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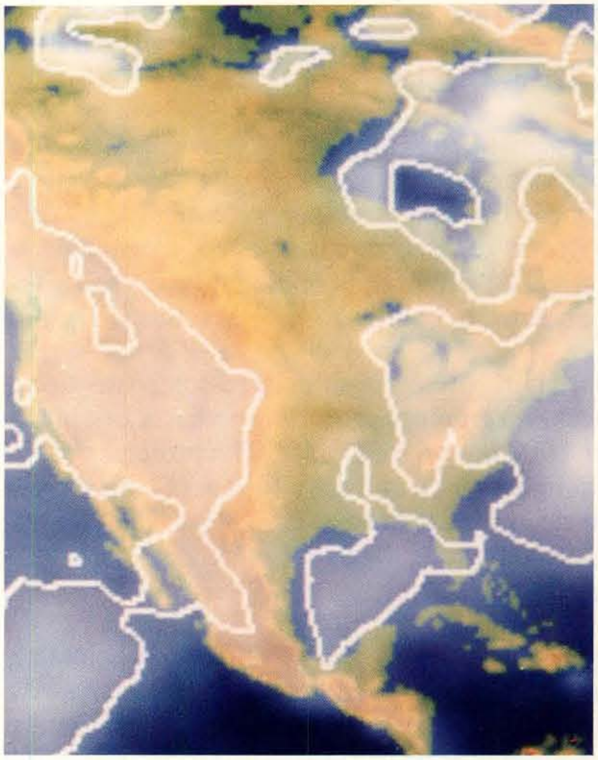
Engineering & Science

Winter 1989



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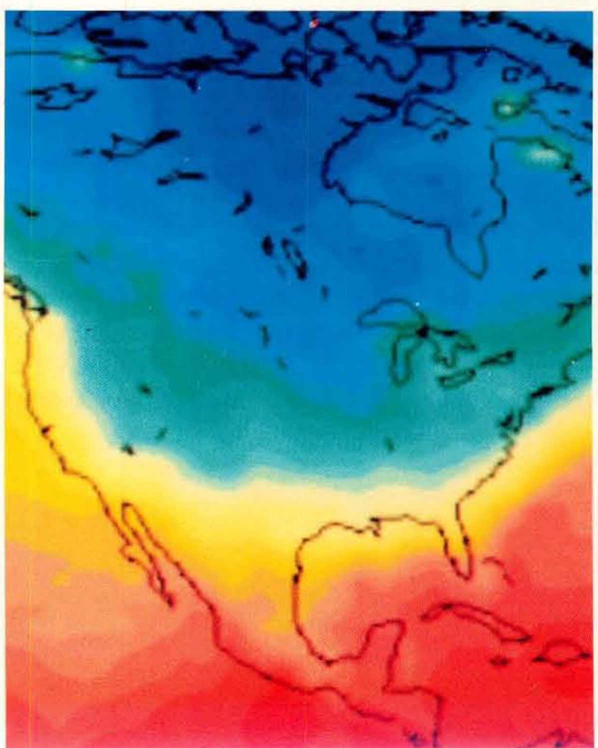

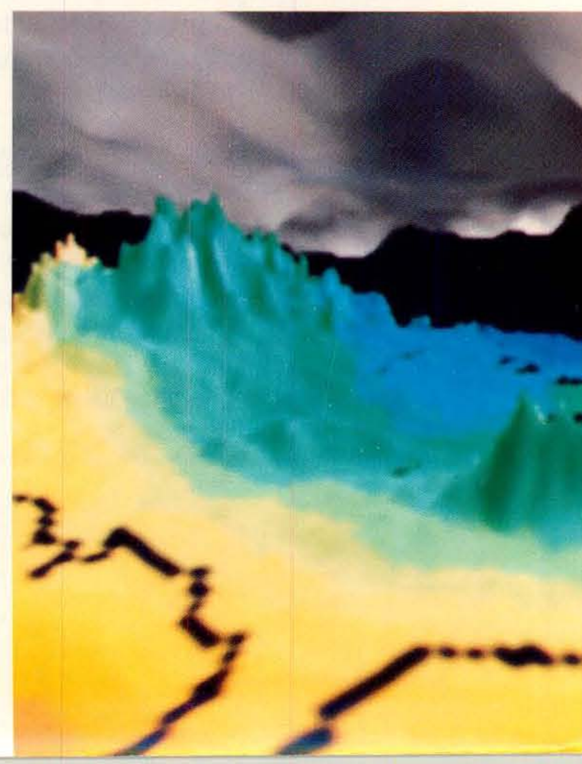

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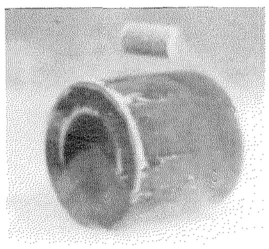
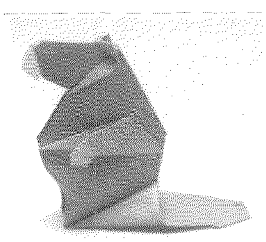
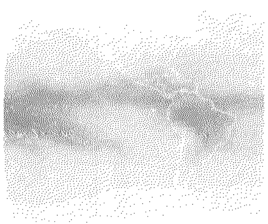


