensive damage in the Bay Area, it didn't rupture the surface. Geologists could not pinpoint the absolute location of the fault. The Landers quake, on the other hand, which fortunately struck in the sparsely populated desert 100 miles east of Los Angeles, occurred in a tectonic setting luckier for scientists too. "The rupture came right up to the surface," said Ken Hudnut, at the time of the quake an associate scientist at Caltech's Seismological Laboratory and now with the U.S. Geological Survey . "It's not quite bedrock faulting, but we're looking at bedrock on one side of the fault and sediment on the other. The bedrock is closer to the surface and not buried by a thick sedimentary layer. So we have a relatively unobscured view of the slip distribution from the surface faulting of this earthquake."

The "unobscured view" was particularly remarkable from above, and the scientists took to the air right away. "You could follow the crack in the ground," said Hudnut, one of the first out in the field. "This is the first time we've gotten out there with a couple of helicopters and were able to do a really rapid evaluation of faulting along the whole fault. Within two days we had enough information on where the surface faulting was, so that by the third morning I was able to go up in an aircraft and navigate for the pilot when we took the aerial photographs. The aerial photographs were done very quickly after the earthquake and were done quite well."

When they weren't observing the fault from the air, about a dozen scientists tracked and measured the Landers earthquake's traces on the ground. (The magnitude 6.6 Big Bear quake, which followed the Landers quake by about three hours, did not rupture the surface.) The team, which included Hudnut, Professors of Geology Kerry Sieh and Brian Wernicke, Associate Professor of Geology and Geophysics Joann Stock, and a number of grad students and postdocs, found offsets they could measure—to determine how far one side of the fault had moved past the other—in interrupted stream channels, in fences, and in roads. Disjointed tire tracks also provided very specific information on how far the ground had moved—particularly motorcycle tracks. "Motorcycle tracks are unambiguous in a lot of cases," according to Hudnut. "The tires are nicely aligned, and they make a deep furrow in the sand or silt"—a furrow

Right: Seen from a helicopter, the rupture from the Landers quake snakes across the desert, its relief highlighted by late-afternoon shadows. Below: A TV cameraman surveys a disjointed road near the site of the largest offset—6.7 meters.



that can be neatly offset by a fault running across it. "This is the first time I found myself wishing I could find *more* motorcycle tracks in the desert," said Sieh.

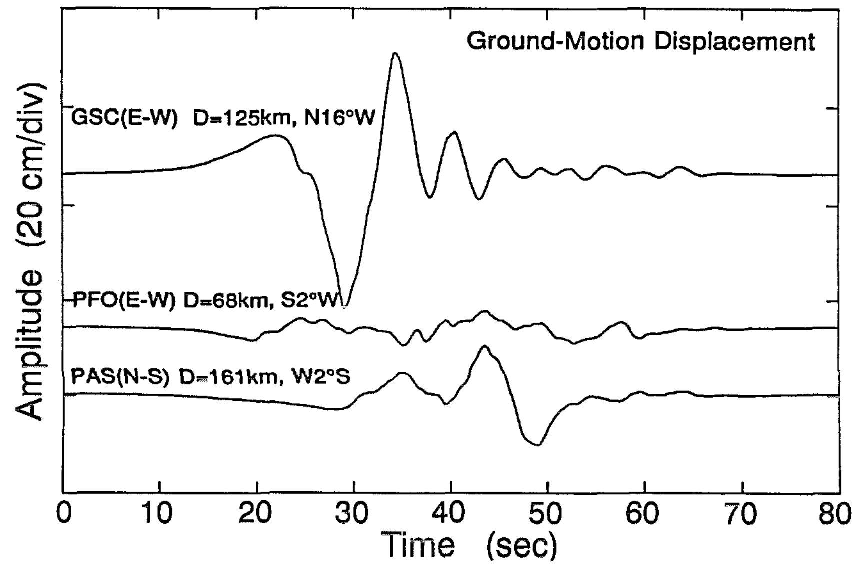
"That's the kind of thing we were looking for," said Hudnut, "and we would measure slip along the orientation of the fault. We were actually measuring the slip vector at all of these sites, instead of measuring just the lateral offset or the vertical offset. When you can see that there was some vertical movement as well as lateral, you really want to measure the slip vector to be very precise about what it is you're measuring. So we were spending about a half hour at each site measuring slip vectors in three dimensions instead of just making a single-length measurement."

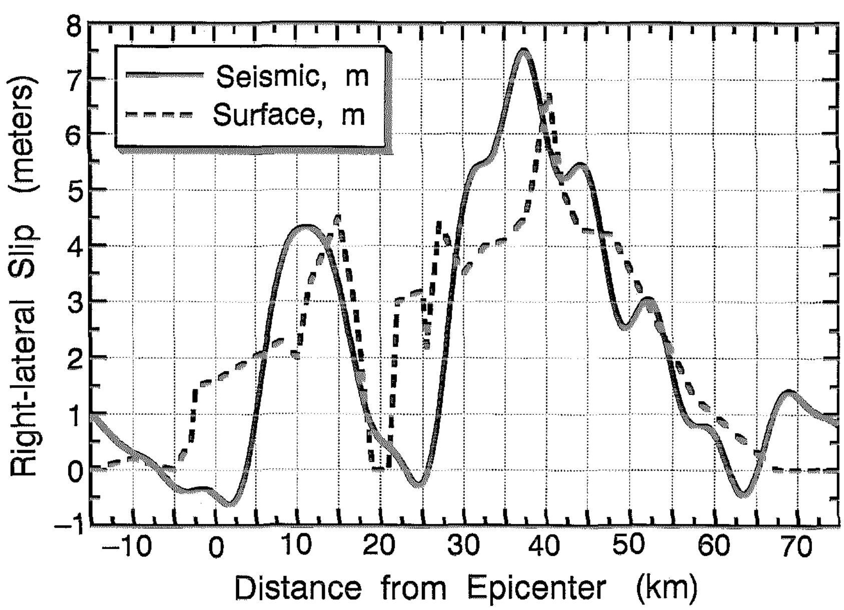
In mapping the surface faulting to determine the slip distribution, the scientists found one segment of the fault running almost due north from Yucca Valley about 20 kilometers. They measured slip up to about three meters in this section, but the slip fell to zero where the direction of motion appeared to bend and sidestep about two kilometers across Johnson Valley, where it picked up again in a northwest-trending direction for about 50 kilometers. Offsets along this segment were larger; the Caltech crew found a road offset by 6.7 meters, described by Sieh as "the largest offset in North America in the 20th century."

But what was most interesting about the slip distribution was not the size of the slip but the way it jumped between faults. The system that broke on June 28 actually involved four previously mapped faults—the Johnson Valley, the Homestead Valley, the Emerson, and the Camp Rock faults—and some geologists have split it even more finely into six segments. "It should be fun to model," said Sieh. The slip gap occurred over a two-km. transfer of the rupture from the Homestead Valley fault to the Emerson. There are a number of other significant faults parallel to the Emerson, all part of the complicated zone where the Pacific plate, on its journey northwestward, rubs up against the North American plate. This area, the Mojave shear zone, had been mapped and the faults identified, but the magnitude 7.5 earthquake in June was a surprise. "This is probably larger than anyone might have expected," said Hudnut. "The largest size anyone might have expected for an earthquake out there would have been based on the maximum length of any continuous fault segment that looked straight. And now we see that, there at least, the larger earthquakes can certainly rupture multiple fault segments. In this case there are just the two main fault segments, although the surface faulting does involve several subsidiary faults."

It took the geologists a week of laborious measurements in the field to come up with the plot of the slip distribution of the Landers quake (the broken line in the bottom figure on the opposite page). The graph shows the first segment rupturing northward from the epicenter with slip up to about three meters; then the motion stops—the graph drops to zero as the break sidesteps over to the neighboring fault. This is then followed by the greater slip—up to

The top figure below shows the wave produced by the Landers quake as recorded at three TERRAscope stations: the top seismogram from the north (the direction of the rupture), the middle one directly south, and the bottom one a side view from the west. Analysis of the TERRAscope data produced the curve of slip distribution along the fault represented by the solid line in the bottom figure. It matches almost perfectly with geologists' surface mapping (broken line).



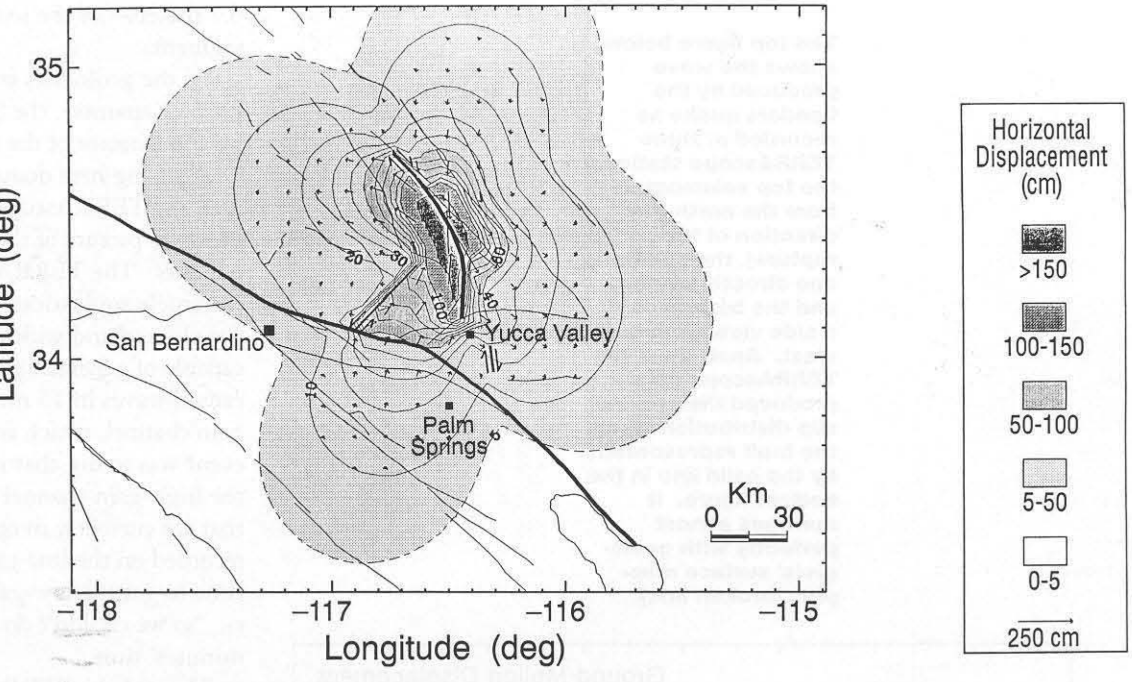


6.7 meters—of the longer northwest-trending segment.

As the geologists tramped around the desert, Hiroo Kanamori, the Smits Professor of Geophysics and director of the seismological laboratory, "just sitting here doing nothing" in Pasadena, used the TERRAscope to put together an almost identical picture of the double-pulse in a couple of hours. The TERRAscope, a network of extremely sophisticated seismometers with broad-band and wide dynamic range, is usually capable of generating a picture of the quake-caused waves in 15 minutes through its high-gain channel, which is easier to use. The Landers event was so big that it "clipped" (went off-scale) the high-gain channel of all six TERRAscopes that are currently in operation, but it was recorded on the low-gain channel. "It takes some time to get the low-gain channel," said Kanamori, "so we couldn't do it in the ordinary 15 minutes' time."

Three of the TERRAscope stations happened to be propitiously placed to determine the fault-rupture pattern of the Landers earthquake. One station had been set up at Goldstone (GSC), 125 km almost due north of the source; one at Pinyon Flat (PFO), 68 km away, near Palm Springs, to the south; and another in Pasadena (PAS), due west and almost perpendicular to the fault. The original three TERRAscope records are shown at left. From the source (the epicenter near Landers) a wave of energy propagated northward, its energy narrowly focused in the large amplitude picked up at Goldstone. The amplitude recorded at Pinyon Flat was smaller, the energy more spread out, even though it was closer to the source. "So just from that, without doing anything, you can immediately tell that the source propagated to the north," said Kanamori. The view of the fault rupture from Pasadena was "like looking at a train going past you from the side rather than coming straight at you," he added. From the side, the original trace combines the effects of both rupture propagation and amount of slip (whereas with a train you only have to consider its speed), but the two pulses of the quake are still clearly visible.

To get his final plot of the slip distribution (the solid line in the figure at left), Kanamori had to do some analysis and make some assumptions. Because the wave is propagating through a complex medium, it is constantly being modified. Correcting for this is easy, according to Kanamori, because the TERRAscope has recorded many small quakes in the area, a record that allowed him to unscramble the signal. Seismologists term this "deconvolution," a process that



Geodetic data from the Global Positioning System are confirming this model of ground displacement in the Landers earthquake. The boomerang-shaped dark line running north-south and then veering to the northwest represents the two segments of the fault which ruptured northward from Yucca Valley. Running almost perpendicular to the main fault from the west is the Big Bear fault, whose westernmost end just grazes the San Andreas fault, the dark line crossing the center of the frame diagonally from northwest to southeast. The shading indicates the amount of horizontal displacement, and the small arrows its direction as well as size.

Kanamori calls "a bit complicated" but a standard method of analysis. The assumptions involved rupture speed and fault depth. To determine the slip distribution along the fault from the seismogram, Kanamori had to assume that the fault rupture propagated at a constant speed. He also assumed that the depth extent of the faulting was 15 km.—a reasonable assumption based on the maximum depth of earthquakes in California which is about 15 km. Aftershocks of the Landers quake have borne out this assumption.

Usually seismologists can calculate only the average slip along a fault in an earthquake, but the position of the TERRAscope network and the clarity of the ground offsets were able to document the *change* in slip along the fault. And Kanamori's assumptions seem justified by the close agreement with Hudnut's graph of displacement from surface mapping; the two plots match almost exactly. "I never thought I'd see it happen that seismologists and geologists are agreeing to a factor of one," said Kerry Sieh. Kanamori claims to be not *too* amazed. "Seismology works very well for this kind of problem," he says. "So to me it wasn't too surprising, but it's still good to see that there's good agreement." For most earthquakes, which don't rupture the surface, there's no opportunity to compare data anyway. The 6.1 magnitude Joshua Tree quake on April 22, for example, which scientists consider part of the Landers sequence, left no traces on the surface of the earth. "So from a geologist's point of view, the earthquake didn't happen," says Kanamori.

Still other instruments are contributing to the total picture of what happened on June 28. A network of geodetic markers for high-accuracy surveying was already in place, recording tiny changes in movements of the earth's surface but also lying in wait for something more exciting. Ken Hudnut had survey networks all along the nearby San Andreas fault and through the San Bernardino Mountains that caught the south and west sides of the rupture. And the U.S. Geological Survey had the north end covered that Hudnut missed. Altogether, in the immediate area of the Landers quake, a total of about a hundred stations were in place. These can monitor any movement in relation to one another using the Global Positioning System (GPS) satellites—17 military satellites continuously transmitting a complicated set of radio signals to be used for navigation. The differences in the time it takes for a signal to be received by two stations can be used to determine a station's exact position. Geologists use the signals to detect very small shifts in the ground—on a baseline of several hundred kilometers to an accuracy of a couple of parts in 10^7 —and, on occasion, very large ones like those produced by the Landers quake. "We use the parts of the signal that are accessible to civilians," says Hudnut, "and we do some little tricks to essentially perform interferometry with the radio signals. We take signals from a number of stationary receivers on the ground, including some stations that are at known reference sites, called fiducial stations, whose coordinates we know to within a very small tolerance."

The GPS data on the Landers quake are

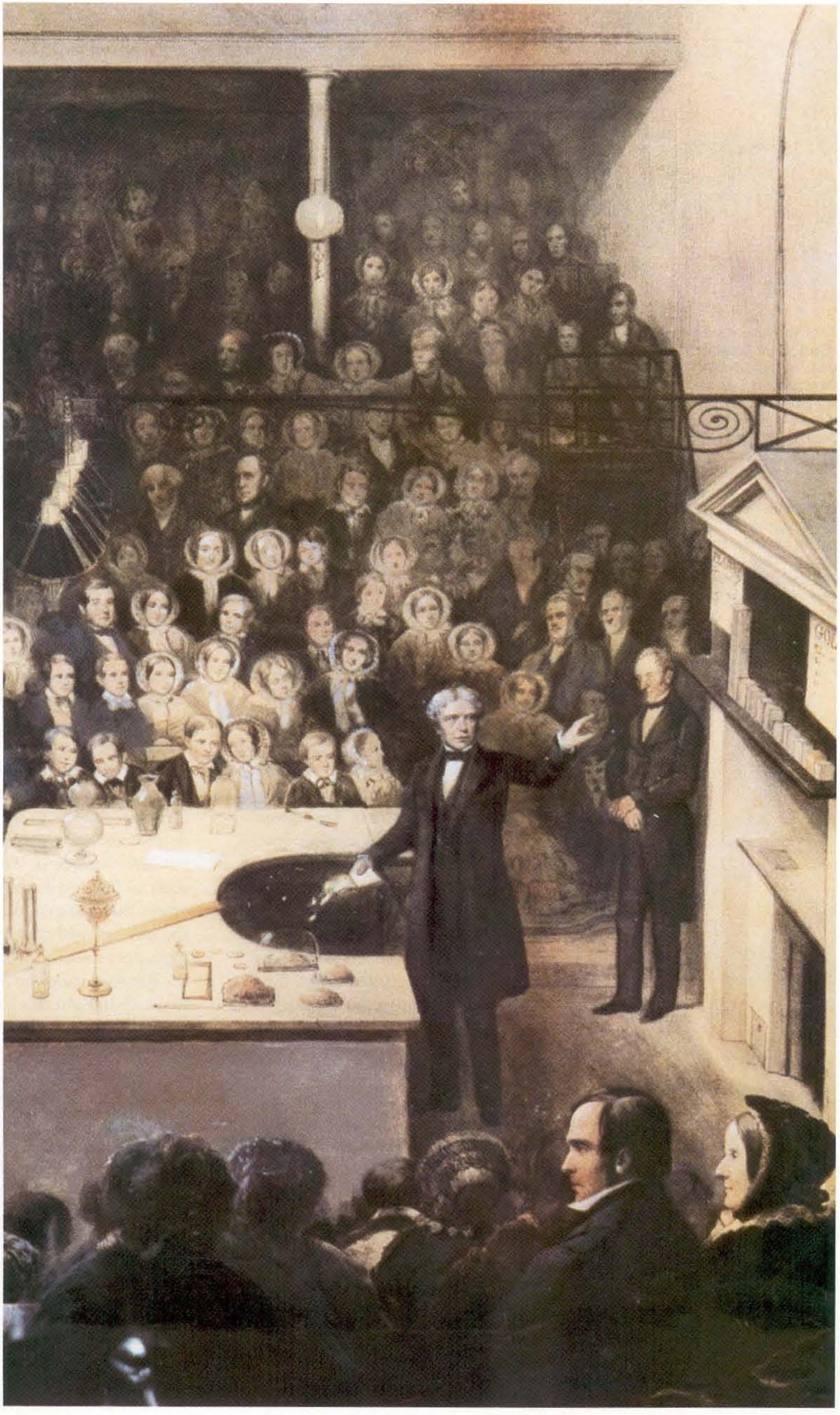
Right: This asphalt road near Landers exhibited one of the first offsets observed by the helicopter-borne geologists. Below: Another fence offers a clear illustration of right-lateral slip, in which objects on the far side of the fault appear to have been shifted to the right. The fault runs horizontally through the middle of the picture.

accurate to a few millimeters on slip displacements up to several meters. But it takes longer than two hours with the TERRAscope or a week of measuring motorcycle tracks to get the geodetic picture. After the task of just collecting the data from 100 stations, "we go through a long tedious procedure of cleaning the data—getting out all the errors in each receiver's data," says Hudnut, "and getting it all into the proper formats. And once that's all done, we just lump all the data into a large matrix and solve it for the coordinates of each station." When this is done, the modeled "butterfly" pattern of displacement (with "nodes" similar to those of an electromagnetic field) is expected to emerge.

In the computed displacement pattern on the opposite page, the small arrows indicate the size and direction of the displacement. The two fault segments that broke in the Landers quake form the boomerang-shaped dark line through the center; the San Andreas fault runs diagonally northwest/southeast through the center of the frame from just above 35.5 degrees latitude. Just three hours after the Landers quake, the magnitude 6.6 Big Bear shock, on the fault running almost perpendicular to Landers from the west and just grazing the San Andreas, did produce "a notable change in the usual butterfly pattern of displacement from the earthquake," according to Hudnut. The Big Bear earthquake was important in defining the overall pattern of deformation and also caused local stress changes on the nearby San Andreas fault.

Some scientists consider Big Bear an aftershock to the Landers earthquake. The numerous aftershocks since the end of June, although unsettling to the millions of people in southern California, follow a declining pattern that conforms to a normal rate of decay, and in that sense seismologists consider Landers a normal, "generic," earthquake. Its proximity to the San Andreas and the consequent change in stress along that fault, however, is causing some scientists to reassess the probability of a large earthquake on the southern section of the San Andreas in the not-too-distant future.

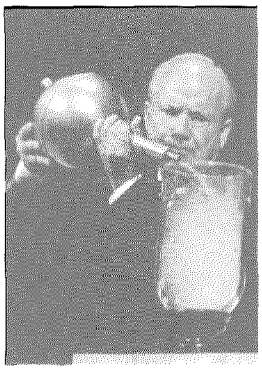
And in a couple of other ways, too, the Landers quake seems to be, if not unique, at least a demonstration of phenomena that scientists had not observed before. One was the rupture of separate faults, jumping across from one to the other. Sieh believes that this multi-fault path of the Landers earthquake could have implications for faults closer to the Los Angeles area, such as the Raymond and the Sierra Madre faults, which are *really* in Caltech's back yard. The second, probably unique, phenomenon was the increased seismic activity that the quake seems to have triggered all over the state, particularly in the volcanic areas in northern California. Speculation has it that this could be just a sort of plumbing problem—shaking up the gas bubbles in the volcanic pipes—but it's not at all well understood. Despite what isn't understood, however, what has already been learned from the data on Landers, consistent from so many sources, fills in one more piece of the puzzle. Ultimately this will help scientists to chart California's substructure and perhaps learn what it holds in store for the future. □ *—JD*



The Genius of Michael Faraday

It was Faraday's faith . . . that the obscure and apparently unrelated curiosities of electricity and magnetism were indeed related.

by Sir John Meurig Thomas



Above: Earnest Watson performs his famous liquid-air demonstration at the opening of Beckman Auditorium in 1964. Left: Faraday lectures at the Royal Institution of Great Britain (detail of painting reproduced on page 25).

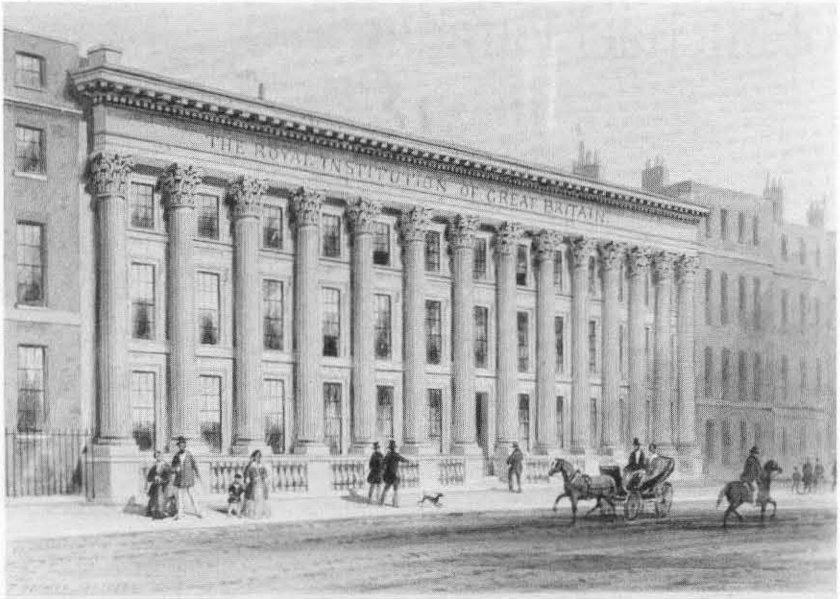
Caltech's centennial coincided with the bicentennial of the birth of one of the greatest experimentalists of all time, the self-taught genius Michael Faraday. One of his lesser known talents was the popularization of science. The Friday Evening Discourses, which he founded at the Royal Institution of Great Britain in 1826, could have been the model for Caltech's Earnest C. Watson Lectures. Watson, who wrote an article about Count Rumford and the Royal Institution in the June 1949 issue of E&S, *was clearly familiar with this tradition. He founded Caltech's Friday Evening Lecture Demonstrations in 1922, first giving his own demonstration of the properties of liquid air in January 1923. A 1925 announcement attested to the lectures' popularity: "This series of popular public lectures covering the whole of the field of physical science and accompanied by a wealth of interesting experiments which has been given for the past three years by the staff of the California Institute of Technology, has met so hearty a response and seems to be filling so real a need in the life of Southern California, that the authorities at the Institute have yielded to the general demand for their continuation." In 1964 Watson's now-famous liquid air demonstration re-inaugurated the public lecture series in the new Beckman Auditorium, and in 1972 the series was named after him.*

Last fall Sir John Meurig Thomas, director of the Royal Institution from 1986 to 1991, who currently holds the Fullerian Professorship of Chemistry, the chair created for Faraday, gave a Watson Lecture on Faraday, his work, and the links of his legacy to Caltech. The following article is adapted from that lecture. Thomas is also the author of a 1991 book on Faraday's life and work, Michael Faraday and the Royal Institution: The Genius of Man and Place.

Albert Einstein had a portrait of Michael Faraday, the blacksmith's son from London, on the wall of his study in Berlin. How appropriate, for it was Faraday's grand revision of humanity's view of the nature of the physical world that laid the foundation for Einstein's work. Newton's picture of the world has permitted us to predict solar and lunar eclipses; it has enabled us to build bridges and space vehicles, to land men on the moon, and to foretell the ebb and flow of the tides. It did not, however, lead to the telegraph, the telephone, radio, television, the magnetic disc, the compact disc, or the fax machine. All those devices, so much a feature of the ferment of modern life, can be traced, step by step, back to Faraday and to his picture of lines of force and the concept of a field.

It was Faraday's faith, nourished by the experiments of others, that the obscure and apparently unrelated curiosities of electricity and magnetism were indeed related; and in the late summer of 1831 Faraday brilliantly elucidated the nature of electromagnetic induction. In just 10 days of effort, spread over a period of 10 weeks, he showed that—and explained how—with the aid of a magnet, electricity could be generated. The dynamo was discovered. That work, together with his demonstration in 1842 that magnetism and light were also connected, coupled with the work of Clerk Maxwell in Cambridge, Hertz in Karlsruhe, Marconi in London, and others, initiated the world of modern communications.

Michael Faraday, the third child of an ailing and impoverished journeyman blacksmith, was born on September 22, 1791, in a part of London



Rumford's idea in setting up the Royal Institution was to create a center "for teaching by courses of Philosophical Lectures and Experiments the application of science to the common purposes of life."

now called the Elephant and Castle, two miles or so south of and across the river Thames from St. Paul's Cathedral. He left school at 13, having had only the most basic education. He became an errand boy and later an apprentice to a kindly bookbinder and bookseller, who encouraged Faraday's propensity to read books—those handed to him for binding and any others that he could lay his hands upon. By his late teens he had read the "Electricity" entry in the third edition of the *Encyclopaedia Britannica.* It was 120 pages long and dealt entirely with static electricity, and it prompted him to build a hand-operated electrostatic generator.

A few years after Alessandro Volta was invited to demonstrate to the Emperor Napoleon (about 1805) his pile of copper and zinc interspersed with sheets of paper soaked in a solution of common salt, Faraday built himself a voltaic pile, and he wrote about it in excited terms to a friend. At about that time he also read hymnwriter Isaac Watts's book on self improvement and Mrs. Marcet's book, *Conversations in Chemistry*, for well-mannered young ladies. His habit of keeping a detailed diary—a practice in which he was to persist with meticulous devotion for over 50 years—was already well formed.