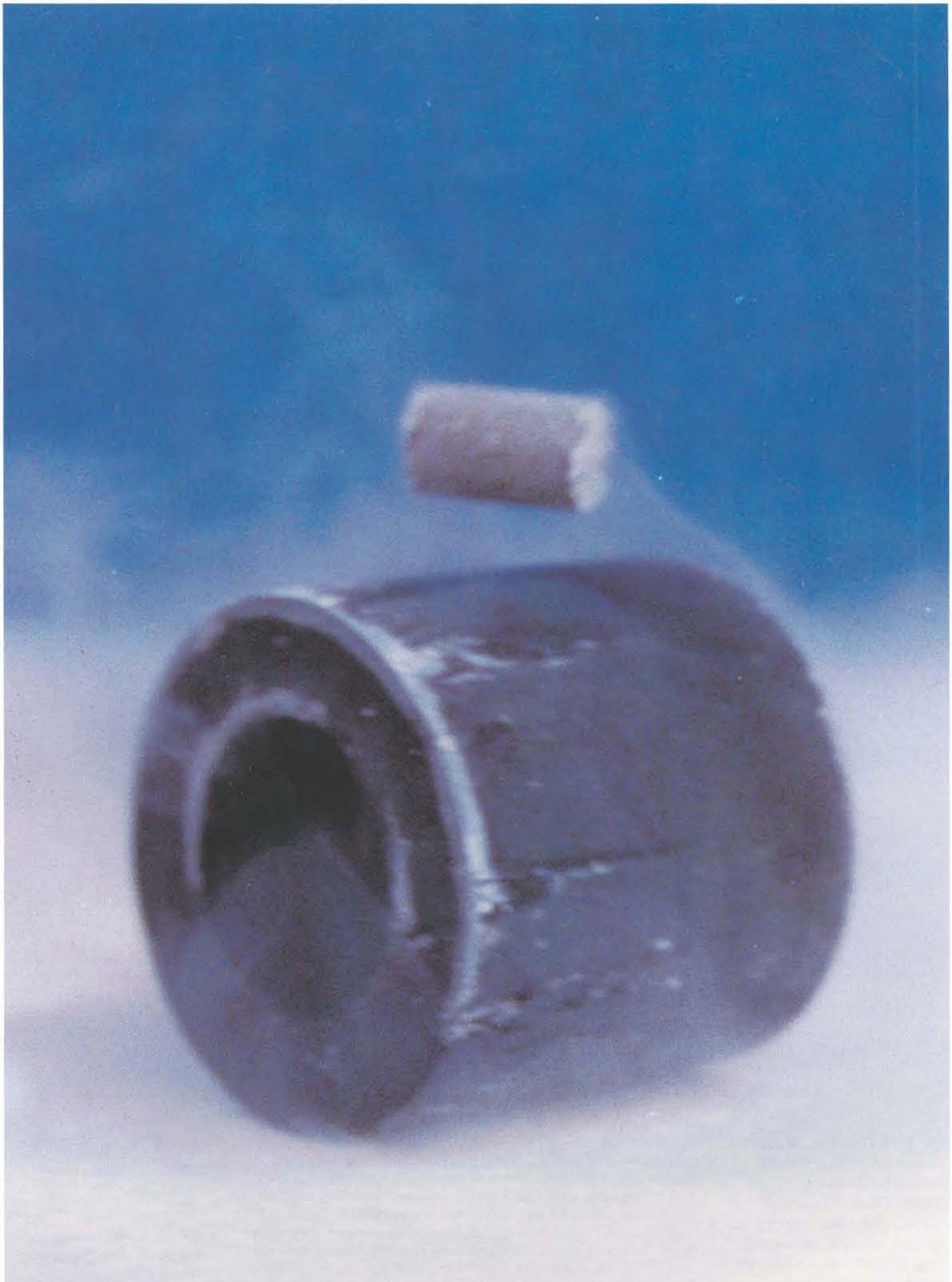




On the Cover: A cold front pushing down into the Midwest, as seen from satellite data. Top left: gray to white shows increasing cloud cover above 50% (heavy line); colors are keyed to topography. Right: same, but with cloud and ground elevations in 3-D, exaggerated 20×. Bottom left: surface air temperature. Right: 3-D view with temperature added. Cold air is cloud-free.

Engineering & Science (ISSN 0013-7812) is published quarterly, Fall, Winter, Spring, and Summer, at the California Institute of Technology, 1201 East California Boulevard, Pasadena, California 91125. Annual subscription $8.00 domestic; $20.00 foreign air mail; single copies $2.00. Third class postage paid at Pasadena, California. Published by the California Institute of Technology and the Alumni Association. Telephone: 818-356-3630. Postmaster: Send change of address to Caltech 1-71, Pasadena, CA 91125.

PICTURE CREDITS: Cover, 24, 28, 29, 31 – NASA/JPL; 2, 7, 8, 9 – Rockwell International; 5 – Leyden Museum of Science; 6, 10, 16, 18, 20, 21, 23, 44 – Robert Paz; 11 – Japan Railways Group; 12, 29, 30, 32, 33 – NASA; 14 – Bechtel; 35 – John Lebens, Mike Hoenk; 25 – NOAA; 36 – Mike Hoenk; 39 – Black Star; 40 – Leigh Wiener; 43 – Jim Mendenhall.



High Temperature Superconductivity

by David L. Goodstein

There is a good deal of excitement because some people suspect that somebody may someday find something to do with this stuff.

In a cloud of liquid nitrogen, a small piece of high temperature superconducting material hovers above a permanent magnet.

The two researchers who discovered the phenomenon of high temperature superconductivity in 1986 were working in a field in which most people had given up hope. In fact, J. Georg Bednorz and A. Karl Mueller at IBM in Zurich, Switzerland, had to disguise their work from their own supervisor in order to be able to do it. And even after they had made their discovery, the poor guys had to wait nearly an entire year before they got their Nobel Prize. The discovery was quickly confirmed in unexpected places such as China and Japan, and especially in Houston, Texas, and Huntsville, Alabama, where Paul Chu and his students and associates and former students not only confirmed the discovery but soon found a new class of materials that became superconducting at even higher temperatures. And that's when all the excitement really began.

The program for the 1987 meeting of the American Physical Society in New York City had gone to bed in December before the discovery was announced, so it contained nothing about high temperature superconductivity. But the organizers of the meeting, sensing that there was some interest in the subject, obligingly arranged for a special evening session to be held in case anyone had anything to present about the topic. That session was held in the hotel where the meeting took place. Four thousand people attended; it began at 7:00 in the evening and finally broke up at 6:00 the next morning. *The New York Times* front page story called it a "Woodstock for physicists." One month later, in April 1987, the whole scene was repeated at the annual meeting of the European Physical Society in Pisa and, although I was in Italy at the time, I declined to go. Once had been enough.

Since the discovery was made, there has been an absolute torrent of scientific papers on the subject—so many that some journals have had to bypass the normal peer-refereeing system; instead, a special panel reads the flow of papers on the subject as they come through. One consequence of this was that I found myself on the high temperature superconductivity panel of a journal I had never seen a copy of.

Of course, the news of this great discovery got into the press, and everyone who reads a newspaper must have read about the discovery during the past couple of years. It even became sound bites on TV. In August 1987 the U.S. government organized a conference at which businessmen and scientists got together to explore the commercial possibilities for the future competitiveness of our nation. Foreigners were not permitted to attend. Presumably this reflected the all-American origins of the subject in such American principalities as Switzerland, China, and Japan. There has been a flood of extremely expensive seminars—not for scientists, but for businessmen who feel they need to keep up on the latest developments in this field in order to keep their companies competitive. There has also been a flood of very expensive newsletters (again, not for scientists but for businessmen) and scientific journals (not for scientists but for libraries who feel obliged to buy every scientific journal that comes out). So far as I know, these seminars, newsletters, and journals

This curiosity has suddenly become cardiac country for CEOs, and the question is: What's going on here?

have been the only successful commercial applications of high temperature superconductivity.

My favorite remark to come out of all this was made at the federal conference in Washington, where Clayton Yeutter, the U.S. trade representative said, "Chief executive officers are paid to succeed." This was in reference to superconductivity, a subject that had been a mere scientific curiosity a few months before. This curiosity has suddenly become cardiac country for CEOs, and the question is: What's going on here?

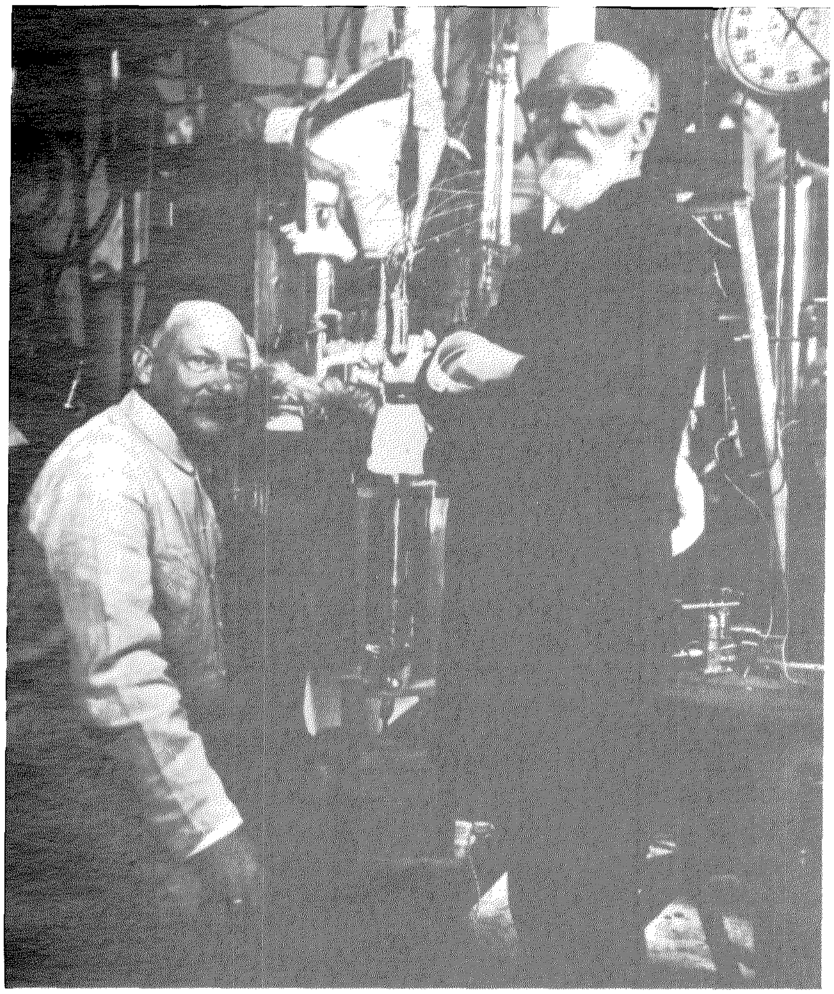
To try to answer this question, I'll first explain what superconductivity is; then I'll define what we mean by high temperature in regard to superconductivity; then I'll describe what the new discovery is; and finally I'll discuss whether anything might be made of it.