Toward the end of his seven-year apprenticeship he had the good fortune to receive from one of his master's customers tickets for four lecture-demonstrations given in the spring of 1812 at the Royal Institution of Great Britain by one of Europe's foremost scientists, Sir Humphry Davy. The Royal Institution had been founded in 1799 by a colorful and inventive American, Sir Benjamin Thompson, better known as Count Rumford, once described as:

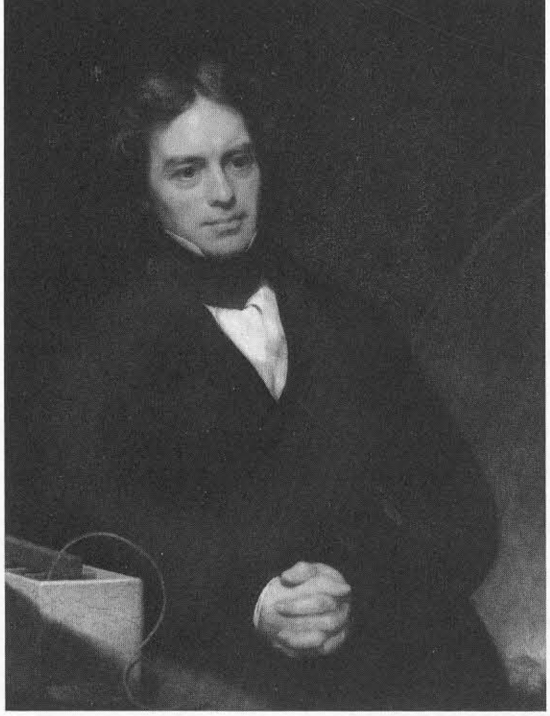
> . . . a loyalist, traitor, spy, cryptographer, opportunist, womaniser, philanthropist, egotistical bore, soldier of fortune, military and technical advisor, inventor, plagiarist, expert on heat (especially fireplaces and ovens) and founder of the world's greatest show-place for the popularization of science, the Royal Institution.

Rumford's idea in setting up the Royal Institution (RI) was to create a center "for teaching by courses of Philosophical Lectures and Experiments the application of science to the common purposes of life." In the prospectus and charter of the RI there are words that resonate with those used by the founders of Throop University, later to become Caltech:

> The two great objects of the Institution being the speedy and general diffusion of the knowledge of all new and useful improvements, in whatever quarter of the world they may originate, and teaching the application of scientific discoveries to the improvements of arts and manufacture in this country and to the increase of domestic comfort and convenience.

The laboratories that Rumford set up in the heart of London's Mayfair predate those of the Cavendish (Cambridge) and the Clarendon (Oxford) by more than 70 years. They are the oldest continuously used scientific laboratories in the world. And the unique lecture theater, which Rumford personally designed and which is still in daily use, has been described by an eminent British broadcaster as "the best studio in the world." Nowadays, the RI is part university, part museum, part research center, part classroom, part library, part club, part exhibition hall, and part broadcasting center. Over the years it has been the scene of perhaps the greatest number of scientific discoveries per unit area anywhere on Earth. Though it has never had a large staff, 15 of its professors have been recipients of the Nobel Prize.

Rumford also knew how to pick winners. In 1801 he appointed two promising young West-country Englishmen. One was 28-year-old Thomas Young from Somerset, later renowned as a physician, physicist, philologist, and physiologist—famed for his work on the modulus of elasticity, wave-theory of light, color vision, capillarity, and the Rosetta Stone. Young was versed in some nine languages, including Syriac,



Left: The Royal Institution of Great Britain on Albemarle Street, London, painted by Thomas Hosmer Shepherd. Right: A copy of this portrait of Michael Faraday by Thomas Phillips hung on the wall of Albert Einstein's study in Berlin. (Reproduced with permission of the National Portrait Gallery, London.)

Samaritan, and Chaldean, and had read the Bible from cover to cover at the age of four. But he was an irredeemably poor lecturer—in contrast to the other appointee, Humphry Davy, the 22-year-old Cornishman, who was a coruscatingly brilliant lecturer. By the time Faraday heard him in 1812, Davy had already discovered sodium, potassium, calcium, barium, strontium, and magnesium, and had isolated boron; he had invented the electric arc (in 1802), as well as methods for bleaching cloth, for copying paintings on ceramics, for tanning leather; and, before his arrival at the RI, as a lad of 20, he had discovered the anesthetic properties of nitrous oxide. Later he invented the miner's lamp and the technique of cathodic protection for arresting the corrosion of ships.

In 1826 Faraday initiated two brilliantly successful educational ventures in the public understanding and popularization of science, which continue to this day: the Friday Evening Discourses for lay audiences and the Christmas Lectures for children.

Faraday was mesmerized by Davy's carefully prepared, well-rehearsed, fluently delivered performances and breathtaking demonstrations. He took copious notes, rewrote them with illustrations, indexed and bound them, and sent them to Davy along with his request to be employed in the service of science at the RI. On March 1, 1813, Faraday started his duties, essentially as a bottle-washer. But such was his promise, dexterity, devotion to duty, mental alertness, and general intellectual awareness, that by September of that year Faraday was already engaged in helping Davy with preparations such as that of the capriciously explosive compound nitrogen trichloride.

In October 1813, Davy and his new bride set out from Plymouth on a grand European tour, taking the young Faraday with them as secretary and amanuensis. And so Faraday, who had not hitherto traveled more than 12 miles from home, was visiting Paris, Geneva, Milan, Rome, Genoa, Florence, and other European cities. He and Davy met the great scientists of Europe—Ampère, Arago, Gay-Lussac, Cuvier, Humboldt, and Volta. And they conducted numerous experiments along the way. They discovered iodine while in Paris, and burned a diamond completely in oxygen to carbon dioxide, thereby demonstrating that a diamond is a polymorph of carbon—a contentious issue at the time. In a sense it could be said that Faraday received his university education in the course of his 18-month tour of Europe. He probably had almost daily tutorials with Davy, and he kept a detailed diary of his first and second thoughts, as well as records of the experiments that he performed.

In mid-1815 he recommenced his duties at the RI, quickly acquiring great skills as an analytical chemist, then as a physical and organic chemist. His laboratory was occupied by only one other person, Serjeant Anderson, a loyal assistant who worked alongside him (although the two shared few words with each other) for some 40 years. In 1821 Faraday married Sarah Barnard, a silversmith's daughter who, like him, had been born of parents who belonged to a strict religious sect—the Sandemanians, a Scottish offshoot of the Methodist church. He remained devoutly religious all his life, and their marriage, though childless, was a happy one.

In 1826 Faraday initiated two brilliantly successful educational ventures in the public understanding and popularization of science, which continue to this day: the Friday Evening

Faraday's principal contributions to chemical science

1816	(With Davy) evolution of miner's safety lamp.
1818–24	Preparation and properties of alloy steels (study of Indian Wootz). Metallography.
1812–30	Analytical chemistry. Determination of purity and composition of clays, native lime, water, gunpowder, rust, dried fish, various gases, liquids, and solids.
1820–26	Organic chemistry. Discovery of benzene, isobutylene, tetrachloroethylene, hexachlorobenzene, isomers of alkenes and of naphthalene, sulphonic acids (α and β), vulcanization of rubber. Photochemical preparations.
1825–31	Improvements in the production of optical-grade glass.
1823, 1845	Liquefaction of gases (H_2S, SO_2, and six others). Recognized existence of critical temperature and confirmed the reality of continuity of the state.
1833–36	Electrochemistry and the electrical properties of matter. Laws of electrolysis. Equivalence of voltaic, static, thermal and animal electricity. First example of thermistor action. Fused salt electrolytes; superionic conductors.
1834	Heterogeneous catalysis: poisoning and inhibition of surface reactions. Selective adsorption; wettability of solids.
1835	"Plasma" chemistry (discharge of electricity through gases).
1836	Dielectric constant, permittivity.
1845–50	Magnetochemistry and the magnetic properties of matter. Magneto-optics. Faraday effect. Diamagnetism. Paramagnetism. Anisotropy.
1857	Colloidal metals. Scattering of light. Sols and hydrogels.

Had there been Nobel Prizes in Michael Faraday's day, he probably would have won several.

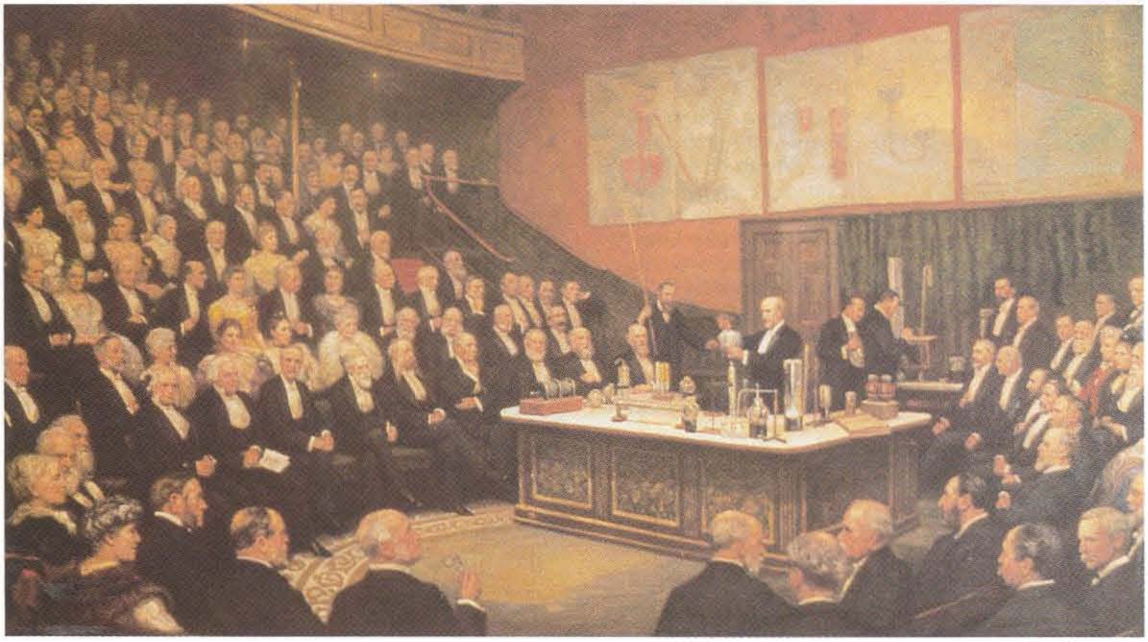
Faraday's principal contributions to physical science

1821	Electromagnetic rotations.
1831	Electromagnetic induction. Acoustic vibrations.
1832	Identity of electricities from various sources.
1833	Electrolytic decompositions.
1835	Discharge of electricity through evacuated gases. (Plasma physics and chemistry.)
1836	Electrostatics. Faraday cage.
1845	Relationship between light, electricity and magnetism; diamagnetism; paramagnetism.
1846	"Thoughts on ray vibrations."
1849	Gravity and electricity.
1857	Time and magnetism.
1862	Influence of a magnetic field on the spectral lines of sodium. Lines of force and the concept of a field. The energy of a magnet lies outside its perimeter. The notion that light and magnetism and electricity are interconnected.

Discourses for lay audiences and the Christmas Lectures for children. Faraday gave the Christmas Lectures on 19 occasions. His most famous series, "The Chemical History of the Candle," first published in 1850, became a classic and was translated into many languages; it is still recommended summer-vacation reading for Japanese schoolchildren.

Faraday established a tradition of inviting not only the leading scientists of the age, but also poets, politicians, musicians, actors, artists, and men and women of letters, to present Friday Evening Discourses. He himself persuaded, among others, T. H. Huxley, John Dalton, Lord Kelvin, Clerk Maxwell, Hermann von Helmholtz, and John Ruskin to lecture at the RI. This tradition has continued. In 1895 the then director, Sir James Dewar, himself a polished presenter of Discourses, arranged for the great actor Sir Henry Irving to give a special Discourse on "Acting: An Art," attracting an audience of more than a thousand. In 1909 he arranged for Caltech's George Ellery Hale to describe at the RI his work on solar vortices: this turned out to be a particularly memorable Discourse as it demonstrated the general magnetic field of the sun and the effects of magnetic fields upon spectral lines, ideas that had been close to Faraday's heart. Several Caltech scientists have given Friday Evening Discourses since Hale's day, including Linus Pauling (three times), Murray Gell-Mann, and (in 1991) Ahmed Zewail. And Caltech's Earnest C. Watson Lecture Series follows the tradition of the Discourses inaugurated by Faraday.

The extraordinary speed of Faraday's develop-



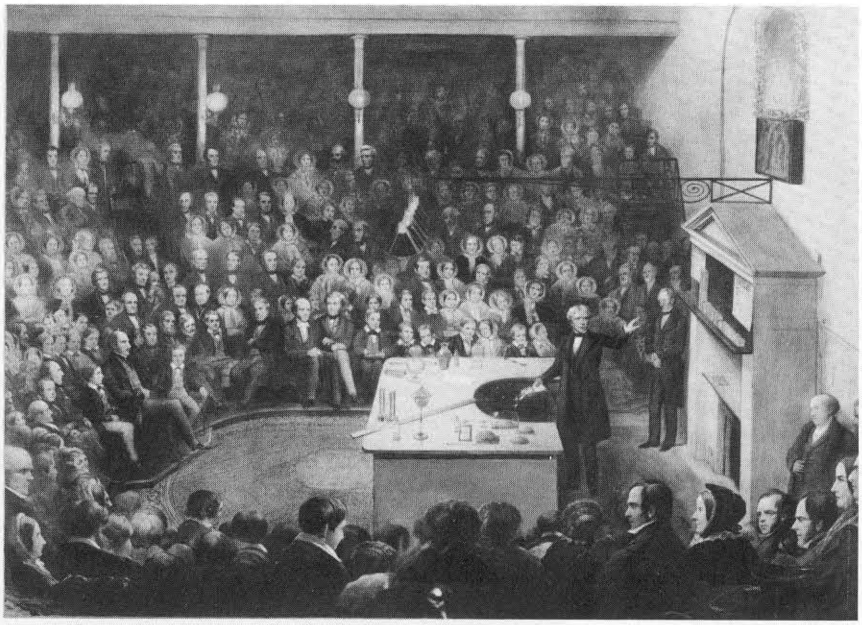
As director of the Royal Institution, Sir James Dewar, known for his work on low-temperature phenomena and the vacuum flask named after him, was also a regular Discourse lecturer. Here he presents what might be the original production of Earnest Watson's liquid-air show. Seated in the front row are Lord Rayleigh, Sir William Crookes, and Prime Minister A. J. Balfour. Stokes, Marconi, and Kelvin are also in the audience.

ment and the astonishing range of his output can be seen in the chronological record of his achievements in chemical and physical science at left. Following his work with Davy on the miner's lamp, on the protection of ships against corrosion, and on the preparation of many dangerously unstable chemical compounds, Faraday was already by 1819 the foremost analytical chemist in Britain, and in demand as an expert witness; and he had started with James Stodart, a surgical instrument maker, his pioneering work on the composition and preparation of alloy steels. In 1823 he discovered and analyzed the first recorded example of a gas hydrate, a material now termed a clathrate (from the Latin word for grating) because the guest molecule, chlorine, is enclosed in a cage formed by molecules of the host, in this case the crystallized water. Faraday also liquefied chlorine, an achievement that aroused the jealousy of Davy, who felt that he had initiated the work and was entitled to the credit. During this year and again in 1845 he succeeded in liquefying many more gases and confirmed the existence of the critical temperature above which, no matter how high the pressure, a gas will not liquefy.