The phenomenon of superconductivity was discovered in 1911 by the Dutch physicist Heike Kamerlingh-Onnes. Three years earlier Kamerlingh-Onnes had succeeded in becoming the first person ever to liquify the element helium, and in liquid helium he had a bath in which he could cool things to the lowest temperature ever achieved on earth. So any measurement he decided to make would be the first measurement ever made at this new lowest temperature. The measurement he decided on was the resistance of a sample of metal. He chose mercury, because he could distill it and make it very pure. The experiment is done by passing an electric current through the sample and measuring the voltage that develops across the sample in order to push the electric current through it. The ratio of voltage to current is called the resistance. Kamerlingh-Onnes wanted to find out how the resistance of mercury behaved as a function of temperature when it was cooled down to this very low point.

It was well known at the time that, at higher temperatures, as the temperature went down the resistance went down in a nice, smooth curve. You might wonder why this man, with a whole new world to explore, would choose to add a few more points to a well-known curve. The answer, I think, was that he didn't expect to do that at all; he expected to make a spectacular discovery. His mental image of how a metal worked would have been much the same as ours today—a metal is basically a container full of a fluid of free electrons that can move around inside and give the metal its familiar properties, such as its shiny surface, electrical conduction, and so on. He also would have known that all fluids freeze if you cool them down enough, so he might have thought that if he got a metal like mercury cold enough, the electron fluid would freeze, and it would cease to be a metal. If that happened, then at the point where it ceased to be a metal, the resistance would suddenly jump up to infinity. I think that must have been the dramatic discovery he expected to make. But when he made the measurement, what he found instead was exactly the opposite—the resistance jumped down to zero. And that was the discovery of superconductivity.

Superconductivity has, we now know, three principal properties associated with it. One is that the electrical resistance is zero; the second is that superconductors are destroyed by magnetic fields; and the third is called tunneling.

In saying that the electrical resistance is zero, I mean really zero, not just very small. The way to find that out is not by Kamerlingh-Onnes's method; in that case all you find out is that the resistance is smaller than you're able to measure with your instruments. There's a better way of doing it, which is to take a doughnut of superconducting material, such as lead, and induce a current to run around in the ring with nothing driving it. If you did this with the very purest and best ordinary conductor—for example very pure copper at low temperature—the natural resistance of the material would cause the current to decay away to zero in a tiny fraction of a second. But when this experiment is done with superconducting lead, the current flows with no noticeable decrease for a period of years. So the resistance to the flow is really zero.



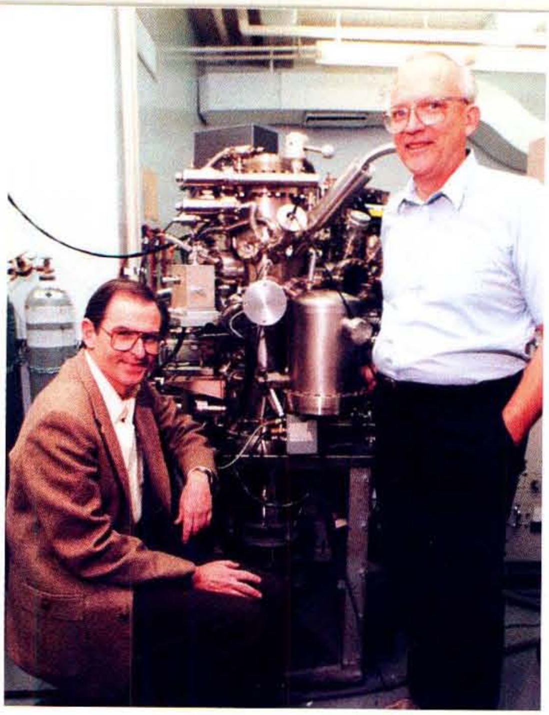
Heike Kamerlingh-Onnes (left) poses with the first helium liquifier. At right is Johannes Van der Waals, known for his theoretical studies of liquification. And lurking at far right behind the gauge is the unknown technician who probably did all the work. (Leyden Museum of Science, Caltech Archives)

Superconductors are destroyed by magnetic fields. If you apply a magnetic field to a superconductor, the superconductor actually expels the magnetic field—keeps it outside so that the inside has no magnetic field and can remain superconducting. Of course, if you make the magnetic field stronger, it becomes harder for the superconductor to expel it, and if you make it strong enough, the superconductor can no longer do it. The field collapses and the material ceases to be superconducting.

In the early 1960s, however, somebody discovered that certain superconductors (not all of them, but some) actually could support extremely large magnetic fields before they were destroyed. Nobody remembers who discovered high field superconductors (well, I'm sure the discoverer remembers, but I don't), but I think that in the long view of history that might turn out to be a more important discovery than that of high temperature superconductivity.

If you have a superconductor that can exist in a high field, it can also be used to create a high field. To do that, you make the superconductor into a wire and make the wire into a coil; then you run a very large current through the coil, and that creates a magnetic field inside the coil. So the second property is that superconductors can be used to create magnetic fields and in some cases very large magnetic fields.