Faraday's most important contribution as an organic chemist came in 1825. His interest had been aroused by the fact that at the bottom of containers of gas delivered to the RI by his brother Robert, who worked for the London Gas Company, was a clear aromatic liquid, now known as benzene, which Faraday soon produced by an independent method involving the thermal treatment of fish oil. The skill with which he characterized benzene and established its chemical formula elicited the admiration of Europe's foremost chemist, Berzelius, in Stockholm. (The actual sample prepared by Faraday was recently analyzed: it is 99.7 percent pure.) Benzene and the closely related naphthalene, the various derivatives of which were first prepared by Faraday, are the premier members of an enormous family of compounds called aromatic hydrocarbons. Such molecules, benzene especially, apart from their role as fuels, are important building blocks in the modern pharmaceutical industry, and form the basis of the aniline dyes that are responsible for the wealth of color in modern man-made materials.

Had there been Nobel Prizes in Michael Faraday's day, he probably would have won several. His discoveries included:

- Electromagnetic induction, which, along with his earlier related work on the relationship between electricity and magnetism, brought forth the first transformer, dynamo (electric generator), and electric motor.
- The laws of electrolysis, which rank among the most accurate generalizations in science. These led, through the subsequent work of Johnstone Stoney, Helmholtz, and J. J. Thomson, to the realization that matter is electrical in nature. It also led to the idea of ions, electrodes, and electrolytes—all terms that Faraday coined (along with his polymathic Cambridge friend, William Whewell)—as well as to electrodeposition, electroplating, coulometry, and electrochemical analysis.



The Prince Consort frequently attended the Friday Evening Lectures and brought his young family to the Christmas Lectures at least once, as captured in this painting. Prince Albert (with mustache) sits at left directly opposite Faraday, the lecturer.

- The magnetic properties of matter and the foundations of magnetochemistry (the terms paramagnetism and diamagnetism were coined by him, and he was the first to discover the paramagnetism of oxygen).
- Benzene and the analysis of its composition. Faraday was as much the founder of the chemical—certainly the dyestuffs and explosives—industry as of the electrical power generation and electroplating industries.
- The Faraday effect—the rotation of the plane of polarization of light by a magnetic field—and the foundations of magneto-optics.
- The notion of a field. Unlike his contemporary scientists, Faraday refused to be guided solely by the mathematical precision of Coulomb's law in interpreting the force between charges. He reflected deeply upon what occurred in the intervening space. This led him, in turn, to discover induction, inductive capacity, and permittivity. He also convinced himself that the energy of a magnet could extend beyond the perimeter of the magnet itself.

Faraday's lifelong interest in platinum—in the 1920s he and Stodart had given stainless-steel razors of platinum-containing steel to friends, and it was the subject of one of his most famous Friday Evening Discourses at the RI in 1861—led him to the study of catalysis. He discovered that minute quantities of gas bound to the surface of platinum (that is, adsorbed) could radically diminish its ability to promote chemical reactions. This discovery prompted him to experiment with the phenomenon of selective adsorption in which one gas in a mixture is preferentially retained by the surface of a finely divided solid, a technique which has been further developed for the purification of natural gas.

Among Faraday's later experiments was the study in 1856 of the scattering of visible light, often with brilliant color effects, by liquid suspensions of very finely divided metals such as gold, platinum, copper, and silver. This study of matter in an ultramicroscopic state paved the way for his colleague and admirer John Tyndall (and later Lord Rayleigh, the first RI professor to win the Nobel Prize) to explain the blueness of the sky, the opalescence of certain solutions, and the colors of birds and butterflies.

In 1862 (he died in 1867), the very last of his experiments to see if a magnetic field changed the quality of the orange light from a gas flame seeded with common salt, yielded nothing. Yet Faraday's intuition was sound for, nearly 40 years later, Pieter Zeeman found the effect that now bears *his* name and provided the first hints of what was to become the modern theory of atomic structure. If through his success Faraday changed the world he knew, even his failures pointed toward changes in a world he could not have foreseen.

To say that Faraday was an experimenter of genius is to risk exhibiting him as little more than a skilled manipulator; that he certainly was, but one for whom skill was the servant of imagination. His true genius lay in the ability to notice some oddity, to devise some experiments to test its significance and, with astonishing economy of effort, to discover how, if at all, his picture of the physical world must be modified. And though he never mastered anything beyond the basic elements of mathematics, his mind worked with such precision and lucidity that Lord Kelvin and Clerk Maxwell found in his constructs their inspiration for the mathematical theory of electromagnetic fields, a cornerstone of modern physics.

Faraday's detailed diaries illustrate how he thought and worked. He tells of his failures as well as his successes, and reading his work one senses his abundance of optimism (even elation), self-control, and self-criticism. There is also the sense of wonder with which, as a natural philosopher, he contemplated the world and the forces and mechanisms that hold it together. In his diary entry of March 19, 1849, shortly after he began to think that a relation existed between gravity and electricity, Faraday wrote:

> All this is a dream. Still, examine it by a few experiments. Nothing is too wonderful to be true, if it be consistent with the laws of nature and, in such things as these, experiment is the best test of such consistency.

"Nothing is too wonderful to be true, if it be consistent with the laws of nature and, in such things as these, experiment is the best test of such consistency."

Two years later, after extensive experimentation, he ended his lengthy article in *Philosophical Transactions of the Royal Society* (1851) with the following words:

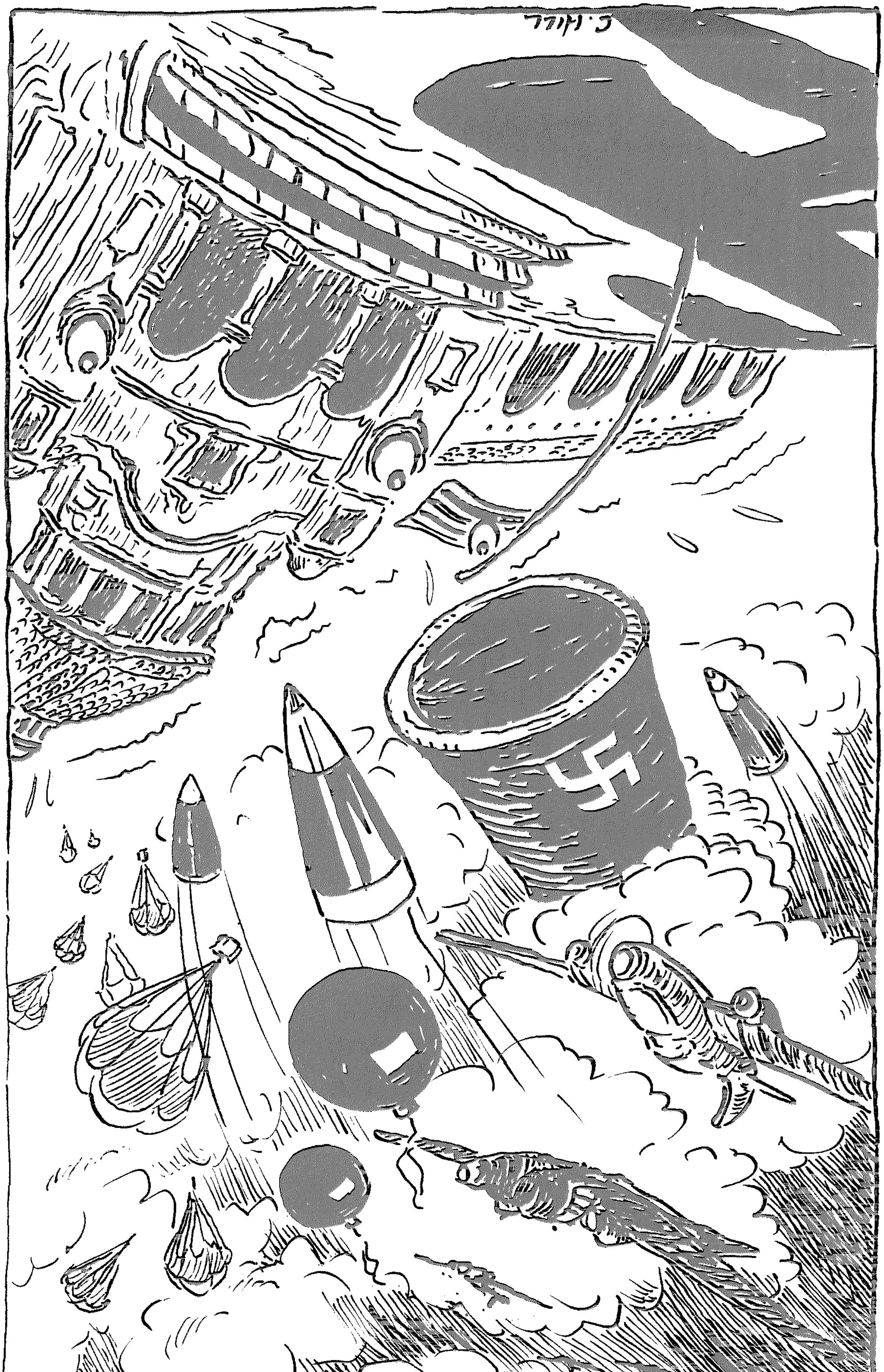
> Here end my trials for the present. The results are negative; they do not shake my strong feeling of an existence of a relation between gravity and electricity, though they give no proof that such a relation exists.

In September 1845, using a special lead borate glass that he himself had prepared almost 20 years earlier, Faraday discovered the so-called Faraday effect, the rotation of the plane of polarization of light by a magnetic field. This was the first demonstrated link between light and magnetism, and it marked the birth of magneto-optics. The opening paragraph of the paper entitled "On the magnetization of light and the illumination of magnetic lines of force," which he dispatched on November 5 of that year to the Royal Society, read:

> I have long held an opinion, almost amounting to conviction, in common I believe with many other lovers of natural knowledge, that the various forms under which the forces of matter are made manifest have one common origin; or, in other words, are so directly related and mutually dependent, that they are convertible, as it were, one into another, and possess equivalents of power in their action.

Faraday's genius is the consequence of a unique combination of a uniquely large subset of major qualities: an infinite capacity to take pains, a restless intellectual energy, and an inexpugnable intellectual honesty, coupled with a measure of technical virtuosity that encompassed the manipulative dexterity and constructive imagination to produce new instruments and new techniques of unsurpassed power and sensitivity. His torsion balances and coulometers were more sensitive, his electromagnets stronger, his glass specimens heavier and of superior optical quality, than those of his predecessors or contemporaries. Always convinced that there were solutions to the problems he pursued and intelligible answers to the questions he raised, he had the supreme gift of selecting those that were really important and also of knowing precisely what to do next. Both his strategy and his tactics were impeccable. Add to all this his prodigious physical stamina, endless curiosity, penetrating intuition, complete mastery of detail, and exceptional facility for arguing from the particular to the general—on his own, and with his own brand of self-criticism and self-discipline—and one sees why Faraday's reputation is deserved. I think Rutherford spoke for all scientists when, in 1931, he said:

> The more we study the work of Faraday with the perspective of time, the more we are impressed by his unrivalled genius as an experimenter and a natural philosopher. When we consider the magnitude and extent of his discoveries and their influence on the progress of science and of industry, there is no honour too great to pay to the memory of Michael Faraday—one of the greatest scientific discoverers of all time. □



The Committee

I doubt that anything close to the scientific brainpower represented by Zwicky, Koepfli, Buwalda, Went, and many others . . . was devoted to such matters anywhere else in America during that spring of 1942.

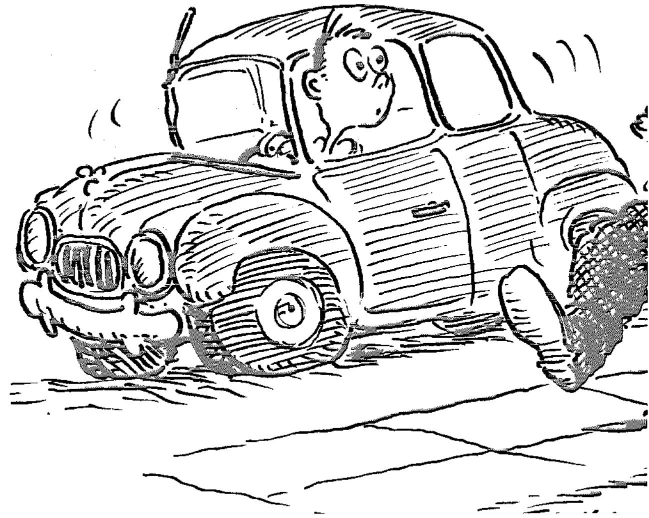
by John H. Rubel

In December 1941 I was living out my senior year at Caltech in Dabney House, where water bombs were the current rage. But on Sunday, December 7, the real bombing of Pearl Harbor forced us to put such adolescent craziness behind us. A new kind of craziness was about to begin.

The attack mobilized public outrage and aligned public sentiment in a readiness to fight World War II. It also aroused—especially on the West Coast—dread of sabotage or attack, both of which were instantly and widely imagined in a multitude of forms. Robert Millikan quickly appointed a Committee charged with taking measures to diminish the exposure and increase the security of the Caltech campus, and in a day or two I was notified that a group of seniors, including me, had been chosen to guard critical buildings. Service was voluntary, but if we elected to serve we would be excused from final exams, and so far as I know, no invitee declined to join up. We were organized into squads of about a dozen, spaced out so that every part of Guggenheim and Kellogg was always under surveillance by someone, and given a schedule of six hours on duty and six hours off, which somebody said was how the Navy did it. Why, we wondered, would the Japanese be interested in sabotaging the 200-inch Hale Telescope mirror then being ground in the optical lab back of Guggenheim? We never thought about the wind tunnel in Guggenheim as a military target (and maybe that wasn't it), and we knew nothing then about what was going on in the lower part of Kellogg (see *E&S* Spring 1991).

There was a delay in getting started while the Powers That Be decided how we were to be armed. Rumor had it that we would be furnished with rifles. There were arguments against rifles, not the least of which was that few or none of us had ever held a rifle in his hands. The thinking went that squads of armed seniors would probably be more dangerous to one another and certainly to innocent bystanders than to any would-be saboteur. The next day the Powers That Be were said to have settled on pistols, but as it turned out, much to our regret, pistols also ended up on the Too Dangerous list, and when we reported for duty we were issued ax handles that someone had bought at the local hardware store. We were told to shoulder our ax handles as if they were rifles and to stay on the qui vive—ready, by implication, to do something terrible to the would-be saboteur who had made his way to the portals of Kellogg or Guggenheim, presumably armed to the teeth, equipped and determined to blow it to Hell.

On the night of our first patrol along California Boulevard, we lined up in back of the optical lab near the driveway leading into the campus between Kellogg and Guggenheim, looking, I thought in a seditious flash, like some apparition from a modern parody of *A Midsummer Night's Dream*. Of course, it was not summer; it was the middle of a California winter, and crisp enough to make us want to get moving, which we shortly did. But after only a few paces Professor of Geology John Buwalda stopped us cold. "Not like that!" he commanded. Remarkably enough, the war had already altered his usually professorial demeanor. "Don't just march around! Look!



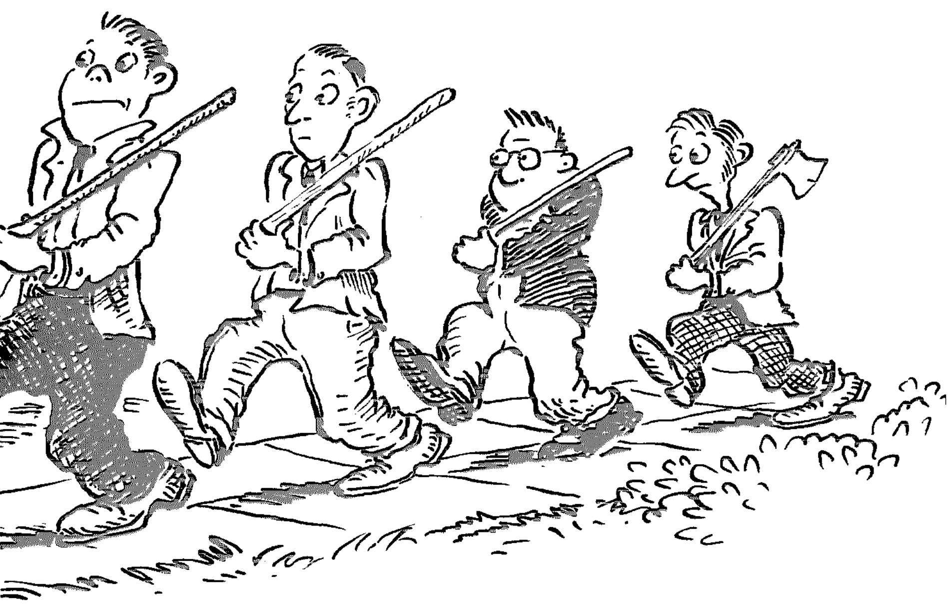
I wondered briefly what motorists might think was going on at Caltech if they happened to notice our straggly band of students armed with ax handles writhing along California Boulevard in the middle of the night.

Look in the bushes! Look in the shadows!" So we resumed, each of us making conspicuous searching movements as we walked, peering here and bending there. I wondered briefly what motorists might think was going on at Caltech if they happened to notice our straggly band of students armed with ax handles writhing along California Boulevard in the middle of the night, but I was soon caught up in the spirit of the thing, and patrolled my assigned circuit for the next six hours that night, and for a number of subsequent patrols. Ultimately the Committee made more permanent security arrangements, and we all had to get back to our books.

Things had settled into a manageable routine but the novelty had not yet worn off when, close to midnight a few nights later, I heard my classmate Alf Landau shouting at the top of his lungs somewhere around the Old Dorm. There he was, a rifle pointed at the foundations of the decrepit old building, yelling in his German accent "Come out! Come out, whoeffer you are!" Landau had served in the Austrian tank corps before the *Anschluss* hastened his departure for America and Caltech. Normally there wasn't anything military about him, but this night there was, especially as he fingered the rifle he had managed to come by. He shouted some more. Silence. Then, sure enough, in that midnight silence you could hear a rhythmic, metallic tapping, as if someone were hammering on iron pipes. A small crowd gathered while Landau shouted more guttural commands into the otherwise silent night, until we realized that the steam pipes under the building were making their usual noises, and Landau went off in search of other dangers. Meanwhile, the Caltech switchboard lit up with callers who had begun to fear that the other enemy had arrived ahead of the Japanese. (Landau later served with the U.S. Army, impersonating Germans behind enemy lines as the U.S. forces advanced across the Rhine.)

But clearly there were many dimensions to the business of protecting the campus. Millikan's Committee asked for student help, and Bill Hicks, our student-body president, appointed me the student representative to it, to organize whatever student assistance and participation the Committee decided to require. The Committee met in a small room somewhere on the second floor of Throop, empty, as I recall, except for a library table and a few armless chairs around it. Its first chairman was William Michael, associate professor of civil engineering. He was well known on campus, even to those who had never taken a course from him, for his yearly lecture on the scientific aspects of trout fishing—how the fisherman looks to the fish, given the index of refraction of water and air, how the wind affects its vision, the effects of light and shadow, etc. The Committee members included—besides John Buwalda—Joseph Koepfli, research associate in chemistry; J. Wallace Sterling, associate professor of history; and Wesley Hertenstein, head of buildings and grounds. Fritz Zwicky, associate professor of theoretical physics, spent a lot of time on Committee concerns, but he came to few meetings and was not officially a member of it, as I recall.

As the weeks passed I discovered that some



Field, where even more people could stop in their flight, surrounded by combustibles. But then, our job was only to protect the campus.

Professor Koepfli, the chemist, feared attack by poison gas. First, he said, the Japanese would drop high-explosive bombs. Having shattered the windows, they would then drop poison gas. The Caltech basements were a logical place to shelter people from the high explosives, but would be a bad place if poison gas were dropped, since these agents are heavier than air and would seep to the lower levels. Besides, water mains would probably be hit, and water would flood the basements unless major control valves were turned off. Some Committee members thought we should consider keeping people out of Caltech's basements, but others argued that since they were considerably safer than ground-floor shelters against high-explosive bombing, we could hardly deny access to them. So we organized a student-operated system to insure that there was always a team on campus familiar with (and possessing the keys to) the valves that would have to be shut off if the mains were broken on the campus side of the valves. We could do nothing about it if mains were broken on the city side of the cutoff valves, but at least we were prepared to deal with what we could do something about.

There remained the more formidable problem of what to do if poison gas were used. Whatever was to be done, there needed to be a cadre of people who knew something about poison gases and what to do about them. There were several foreign-born chemists and biologists around, Frits Went among them, who knew a lot about poison gases and gas warfare, and Koepfli got them to set up a brief but quite comprehensive course on the subject. Many students, including me, volunteered to take the gruesomely interesting course. The professors made up small quantities of several agents so that we could learn what they smelled like in low concentrations. As we learned more about them it got pretty scary to think about what would happen if there ever were a gas attack! Even gas masks would be quite inadequate against some of them, and anyway, a survey had recently disclosed that Pasadena possessed only one gas mask, and it belonged to the Pasadena fire department. If anybody else in town had one, nobody found out about it. Even one small poison-gas bomb, dropped in a residential neighborhood, could contaminate just about everything in sight, especially if something as bad as Lewisite were dropped. It would penetrate raincoats or other garments made out of rubber, and only a sophis-

members brought their own expertise and interests to bear on one or another aspect of campus protection, often with singular insistence and persistence.

Professor Buwalda, for example, focused on certain sequelae of the 1923 Tokyo earthquake. There, he said, people had fled a vast conflagration started when the earthquake upset charcoal stoves in highly combustible houses, fleeing with all the possessions they could pile on wagons or carry on their persons, and stopping to rest at the first large open space they came to. "Then," he intoned on the many occasions when he repeated this disquisition, "surrounded by the highly combustible materials with which they had fled, they were consumed by the flames that overtook them." This experience, he thought, would inspire a Japanese tactic. "So," he would conclude, "the Japanese will drop incendiary bombs on the foothills on a night when the prevailing winds from the north will blow the resulting flames toward the city. A great conflagration will ensue. The people will flee their homes carrying with them as many of their possessions as they can. The Caltech campus will be the first large open space which they will encounter, and they will tend to stop here with their combustible burdens. We must prevent that by posting patrols that will keep the crowd moving south. Otherwise the fire will catch up, their possessions will be ignited, and everyone will perish in the flames." So we organized student squads that would keep people fleeing flames from the north moving on to the south. Of course, just across California Boulevard to the south was Patton

The Caltech basements were a logical place to shelter people from the high explosives, but would be a bad place if poison gas were dropped.

You would put the bag over your head, tie it around your neck, put the "raspberry" in your mouth, soak the bag in water and immerse yourself in the bathtub up to your neck.

ticated gas mask would protect against it. Lewisite creates terrible burns not only in the lungs, but on the skin wherever you touch it or it touches you, and it could hang around a long time while helpless people were horribly burned inside and out with ghastly consequences, usually ending in death.

So something would have to be done, Koepfli insisted, to decontaminate infected areas before things like that happened, and to that end he designed a decontamination unit, consisting of a truck with a large tank containing decontaminating chemicals in a water solution to wash the streets down, and a large propeller on top of the tank that would blow a mist of decontaminant into the surrounding air, cleansing the atmosphere as the mist settled. A team of men, dressed in special gas-proof clothing and trained to rescue people from their homes, wash them down, administer first aid, and provide other emergency services, would operate the truck.

But this scheme faltered on the logistical details. Eventually nothing came of the decontamination-truck idea, although the students from the poison-gas course were ready to man it if something did.

Even if all this came to pass and you had a really good decontamination unit and crews to man it ready to go, **protecting the population** still loomed as an overwhelming problem. What was needed was a simple, cheap gas mask that anyone could make on his own, and Zwicky thought he had invented one. I was working with him on some other projects at the time when, one day, he told me his idea. The gas mask would consist of two small flour sacks (in those days you could buy flour in cloth sacks just about the right size to fit over your head), which would be sewn together like a quilt in vertical seams, leaving finger-sized spaces to be filled with bicarbonate of soda. A transparent window made of unexposed, developed film would be sewn in the bags so that you could see out, and a "raspberry" (that common rubber gadget with a wooden mouthpiece for delivering a loud blast of disapproval at baseball games) would be sewn in opposite your mouth. You would put the bag over your head, tie it around your neck, put the "raspberry" in your mouth, soak the bag in water and immerse yourself in the bathtub up to your neck. Air would be filtered through the wet bicarbonate of soda as you breathed in. You would breathe out through the raspberry.

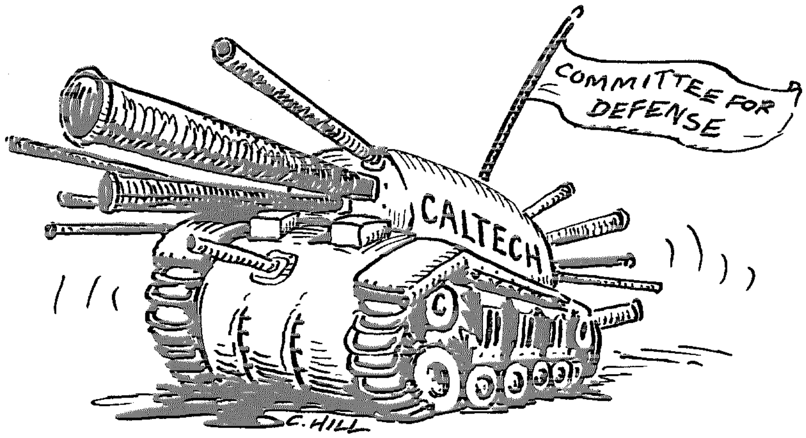
Zwicky got someone to make a first version of the device. When the afternoon of the decisive experiment arrived, he told me his plan—to put the mask on, immerse himself in water up to his chin, get someone to release chlorine gas into his bathroom, and then to breathe in through the wet sodium bicarbonate. He gave me a short demonstration, putting the mask over his head, with the raspberry device in his mouth. Then he vigorously sucked in and blew out. The bag, still dry and not tightly tied around his neck, collapsed gently around his face as he breathed in, and the raspberry made a horrendous noise when he blew out through it. After a few breaths he took it off smiling somewhat impishly. He left the campus that afternoon with his potentially revolutionary mask and a small tank of compressed chlorine gas. The mask would be tested that evening.

The next morning I went to see him in his office. Now, Zwicky was a great scientist and a memorable personality. In the previous four years he had discovered 18 supernovae (only 12 had been discovered before him in the history of astronomy), and in his early forties he was a man of immense physical energy, radiating personal vitality. He told me, among a number of things even more memorable, that in winter he shoveled snow around to make a run so that he could ski over the Mount Wilson observatory, which, if I visualized the feat correctly, required a *lot* of energy. But Zwicky was rather subdued when I encountered him on the morning after his gas-mask experiment, and had a bad cough. "Nah, zomezing vas wrong," he said in his Swiss-German accent. "Maybe a leak. Maybe dze seams need to be sealed. Maybe it chust doesn't vork." That was the beginning and, so far as I know, the end of Zwicky's gas-mask days. The Pasadena population went unprotected.