The third property of superconductivity is known as tunneling. If I put two pieces of superconductor very close together, then it's possible for some of that supercurrent (that is, the current that can flow with no resistance) to leak across from one to the other. Then, if you repeat Kamerlingh-Onnes's measurement, you



David Goodstein (left) and Robert Housley (visiting associate from Rockwell) pose with the CUSP (Caltech Universal Surface Probe), which combines in one machine "every surface analysis technique ever invented by the human mind—or at least more than half." Also involved in Caltech's work on high temperature superconductors is Ken Keester, member of the professional staff.

These new superconductors are complicated, composite materials of a type technically called ceramics. What we're dealing with here is pottery.

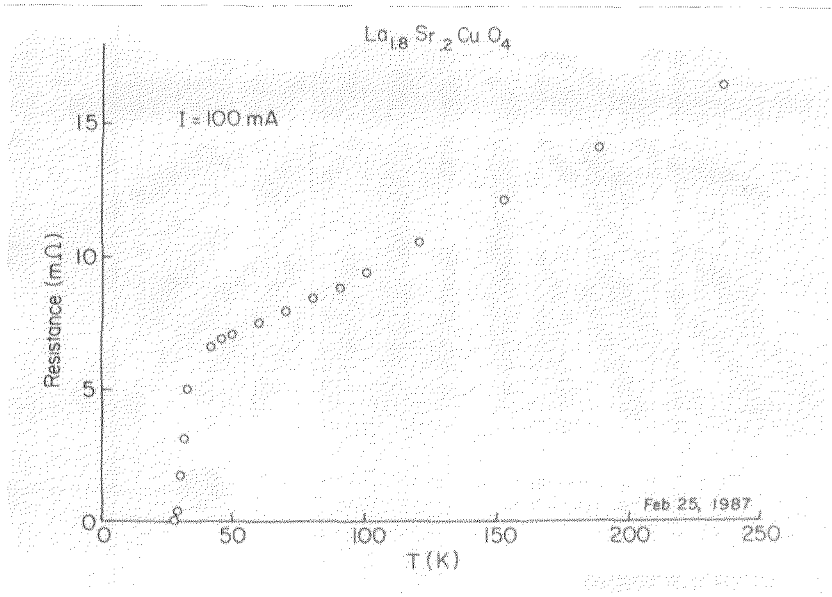
find the same result. The current flows and there's no voltage at all across the circuit, across what we call the tunnel junction. Unlike the case of a single piece of superconductor, however, when the current is flowing through a tunnel junction, the relation between current and voltage becomes exquisitely sensitive to tiny outside influences, such as very small magnetic fields, electromagnetic radiation, and so on.

Now that we know what superconductivity is, let's go on to temperature. In Kamerlingh-Onnes's mercury sample the superconducting transition occurred at a temperature of 4 kelvins. Absolute zero, that is, the lowest temperature that has any meaning, the temperature of a body from which all possible energy has been extracted, is 0 kelvins. That's very convenient; it means we never have to deal with negative numbers. (In the familiar Fahrenheit scale, absolute zero is −459°.) The size of a degree in the Kelvin scale was fixed by the very sensible idea that the freezing point of water should be 273. Once you've made that decision, then it follows that normal room temperature is about 294K and the temperature at which air liquifies is about 80K. At this temperature, which is −330° Fahrenheit, most of the air in the room would form a puddle on the floor. Of course, if the temperature in the room were −330°, other things would happen that don't bear thinking about.

In 75 years of work on superconductivity, scientists managed to push the maximum temperature at which it occurred from 4K up to 24K. It held at that point for a long time, which is why Bednorz and Mueller were working in an obsolete field. The breakthrough that earned them the Nobel Prize was the discovery of material that became superconducting at 30K. The big discovery by Chu and his associates that caused all the excitement was a material that became superconducting at 93K, the crucial point here being that it's above the temperature of liquid air. So now you could cool a sample in liquid air and get a superconductor, whereas before you had to cool a sample in liquid helium.

There have been weekly rumors of discoveries in the room-temperature range ever since, but those rumors have not proved to be true. My colleague Bill Goddard (Caltech's Charles and Mary Ferkel Professor of Chemistry and Applied Physics) has recently published a new theory in the usual places—*The New York Times* and *The Wall Street Journal*—that makes a firm prediction that the highest temperature possible for this kind of superconductivity will be about 225K (−54°F).

The cost of the required refrigerants is a good illustration of the difference between these temperatures. For the old-fashioned kinds of superconducting materials you have to use liquid helium. Liquid helium delivered to our door at Caltech with the morning milk costs $5 per liter—just about the cost of cheap vodka. It even looks a lot like cheap vodka—a colorless fluid. We get liquid nitrogen (liquid air and liquid nitrogen are pretty much the same thing, since air is 80 percent nitrogen) delivered to the door for about 12 cents per liter. I think that's



The graph at left shows the first Caltech measurement of a high temperature superconductor (lanthanum-strontium copper oxide). A closer look at the transition region shows that, unlike the original low temperature superconductors, the resistance doesn't drop suddenly but straggles gradually down to zero. This seems to be characteristic of all the new materials.

Newly baked crystals of high temperature superconductor emerge from the oven in a tiny crucible.

less than what we pay for bottled drinking water in the lab.