Meanwhile, Zwicky trained his energy on another problem. Early on there was concern about the danger of injuries from flying glass shattered by high-explosive bombs. I recall a conference on the subject where I sat near a large window as Zwicky described the problem of fishing myriad glass splinters out of someone unwise or unlucky enough to be in the path of a window blown in by a bomb. The British, he said, were gluing cellophane on windows with treacle to reduce the risk of flying shards. Nobody was sure what "treacle" was, although many of us recalled vague associations with Oliver Twist or David Copperfield or somebody. Some thought it was sugar water; the dictionary said molasses. Zwicky, however, decided we should make a paste out of flour and water and stick cellophane on all the windows. First, though, he wanted to do some experiments to answer a few questions, such as: What is the best color cellophane to use to reduce visibility in case bombers fly over before the lights are turned out? What is the best glue mixture to use? What is the best way to apply the cellophane to windows? And how long will it stay on in our climate?

Someone liberated a number of old French doors from somewhere around the campus, and we used various gluing mixtures to affix different species of cellophane to their many panes. Then we transported them to the steam tunnels somewhere under Bridge, hooked up some lights, and turned them over to Zwicky. He would go down there with a deflated football, stand back a few feet, and then hurl the football at a pane of

He would go down there with a deflated football, stand back a few feet, and then hurl the football at a pane of cellophane-covered glass.



One day, after a couple of months marked by considerable activity preparing to save Caltech from the horrors of war. . . Professor Michael announced at the start of a Committee meeting that Millikan was going to attend for the first time in the Committee's brief existence.

cellophane-covered glass. He didn't always hit the glass, but when he did the glass sometimes broke and sometimes didn't. Zwicky analyzed the results of this scientific experiment and came up with a protocol for selecting the cellophane and gluing it on. All that remained was to choose the right color.

One night he took a couple of students and a supply of cellophane and a powerful flashlight into the foothills north of the campus, while a few of us watched from a balcony in the student houses. He flashed the light at us without any filters over it, somehow we located it, and we then observed relative intensities when he covered the light with cellophane of various colors. Whether the color accounted for it or whether blue cellophane happened to have lower transmissivity than reddish colors, we concluded that any bomber that found itself flying around Pasadena would find it hardest to see Caltech's windows if they were covered with blue cellophane. We then secured a considerable supply of it, mixed up a lot of glue, and covered a number of student-house windows. The idea was to see how the stuff stood up to sunlight and weather. When the efficacy of the technique had been established, we would be ready to glue up every window on campus.

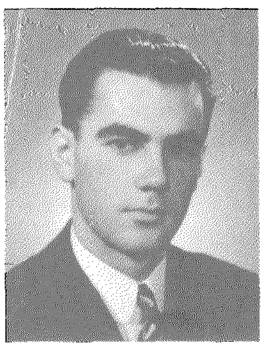
In the end, so far as I know, this part of the project never got beyond the testing phase, just as some others never even got beyond discussion, but I doubt that anything close to the scientific brainpower represented by Zwicky, Koepfli, Buwalda, Went, and many others, not to mention their worthy student assistants, was devoted to such matters anywhere else in America during that spring of 1942.

Despite considerable activity and thought, the problem of saving the Old Dorm in the event of a fire remained unsolved. It had been a fixture on campus since World War I, when it was built as a "temporary" building, but ended up actually surviving for many years after World War II. It stood close to where Winnett Center stands today—a ramshackle, unpainted, two-story, shaky structure. The "Greasy Spoon" occupied the front; the rear was taken up by some spaces where afficionados practiced boxing and fencing; and most of the rooms, which housed a few graduate students, were located on the second floor. There probably was a fire hose somewhere inside the building, but there were no hydrants outside anywhere close, and the building would have burned like a large cardboard carton in a matter of a few explosive minutes if a fire ever got well started. Everybody knew it, but the best the Committee could come up with for its war preparedness was a bucket brigade of students using sand stockpiled nearby. The matter was discussed at length in several meetings of the Committee, but the idea presented the daunting problem, among others, of getting buckets of sand from the ground outside to a burning roof or to a second story fiercely ablaze, with nothing at hand but men on the ground holding the buckets. Since that problem had no practical solution and nobody could think of anything better, nothing was done.

One day, after a couple of months marked by considerable activity preparing to save Caltech from the horrors of war, but without much progress on the Old Dorm fire-protection problem, Professor Michael announced at the start of a Committee meeting that Millikan was going to attend for the first time in the Committee's brief existence. A somber silence descended over the group, a silence that gave me the impression that the group contemplated the imminent visit with foreboding. As we sat there each wrapped in his own thoughts I reflected on the men around the table, all of them well launched on distinguished academic careers, most old enough to be my father, several young enough to be Millikan's son, nervously musing on his arrival. He was then 74 years old, but he neither looked nor acted like the image I had then of a man that age. He was of medium height and build and, as I see him now in my mind's eye, trim and erect with an athletic bearing and radiating vigor, energy, and self-assured authority. He was, after all, America's most famous living scientist, a winner of the Nobel Prize, the man most associated with Caltech's quality and reputation (the Institute's achievements were entirely the result of his exceptional intelligence, vision, energy, and devotion), and a brilliant experimental physicist who knew how to operate in the world of non-scientific affairs. He commanded respect wherever he went, not least among subordinates a generation younger. What, I wondered, would these now-somber faculty leaders—eminent men, Committee-men—do when Millikan arrived?

By the time graduation rolled around in June, the student organization for campus defense was an unexceptional fact of life.

The door burst open and Millikan strode in looking neither right nor left. To a man we leaped to our feet, and in a flash the eminent professors crowded and shoved as each offered a chair to Millikan. He ignored them all until, with a few strides, he reached the head of the table, where he sat down in Professor Michael's seat and without any preliminaries, began to speak. "I am very displeased with the work of this Committee," he said. His chief concern turned out to be the danger of fire in the Old Dorm. "What has been done about that?" he demanded. Michael started to highlight the difficulties, but Millikan interrupted with a gesture of impatience. "It's all very simple," he declared. "There is even a book about it. You can buy it in any bookstore. They sell it in all the drugstores. It tells about civil defense and what to do in case of attack. All you have to do is fill the bathtub with water and have a bucket handy." Everybody except, evidently, Millikan knew that there were no bathtubs in the Old Dorm or that if there were they would be useless in the face of a major fire. He probably knew it, too, but nobody dared challenge him, nobody said a word. Millikan soon got to the point: he replaced Professor Michael with Professor Sterling, whereupon he left as unceremoniously as he had entered.



John Rubel, BSEE '42 (photo from *The Tech* 1942)

With that change we carried on as before to the end of the quarter. Professor Sterling in the beginning stepped up the beat of the Committee's work. We got ourselves even better organized, but then the pace of activities gradually slowed to a virtual standstill. By the time graduation rolled around in June, the student organization for campus defense was an unexceptional fact of life. Some few last vestiges of cellophane hung in melancholy strips from dorm windows where the "treacle" had not yet entirely flaked off. The patrols had long been discontinued; nobody was excused from finals this time, and the students who had patrolled or knew where the water-main shutoffs were, or had learned about poison gases, or been involved with shatter-proofing windows, or selecting the right color for reduced nighttime visibility, left for the summer or graduated. Some of the class of '42 joined the Navy or the Army or the Army Air Corps; some worked on radar or electronic countermeasures or the Manhattan Project, but nearly everyone in the class survived the real war. Fortunately, no armed Nazis menaced the peace of Pasadena, no Japanese attacked, no crowds of refugees perished in the flames of their combustibles on the campus or anywhere else, and the Old Dorm met a peaceful end more than a decade later. □

John Rubel, believe it or not, went on to become assistant secretary of defense (research and engineering) in the early sixties. Along the way he also worked for G.E., Hughes, and Litton Industries. He's now retired in Tesuque, New Mexico, where he recently earned his MA in liberal education from St. John's College and is active in several literary groups. The inspiration to write down these reminiscences came from a talk by Archivist Judith Goodstein at the 50th reunion of the class of 1942.

One way to persuade the molecules to align is to make them go with the flow, as it were.

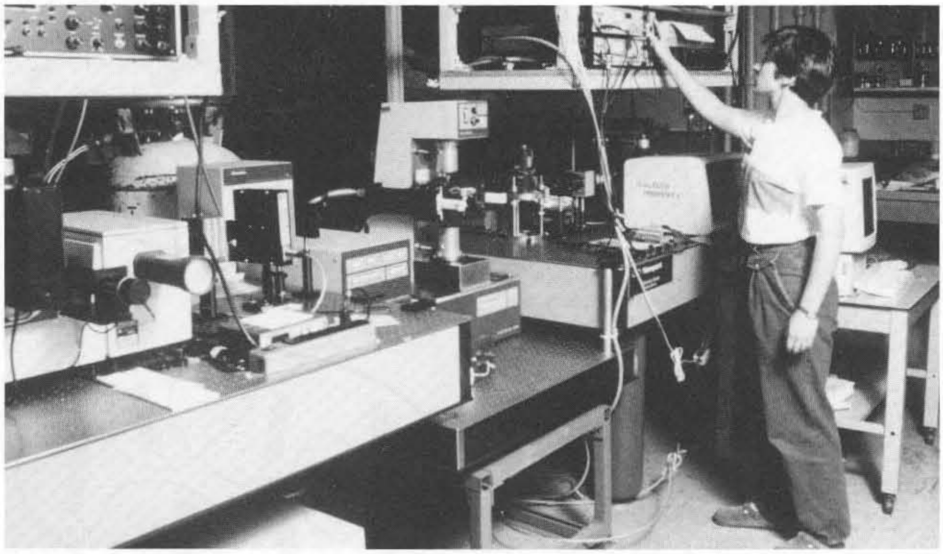
"Fall In!"

Flowing polymers have been studied for decades, but the mechanical methods used can't see how the molecules move, which really determines why the material flows the way it does.

Polymers are long, usually highly flexible molecules. Left to their own devices, they like to lie like cooked spaghetti in a colander. When straightened out and aligned, like a fistful of uncooked spaghetti, polymers can take on new properties. For example, Kevlar, of flak-jacket fame, has the tensile strength of steel but only one-fifth its weight. Other aligned polymers conduct electricity (*Engineering & Science*, Summer 1988), have unusual optical properties, and may even be magnetic. But to make the most of these properties, the molecules must be aligned. One way to persuade the molecules to align is to make them go with the flow, as it were. Molecules in a stream of molten plastic naturally tend to line up along the direction of flow. And although virtually everything plastic, from milk jugs to nylon stockings, is born from a molten polymer mass, very little is known about how flow processing actually works on a molecular level beyond the observation that these highly entangled molecules, particularly in concentrated streams, don't flow like everyday liquids.

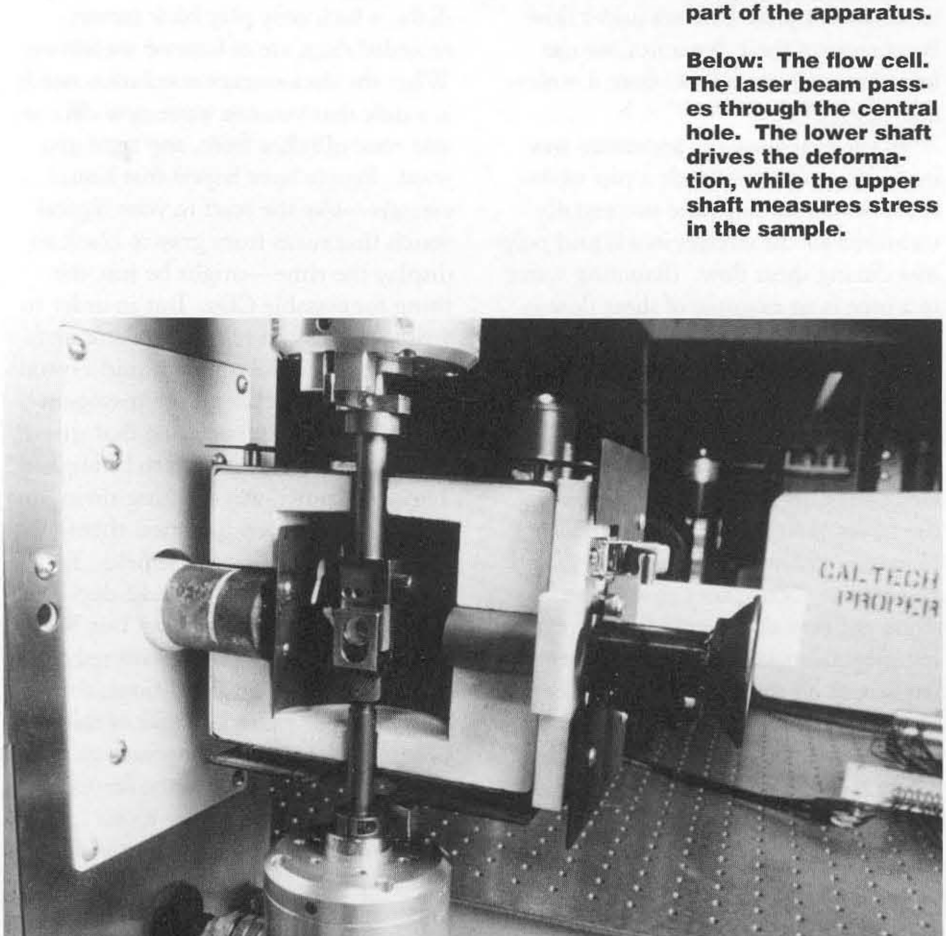
In fact, relatively little is known about how the motions of a single polymer molecule, repeated ad infinitum, translate into such basic properties as viscosity and elasticity. To further complicate matters, many commercially important polymeric materials—bulletproof glass, for example—are blends of two different polymers. Many other polymers contain only one kind of molecule, but one that includes regions of different composition, like a necklace made of ten red beads alternating with ten green beads. Synthetic rubbers, such as the Kraton used in gaskets and O-rings, are like this. Trying to predict the viscosity, say, of such polymers without knowing why their molecules behave the way they do or how they interact has, not surprisingly, been a matter of guesswork. Flowing polymers have been studied for decades, but the mechanical methods used can't see how the molecules move, which really determines why the material flows the way it does. The optical methods by which molecular information can be gleaned were ill-adapted for studies of polymers in motion—the action had to be frozen and the sample removed for analysis. But now Julia Kornfield (BS '83, MS '84), assistant professor of chemical engineering, has developed a system that for the first time records not only the polymer's dynamic mechanical properties, but also the molecular and microscopic changes that occur during flow.

At the center of the apparatus, built by graduate student Rangaramanujam Kannan, is a flow cell consisting of two parallel plates. One plate is stationary while the other oscillates, rubbing the



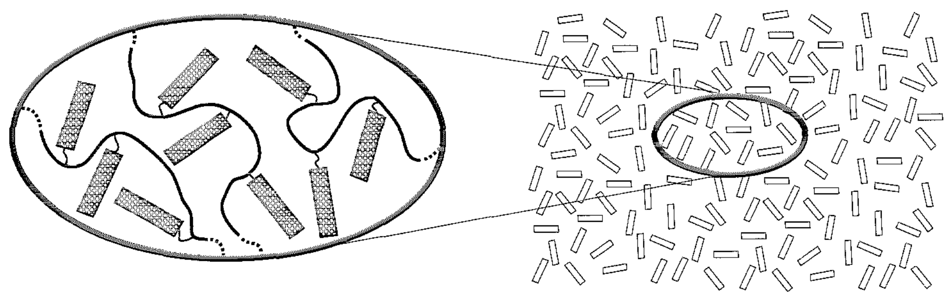
Above: Kornfield and the lab setup. The laser and associated optics are at the left. The flow cell is in the center, mounted in what looks rather like a Mixmaster but is really the mechanical part of the apparatus.

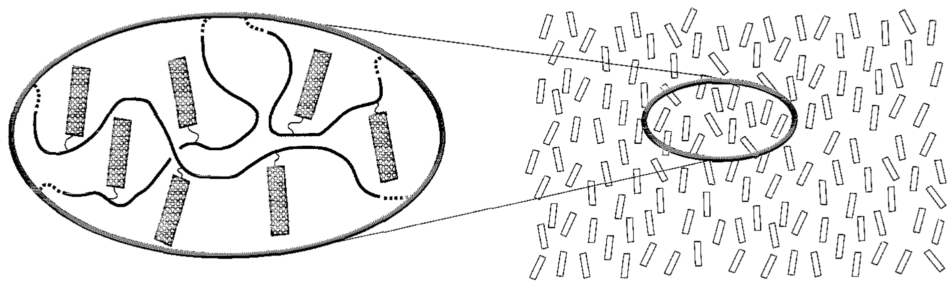
Below: The flow cell. The laser beam passes through the central hole. The lower shaft drives the deformation, while the upper shaft measures stress in the sample.



polymer sample between them like a wad of clay being rolled between the palms of your hands. (The apparatus can hold the sample at temperatures between –150° and 400° C, a range broad enough to ensure that practically any polymer will be malleable somewhere within the span.) Stuck to both plates, the sample flows like pulled taffy with each oscillation, stretching and contracting while sensors record the stress on it.

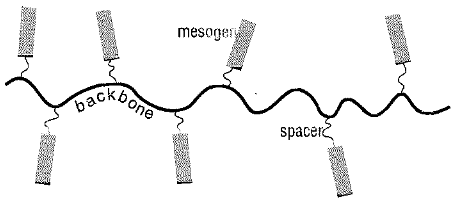
Windows in the flow cell allow optical instruments to collect data on the flowing sample. A laser beam, polarized so that all of its light waves vibrate in a single plane, is sent through the sample and to a set of detectors. One detector measures how much the phase of the polarized light has been rotated by its passage through the polymer, which provides information about how segments of the long, chainlike molecules are oriented by the flow. The other detector measures how the light is absorbed differently depending on the plane of its polarization, which provides information about the orientation of specific molecular structures in the polymer. This specificity is achieved by deuterium labeling: replacing a chosen hydrogen atom in the molecule with deuterium, its heavier cousin, lowers the frequency at which the bond connecting that atom to the molecule vibrates. An infrared laser tuned to that lower frequency will





Below: In side-chain liquid crystals, like the ones that may be the basis for erasable CDs, the mesogens dangle from the polymer backbone like charms from a bracelet.

Right: Normally, the mesogens are randomly oriented, as in the top diagram. But under the right conditions, they will form ranks.

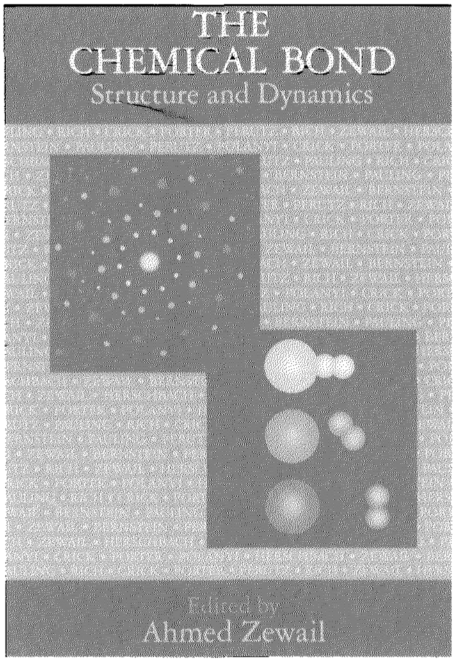


"see" that bond and no others. Says Kornfield, "We can label one type of molecule in a mixture, or distinct parts of a polymer—a part of its backbone, or a bit that dangles off the backbone—and see how that piece behaves under flow. By observing their dynamics, we can learn how polymers flow, from a molecular point of view."

In the year since the apparatus was built, the group has made a pair of discoveries. First, they have successfully measured all the stresses in a liquid polymer during shear flow. (Running water in a pipe is an example of shear flow—the layer of molecules next to the pipe wall hardly moves at all, the next layer out moves a bit faster, and so on.) In fluids made up of small molecules, like air and water, the only stress is the one along the direction of the flow driving the layers of fluid over one another. However, polymer molecules are long and elastic. When they're stretched along the flow they tend to resist, exerting perpendicular forces, called normal stresses, in all three dimensions. "Everyone knows these stresses exist, but they are very difficult to measure precisely. There are theories about them but very few experimental results to test the theories against," explains Kannan. "We've been able to measure them for a variety of polymers."

Exciting as that is to the theorists, the group has just recently found something that may be useful to a new generation of data-storage media. Optical data storage on compact disks like those your CD player takes offer an efficient way to handle vast quantities of data. But today's disks, which only play back factory-recorded data, are of limited usefulness. What the data-storage revolution needs is a disk that you can write new data on, and erase old data from, any time you want. People have hoped that liquid crystals—like the stuff in your digital watch that turns from gray to black to display the time—might be just the thing for erasable CDs. But in order to write on a disk, it has to be blank first. In the case of a polymeric liquid-crystal disk that means that all the mesogens—the portions of the molecule that give it liquid crystallinity—have to be aligned. The only known way to bring them into alignment has been to anneal them in a strong electric or magnetic field. For a very long polymer, it can take days for the mesogens to form ranks. But Kannan and Kornfield have discovered that under the right flow conditions, the mesogens line up in a matter of minutes. "These discoveries have opened up a variety of opportunities for the future," says Kornfield. "There are a vast array of mysteries in the field of polymer dynamics that really demand molecular-level understanding. We're very excited that this new window on these fascinating materials is now open to us." ☐ —*DS*

Books



Academic Press, 1992
$42.95
313 pages

This volume is an outgrowth of a remarkable symposium held at Caltech on Linus Pauling's 90th birthday, February 28, 1991. The seven speakers included six Nobel laureates in molecular structure and dynamics. The talks, given before a gathering of close to a thousand in Beckman Auditorium, were aimed in part at a general audience and in part at those more sophisticated in chemistry and molecular biology. The symposium was organized by the present volume's editor, Ahmed Zewail, who is, most fittingly, the first Linus Pauling Professor of Chemical Physics, and who also coauthored the book's only contribution not presented at the symposium. Richard Bernstein, a pioneer in modern reaction dynamics, had been invited to speak; because of his untimely death in July 1990, the editor included an updated version of a review of femtosecond (10^{-15} second) chemistry that he and Bernstein had written two years earlier.

The book contains nine chapters, two by Pauling himself, as well as biographical information on the other authors, and a helpful index. It is copiously illustrated. The opening lecture was by the honoree—a vintage Pauling presentation, in which he spoke for 45 minutes without notes. The printed essay is essentially his talk: in part a rather personal account of the impact of X-ray crystallography on the development of ideas about chemical bonding, and in part a discussion of his recent work, done at intervals over a six-year period, on icosahedral quasicrystals. These puzzling materials, discovered within the last decade, appear to have five-fold symmetry down to the atomic level, in violation of crystal-lattice theory. Pauling's account of his reasoning and calculating (done without a computer, to maximize the need for *thinking*) about possible interpretations of the experimental evidence is a fascinating exposition of his scientific style. He interprets these crystals as twinned cubic crystallites and, after gathering additional evidence in favor of his hypothesis, concludes: "I am now satisfied that the solution to the puzzle of the existence of icosahedral quasicrystals has been found, and that I may from now on devote my time to other pursuits."

Pauling's other brief chapter, "How I Became Interested in the Chemical Bond: A Reminiscence," is of particular interest to those who knew Caltech in the 1920s and '30s. (One of the few misprints in the book is in the middle name of Richard Tolman, in the picture caption on page 105; Pauling, naturally, gives it correctly on page 104).

Two of the other chapters are, in essence, the lectures given by Max Perutz, "The Significance of the Hydrogen Bond in Physiology," and by Francis Crick, "The Impact of Linus Pauling on Molecular Biology: A Reminiscence." Each of these contributions, as well as most of the others, emphasizes Pauling's fertile imagination and remarkable prescience. Crick's remarks are especially gracious and generous, but every chapter contains more than a few genuine and varied tributes to the honoree.

The remaining chapters are longer (25 to 57 pages). Some constitute rather specialized and critical reviews (with detailed bibliographies), others are guided tours illustrating the development of the fields represented. Each is by

When Ahmed Zewail was named the first Linus Pauling Professor of Chemical Physics in 1990, the two visited on the Caltech campus.

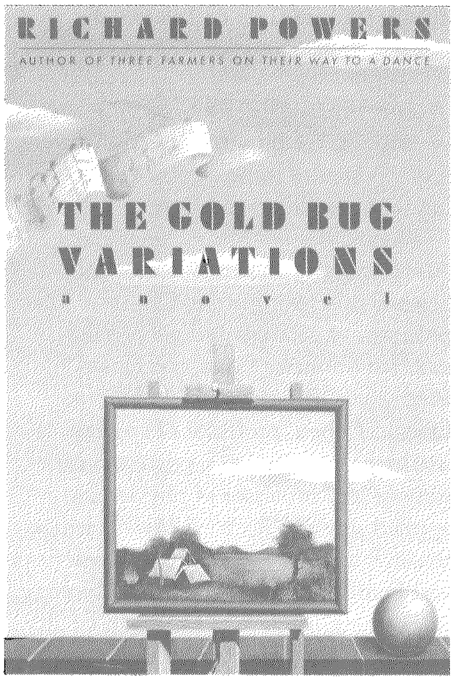
someone who has helped to create and define the field. The speakers were chosen, however, not just for the substance they could offer but for their style, and most of the chapters are eminently readable and contain new ideas and suggestions. They are by Alex Rich, the only former coworker of Pauling among the speakers, "Molecular Recognition between Protein and Nucleic Acid"; George Porter, "Chemistry in Microtime"; John Polanyi, "The Transition State"; Dudley Herschbach, "Chemical Reaction Dynamics and Electronic Structure"; and Ahmed Zewail and Richard Bernstein, "Real-Time Laser Femtochemistry: Viewing the Transition from Reagents to Products." There is little redundancy in the different contributions. Some contain valuable insights into the way fashions in science change, and the way in which creative scientists operate, particularly in showing that "accepted limitations" can sometimes be overcome by re*think*ing the fundamentals involved.

The book is of special interest and significance to the Caltech community—not just, but particularly, those who were in Pasadena during the Pauling years—because of the seminal role Pauling played in developing the CIT aura. He made it a mecca for chemists (and eventually molecular biologists) throughout much of his more than 40 years on the campus, and he revolutionized the teaching of introductory chemistry through his Chem 1 course. It is especially gratifying to those who knew the Institute in those days and who were drawn to it by his magnetism and inspiration, that the "distant period" referred to in Zewail's preface, which began after Pauling received the Nobel Peace Prize (1962) and resigned from the faculty (1964), has now been replaced by one of genuine good feeling. The ice was broken during his 85th birthday celebration, also at Caltech, when Pauling discussed his reasons for leaving, but made it clear that his heart had always been in Pasadena. It is highly apposite that the chief architect of this rapprochement has been Professor Zewail.

Pauling's name is synonymous with the nature of chemical bonds and 20th-century structural chemistry. He taught chemists and what are now called molecular biologists to think about chemical structure three-dimensionally, rather than just in terms of the two-dimensional topological diagrams that were universally used through the first half of this century. But it is not so often appreciated that he made seminal proposals in chemical dynamics as well. These, cited by several of the speakers, include his 1946 recognition that enzymes must stabilize transition states of the reactions they catalyze; his 1947 bond-order/bond-energy relationship, which provided a key to early interpretations by Johnston of the changes occurring as reactant molecules pass through transition states; and (at the other extreme of the time scale), his 1965 suggestion, with Zuckerandl, that evolutionary change could be timed by a "molecular clock," the accumulation of mutations in proteins. Dudley Herschbach puts it well in one of his concluding sentences: ". . . compiling this chapter has made me realize more fully the awesome impact and scope of his ideas." Anyone who reads this book is bound to feel the same way.

Kenneth Trueblood
Professor of Chemistry, Emeritus
UCLA

Trueblood received his PhD under Pauling in 1947, remaining at Caltech as a postdoc till 1949. From 1950 he was on the chemistry faculty (x-ray crystallography) at UCLA until becoming emeritus in 1989. He was department chairman from 1965 to 1970 and dean of the College of Letters and Science from 1971 to 1974.