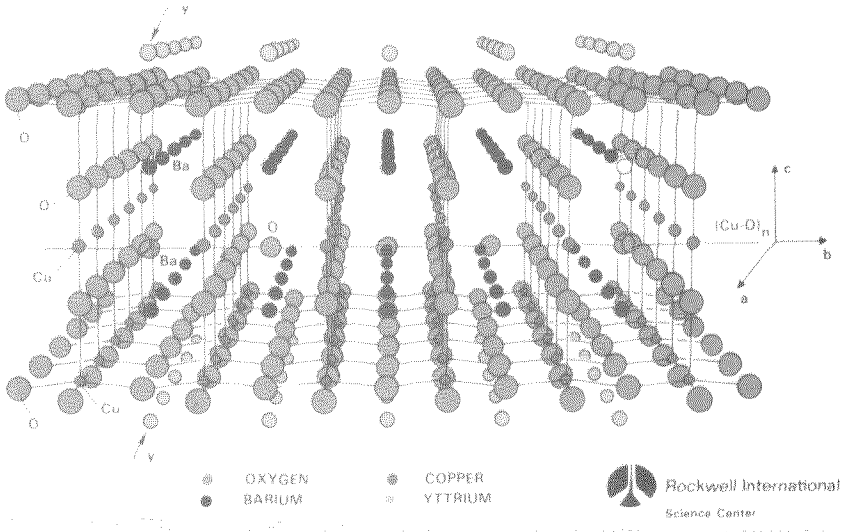
The first superconducting material, as I mentioned earlier, was mercury. But it turned out that many of the metallic elements (lead, tin, indium, aluminum, and so on) become superconducting at low temperatures. Certain materials, however, do not become superconducting; for example, the best ordinary conductors, such as copper, silver, and gold, never become superconducting no matter how low the temperature gets. Also, the magnetic materials—iron, cobalt, and nickel—don't become superconductors. (Magnetism is inimical to superconductivity.) High field superconductivity was discovered in the early 1960s in the material niobium-tin, and other high field superconductors, including niobium-titanium, and so on, were discovered later.

But the new high temperature materials are quite different from the metals and alloys that become superconducting at lower temperatures. Bednorz and Mueller made their breakthrough discovery (30K) in lanthanum copper oxide with a small amount of strontium impurity. The discovery by Chu and his colleagues at 93K was in the material yttrium-barium copper oxide, and more recently there have been a couple of discoveries of newer materials at even slightly higher temperatures—bismuth-strontium-calcium copper oxide at 107K and thallium-barium-calcium copper oxide at 125K.

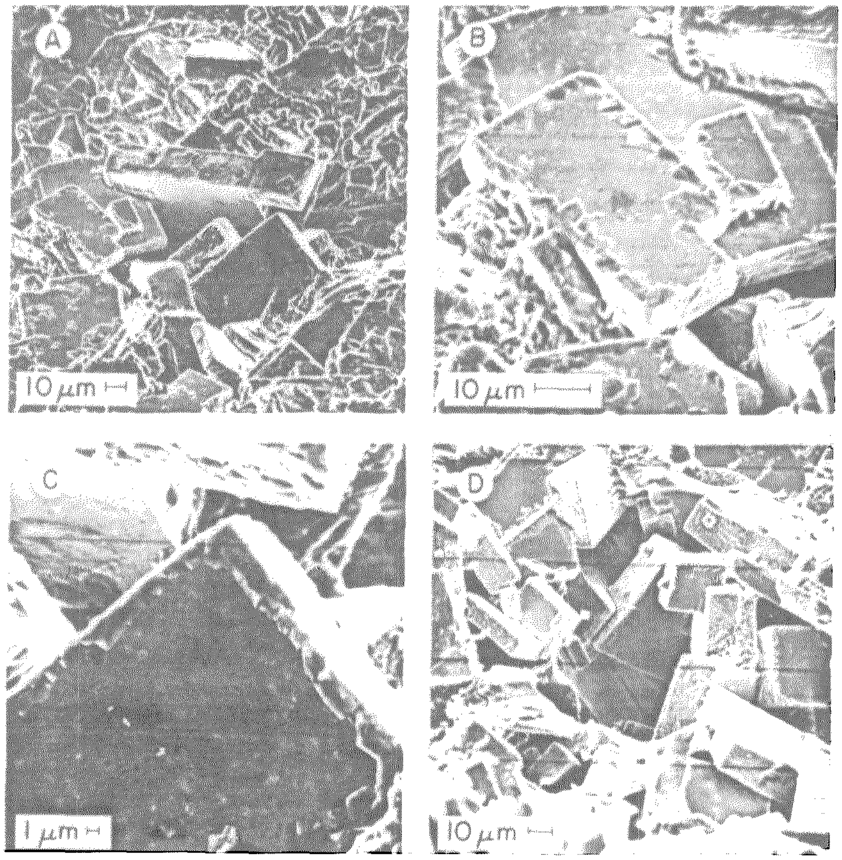
I remember that in the early days of all the excitement about this and of all the speculation about what kinds of materials would be involved in the highest temperature superconductor, Richard Feynman came into my office one day. We discussed the matter a little bit, and he made a prediction. He predicted that the highest temperature superconductor would be based on the element scandium. His first argument was that scandium came from roughly the right part of the periodic table to replace one of the exotic materials in these compounds; and his other argument was that, of all the elements in the entire periodic table, scandium is the only one for which no purpose had ever been found. When I told this to my colleague George Rossman, who is a Caltech professor of mineralogy with 92 personal friends on the periodic table (and that only counts the stable ones), he said that that was completely wrong—there *was* some use for scandium . . . but he couldn't remember what it was. The usefulness of scandium aside, these new superconductors are complicated, composite materials of a type technically called ceramics. What we're dealing with here is pottery.