Morrow, 1991
$25.00
639 pages

From a quick synopsis, Richard Powers's novel *The Gold Bug Variations* would appear relatively simple. Nominally there are three main themes: deciphering the genetic code, as told in the story of Stuart Ressler, a young researcher beginning his career at the University of Illinois in 1957; Bach's *Goldberg* Variations, which become Ressler's parallel obsession; and a pair of more-or-less conventional love stories. But just as Nature has arranged that all biological function arises from the permutations of only four bases in DNA, Powers manages to develop and combine his themes to produce incredible richness: a hymn to the endlessly evolving, infinitely variable, living universe.

The theme of the infinite is sounded continually and in many guises, most notably in the challenge: how should we live our necessarily finite lives in a world of infinite possibility? Ressler gives up his research career, on the very brink of probable success, in the face of the realization that the code problem, as important and challenging as it is, is trivial compared to the complexity and variety of life—even though the latter is contained in the former. In fact, virtually the entire research team (suggestively titled "Cyfer") drops out: one kills himself (taking all the laboratory rats with him); one abandons his wife and daughter based on nothing more than a low genetic probability that the child is his; one undergoes what can only be described as a religious conversion, stuck overnight in the library during a storm. Where else should a religious experience take place, in this Age of Information?

The general concept of code is a major focal point of the work—not only in the obvious manifestations of the genetic code and of computer programming (after abandoning his research career, Ressler reappears years later in a data processing shop), but also concerning language as code. The novel is full of allusions, metaphors, puns, that need to be translated before the underlying message can fully be read. One need read no further than the title—punning on the Bach work as well as the Poe story, where decoding a secret message leads to discovery of a great treasure—to appreciate that the book is in this sense its own subject.

Furthermore, the structure of the work is closely tied to the subject material, both overtly and subtly. The *Goldberg* Variations consist of 32 sections: an aria, thirty variations, and the aria repeated. The book is arranged in an introductory "aria," a poem that has the same number of lines as Bach's aria has measures, followed by 30 chapters, and a closing "recapitulation." Every third variation in Bach's work is a canon, where a theme begins in one voice, continues while the theme reenters as a second voice after some time delay, and a third voice in the bass ties them together. Powers's two love stories—one between Ressler and a married woman on his research team; the other between Franklin Todd, a coworker in the data processing facility, and Jan O'Deigh, a librarian whom Todd recruits to help him find out about Ressler's past—are highly imitative and told simultaneously (or as close to it as the medium allows), but with one displaced in time relative to the other—in this case, by 25 years. O'Deigh also functions as the third voice in this canon, looking back at both Ressler's scientific work and her own part in the story from a couple of years further on.

Powers's intricate interweaving of materials is continually original and striking. One example begins with the recurring metaphor of the Perpetual Calendar: simple rules allow us to determine in which future year the calendar will look the same as this year; but what happens in that year is eternally different; life is far too complex and varied to repeat itself. The end of the *Goldberg* Variations is marked "*Aria da Capo e Fine*"; Powers ends his book with that heading followed by: "What could be simpler? In rough translation: Once more with feeling." It *doesn't* mean that, but rather: "Play the aria again from the beginning, *and end.*" Going back and repeating equals termination. Ressler tells O'Deigh he is returning to Illinois to participate in a research project; for a moment she is excited to think he is resuming his scientific career, then understands: it is a cancer study, and he is going not as scientist but as subject. Ressler hears the *Goldberg* Variations on the radio and first thinks it is the same recording he has been listening to for years, but then realizes it is a new version by the same performer. What great luck, after all these years, to be able to hear a new conception of the piece—but at its end, Ressler learns that the recording is being played in tribute to the artist, who has just suffered a fatal stroke.

The artist in question is, of course, Glenn Gould, who constitutes an important figure in the book even though he is never named. Reminiscent of the phrase beloved by patent attorneys: "The entire content of [an earlier patent] is incorporated herein by reference," here we have an entire character, whose story is in many ways parallel to Ressler's, built into the story simply by allusion. An efficient and essential device, if a book dealing with the infinite is to be kept short of infinite length.

Clearly this book will reward most those readers willing to devote the effort needed to extract its richness from these complexities; but untangling the structural network and deciphering the code are by no means its main points. *The Gold Bug Variations* has an important message for everyone—a remarkable achievement.

Jay Labinger
Administrator, Beckman Institute

Labinger received his BS from Harvey Mudd in 1968 and his PhD from Harvard in 1974. He's been a member of the professional staff at Caltech since 1986 and has a local reputation as a solver of puzzles.

Random Walk

Honors and Awards

Tom Ahrens, professor of geophysics, became the 64th member of the current Caltech faculty to be elected to the National Academy of Sciences.

Elected fellows of the American Association for the Advancement of Science this spring were: Clarence Allen, professor of geology and geophysics, emeritus; Sunney Chan, the Hoag Professor of Biophysical Chemistry; Donald Cohen, professor of applied mathematics; David Goodstein, vice provost and professor of physics and applied physics; Richard Marsh, senior research associate in chemistry, emeritus; and Paul Patterson, professor of biology.

Four members of the Caltech faculty were elected fellows of the American Academy of Arts and Sciences: Michael Aschbacher, professor of mathematics; Marshall Cohen, professor of astronomy; and Richard McKelvey and Peter Ordeshook, both professors of political science.

Jay Bailey, the Chevron Professor of Chemical Engineering, has been named to the College of Fellows of the American Institute of Medical and Biological Engineering.

Seymour Benzer, the Boswell Professor of Neuroscience, Emeritus, is a corecipient of the fifth annual Bristol-Myers Squibb Award for Distinguished Achievement in Neuroscience Research.

This year's ASCIT teaching awards were presented in June to: Bill Bing, director of instrumental music; Delores Bing, director of chamber music;

Barbara Imperiali, assistant professor of chemistry; John Sutherland, professor of literature; Wen-Ching Wang, graduate student in biology and chemistry; Greg Willette, graduate student in applied physics; and Richard Wilson, professor of mathematics.

Christopher Brennen, professor of mechanical engineering has been selected by the American Society of Mechanical Engineering (ASME) as this year's recipient of the Fluids Engineering Award.

Three faculty members, all alumni of the University of Chicago, received honorary Doctor of Science degrees from their alma mater at its spring convocation: Norman Davidson, the Chandler Professor of Chemical Biology, Emeritus; Edward Stone, professor of physics, vice president, and director of JPL; and G. J. Wasserburg, the MacArthur Professor of Geology and Geophysics.

John Doyle, professor of electrical engineering, has been awarded the R. G. Baker Prize (shared with three coauthors) from the Institute of Electrical and Electronics Engineers, Inc., for the most outstanding paper of the past year.

Thomas Everhart, Caltech president, has been named a recipient of the 1992 Clark Kerr Medal, presented by the Faculty Awards Committee and the Chancellor's Office of the University of California for "an extraordinary and distinguished contribution to the advancement of higher education."

Sloan Research Fellowships for 1992 have been awarded to Gian Graf, assistant professor of mathematics, and Peter Weichman, assistant professor of theoretical physics. They will each receive $30,000 over two years in unrestricted funds for their research.

John Grunsfeld, senior research fellow in physics, was selected by NASA as one of 19 new astronaut candidates for the space shuttle program.

Paul Jennings, provost and professor of civil engineering and applied mechanics, was named the recipient of the 1992 Nathan M. Newmark Medal, jointly awarded by the Engineering Mechanics and the Structural divisions of the American Society of Civil Engineers.

Mary Kennedy, professor of biology, has received an NIH Javits Neuroscience Investigator Award, a $1.5 million grant in direct costs over a seven-year period.

Shrinivas Kulkarni, professor of astronomy, has won the NSF's Alan T. Waterman Award, given annually to an outstanding young researcher. He will receive up to $500,000 of research support over three years.

Three awards of $1,000 each were presented by the Division of Biology and Lawrence and Audrey Ferguson to honor excellence in teaching. Recipients were: Gilles Laurent, assistant professor of biology and computational and neural systems; Jean-Paul Revel, the Albert Billings Ruddock Professor of Biology; and graduate student Mark Running.

Ruben Mettler, chairman of the Board of Trustees, is the recipient of the 1992 Arthur M. Bueche Award, presented by the National Academy of Engineering to honor "statesmanship in the field of technology."

Amnon Yariv, the Myers Professor of Electrical Engineering and professor of applied physics, has been chosen to receive the 1992 $35,000 Harvey Prize in the field of technology from Technion, Israel's technology institute.

"Sustainable World" Issue Gets Around

E&S has made Bob Sipchen's weekly column on magazines in the *Los Angeles Times* again. The first time was the Winter 1990 special issue on the Loma Prieta earthquake; this time was the Spring 1992 special issue on the "Visions of a Sustainable World" symposium. Under "Required Reading" (along with family values in *TV Guide* and killing coyotes in *Outside*), Sipchen chose to pick up on John Hopfield's prediction that computers will be smarter than humans in 25 years, and states: "This magazine naturally tends to equate a self-sufficient planet with technological advance." We're not at all sure that's true. But perhaps we should be happy with just getting noticed.

The "Visions" issue was also noticed (even if only a little bit, with all the competition in reading material) at the Earth Summit in Rio de Janeiro in June. Grad students Mitra Hartmann and Sakae Suzuki, who were attending the summit from Caltech, persuaded 15 fellow passengers, good sports all, on the Pasadena contingent's chartered plane to each lug a 50-pound box of magazines along as personal luggage through Brazilian customs. Hartmann and Suzuki distributed 1,500 copies of the magazine at the summit, mostly through Russ Mittermeier's Conservation International booth, and report that it was particularly popular with delegates to the science sessions, some of whom may have actually read it.

The Braun Athletic Center's spacious, two-story lobby with its comfortable seats, landscaped planters, and handy snack machines—stocked with healthy foods, of course—is designed to be a place to hang out and socialize after exercise. The weight room is visible through the windows in the background.

New Athletic Center to Open in October

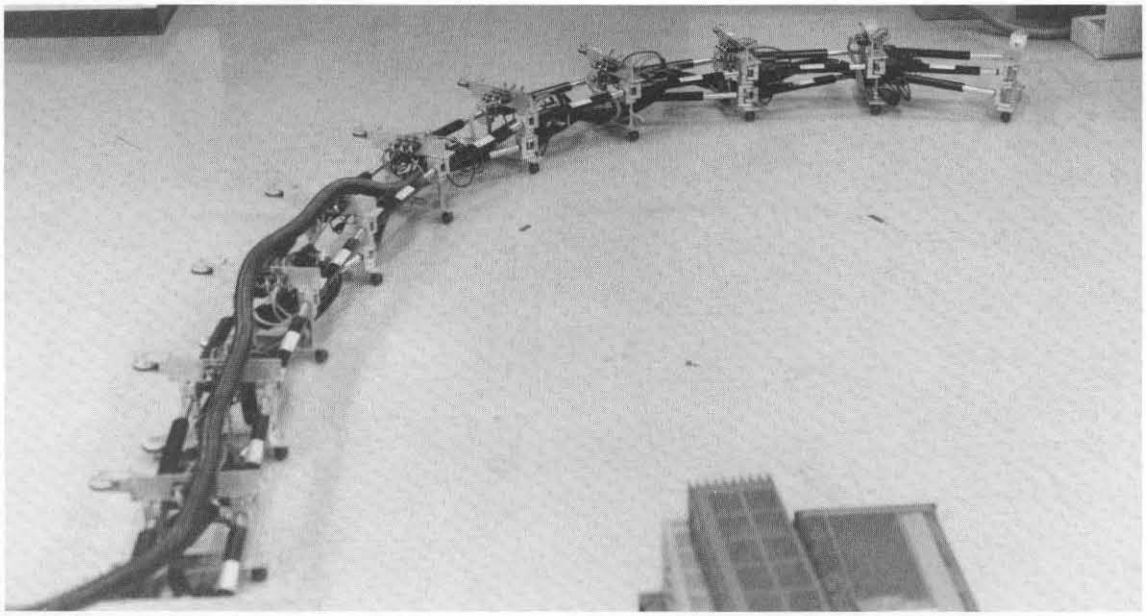
The Braun Athletic Center will be dedicated at noon on Friday, October 9. In addition to a full-sized gym for basketball and volleyball, the new facility houses two indoor squash courts, four racquetball courts, a 3,000-square-foot dance/aerobics room, and a 5,000-square-foot weight room and fitness center with state-of-the-art weight machines, exercycles, stair climbers, and so on that will out-health-club the health clubs. There's also a training room for sports medicine as well as new offices for the athletic staff. Most important, perhaps, are the 152 new men's lockers (an 18 percent increase) and 104 new women's lockers (a 25 percent increase). The building—triple the size of the old gym—will allow Caltech's athletic office to provide a much broader range of undergraduate phys-ed courses and will accommodate the ever-expanding demand by students, faculty, and staff for after-hours recreation, from pumping some solitary iron to the Graduate Student Council's basketball league. Construction was funded by a gift from the Carl F Braun Trust.

Watson Lectures Set

The Earnest C. Watson Lecture Series for this autumn includes: *October 21:* Space Technology and the Discovery of the Lost City of Ubar—Ronald Blom, geologist, Earth and Space Sciences Division, JPL; *November 4:* Magnetite Biomineralization in the Human Brain: What Does It Mean?—Joseph Kirschvink, associate professor of geobiology; *December 3:* Competitive Engineering Design—Eric Antonsson, associate professor of mechanical engineering; *January 6, 1993:* Science at the Supercollider—Barry Barish, Linde Professor of Physics and spokesman, GEM Detector, SSC; *January 20:* What To Do When the Sky Glows in the Dark? The Infrared Astronomical Satellite (IRAS) Ten Years Later—Charles Beichman, director of the Infrared Processing and Analysis Center. All lectures are at 8:00 p.m. in the Beckman Auditorium. Admission is free. Please note that Antonsson's lecture is on Thursday instead of the traditional Wednesday.

Ledyard Appointed Division Chairman

Professor of Economics and Social Sciences John Ledyard has been appointed chairman of the Division of Humanities and Social Sciences. Ledyard first came to Caltech as a Sherman Fairchild Distinguished Scholar in 1977, visited again in 1983, and came to stay in 1985. He earned his AB from Wabash College (1963) and MS (1965) and PhD (1967) from Purdue. Ledyard's research has involved the allocation of resources in organizations, one recent study focusing on NASA's assignment of payload berths on the space shuttle (*E&S*, Fall 1989).



The robot snake built by Assistant Professor of Mechanical Engineering Joel Burdick's group is so limber that it can curl up on itself.