Within a month of the announcement of Bednorz and Mueller's discovery, we had made our own measurement of the superconductivity of lanthanum-strontium copper oxide in our lab. That's not a tribute to how clever or fast we are, but a tribute to how easy the stuff is to make. It was made in a hundred laboratories around the world as soon as the discovery was announced. We also measured the resistance of the yttrium-barium copper oxide material, which drops to zero at about 90K.

The powdered substances from which these



Yttrium-barium copper oxide is made up of repeated planes of yttrium atoms, planes of barium atoms, and chains and planes of oxygen and copper atoms. The superconductivity takes place in the buckled plane of oxygens and coppers near the bottom; the rest of the structure just serves to keep the planes apart and in the right relation to one another.



These electron micrographs of yttrium-barium copper oxide show crystals stacked together like the ruins of a bombed-out building. The supercurrent has to find ways of tunneling from one piece to another, which is why the resistance doesn't drop sharply to zero. The scale is indicated below each micrograph.

things are made—carbonates and oxides of the materials you want in the final compound—are put into a magnesia crucible. Then the magnesia crucible is put into a porcelain crucible, and the porcelain crucible is put into a quartz tube, from which we can pump out the air and substitute pure oxygen (because these materials like to be made in oxygen). Then the quartz tube is put into an oven and heated up under the control of a little microprocessor at whatever rate we set, until it reacts and the compound is made. So, basically, you just buy these powders from the chemistry stockroom, and you shake and bake, and you have a high temperature superconductor. There's a little more sophistication to it, but that's the basic idea.

In the electron micrograph of the yttrium-barium material at left you can see that the crystals (the rectangular-shaped boulders) are stacked together like the ruins of a bombed-out building. Whatever supercurrent passes through this complicated material is actually finding ways of tunneling from one piece to another. Because of this, the transition temperature doesn't drop sharply as it did in the original superconductors; it just sort of straggles down to zero.

Above is an illustration of what the yttrium material looks like at the atomic level. You can see the repeated planes of yttriums and the chains of oxygens and coppers. The important feature is the buckled plane of oxygens and coppers, which is where the superconductivity takes place. The rest of the structure just keeps those planes apart in the right way and in the right relation to one another so that

Crystals of yttrium-barium copper oxide grown recently are larger than those on the opposite page and appear to be homogeneous single crystals when taken out of the crucible. But reflected polarized light reveals "twinning," or breaking up into pairs of different crystal orientation. Each striation here is a change from one orientation to another. The sample is about .1 mm across. (David Marshall, Rockwell International.)

the superconductivity can occur.

(Incidentally, physicists write the name of the compound thus: yttrium 1, barium 2, copper 3, and call it the 1-2-3 compound. Chemists and people from Los Angeles write the barium first and call it the 2-1-3 compound, because that's the area code.)

So that's what high temperature superconductivity is all about. Why all the excitement? I think that there are a number of reasons for it: the first one is the history of the subject. For 75 years people tried mightily to find materials that would become superconducting at a slightly higher temperature but, after inching it up to 24K, couldn't move it up any more at all for 15 years. Just about everybody gave up on the possibility of getting any higher. There was even a theory that predicted that the highest possible temperature for superconductivity was 35K. Then all of a sudden came the discovery at 30K. Within weeks it was up to 40K, and then came Chu's discovery at 93K, and everyone expected it to be up to room temperature within a month at the most. So this generated a great deal of excitement.

The second reason has to do with a mystery. There are two parts to the mystery. One is that we physicists are taught to believe that there is no such thing as a frictionless surface or a liquid with no viscosity—or, for that matter, a conductor with no resistance. Then superconductivity is discovered and, sure enough, there *is* a conductor with no resistance, but because it exists only under such bizarre conditions of extreme low temperature, perhaps that compensates in some sense for something happening that wasn't supposed to. Now all of a sudden we've got stuff becoming superconducting at 100K and above—maybe even at room temperature; who knows? Somehow it seems wrong; it goes against all our instincts, and so it makes us feel that there is a mystery there to be solved. The second part of the mystery is that we don't understand why it occurs. That's not to say there's no theory. I mentioned Bill Goddard's theory, and there are lots of others—in fact, one theory for every theorist. What is lacking is a consensus; that is, there is no agreement among physicists as to what this is all about.

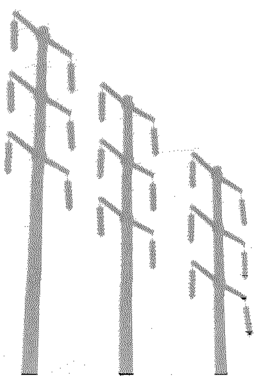
Finally, there is a good deal of excitement because some people suspect that somebody may someday find something to do with this stuff. There may be some practical application for all this. If there is to be any practical application of high temperature superconductivity, it will make use of superconductors' three properties: zero resistance, the ability to create magnetic fields, and tunneling.

When you think of something that conducts electricity with no resistance at all, the first idea that comes to mind is electrical power transmission. Suppose we could make the national power grid out of superconducting material. Wouldn't that be wonderful? In order to think about this seriously, we have to compare three possible types of systems. One is the system we have now; the second is a national power grid of the old-fashioned kind of superconductor; and the third one is a national power grid of high temperature superconductor.

The first thing to think about is the losses in the system. The line losses in our present power grid amount to about 10 percent of all the power generated in the U.S. In other words, the grid we have now is well designed and works very nicely, and a 10-percent loss is not very much. If you could substitute a power grid made entirely of superconductor, one that was completely lossless, you would save that 10 percent. Actually, you might do better than that because, if you were designing from scratch a power grid made of superconducting material with no losses at all, you might design it differently from our present one. Our present one is very efficient because it's designed to use the normal conductors that we actually have. If you have lossless superconductors, you might think of locating the power stations, where the power is generated, farther away from the population centers, where the power is used. Then the power stations could be more radioactive, or more polluting, or whatever. So you might not want to just replace the present system with superconducting materials and leave the stations in place.

A superconducting power system would probably work on direct current, however, not the familiar 60 cycles that we are accustomed to getting when we plug into the wall. This is because superconductors are truly lossless only when the current drifts in one direction, not when it switches directions. The technology does exist for a d.c. power grid, but a.c. is somewhat more convenient. It's a little easier to step up the voltages for long-distance transmission and to step down the voltages at the other end for safe use. So one thing to take into consideration is that a superconducting power grid would be a d.c. system.

Of course, there is the issue of refrigeration, because that's the whole point: The advantage of the high temperature superconductors is that they require less refrigeration than the old-fashioned kind. In the 1960s extensive engineering studies were done to examine the possibility of a superconducting power transmission system. This was long before the discovery of high temperature superconductors, and the system was to be cooled with liquid helium. One of the findings of that study was that the cost of refrigeration was a negligible part of the cost of the system. You don't have to cool the system down from room temperature every day; if you get it cold once, it will stay cold forever. You just have to compensate for the small amount of heat that leaks into a well-insulated system by building refrigerators that tap out a little bit of the power that the system is being used to transmit. So, since refrigeration was never a serious problem, the savings in refrigeration by using high temperature superconductors represents only a fraction of what was already a negligible cost.



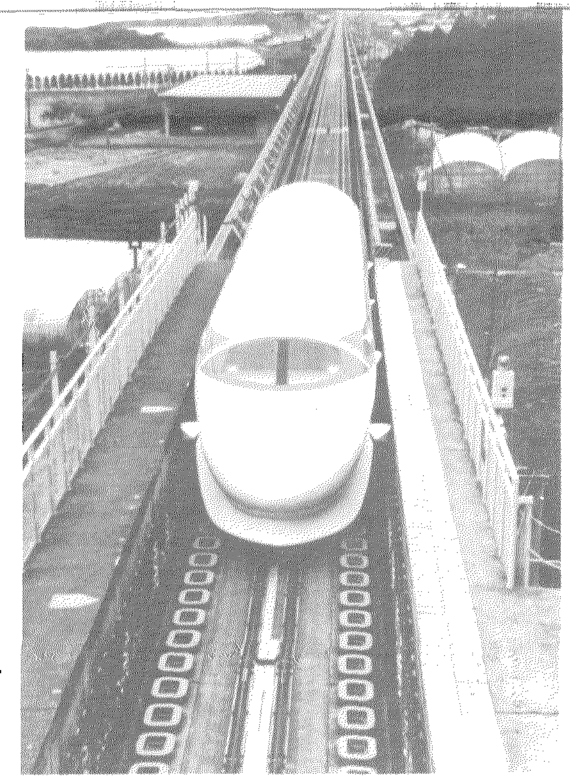
When you think of something that conducts electricity with no resistance at all, the first idea that comes to mind is electrical power transmission.

On the other hand, part of the reason that this system would have been extremely expensive to build in the 1960s was the high cost of the superconducting materials, which are tricky and difficult to fabricate into the kinds of wires that would be needed for a superconducting power transmission system. The new high temperature superconducting materials, even though they are easy to stir up in the lab, seem to be even more difficult to make into wires than the old materials were. So, in a sense, what seems to have happened is that we've solved the wrong problem. Refrigeration was not a problem, and what we've found is a material that doesn't need to be refrigerated as much; materials fabrication was a terrible problem, and what we've found is a material that is more difficult to make. So, all things considered, it doesn't seem to be a big step forward for high power transmission.

There's another problem with these new materials. If you're going to make a practical device out of them, such as a wire that goes into a power transmission system, then you have to be able to pass a very large current through the wire without destroying the superconductivity. In fact, you should be able to pass through about a million amps per square centimeter of cross-sectional area, which is what the old-fashioned superconductors are capable of. The new ones are capable of much less—perhaps a thousand times less current can be passed through without destroying the superconductor. The reason is the nature of the material. The optimists working in the field believe that this is only a temporary problem, and, when we get better at making these materials, it will be solved. For purposes of this article I'm assuming that that's true, because otherwise there's nothing to write about.

In addition, superconducting transmission systems are inherently unstable in the following sense: Just imagine that because of some accident (being struck by lightning, for example), some small portion of the superconducting system suddenly became normal—that is, became for a moment a normal conductor. Instead of cooling down again and becoming superconducting, it would start to get very hot. Essentially, it would become an electric heater—something with a big current passing through it that has electrical resistance. Because it's very hot, it starts to heat up the next section, which then also becomes normal and starts to get very hot, and that heats up the next section, and so on. The net result would be a meltdown of the national power grid, which would be regarded as embarrassing by most engineers. Early engineering designs had a complete backup system of conventional conductors to back up the superconductors, just to avoid that possibility. This was one reason the system would have been so expensive. I see no reason to believe that this would be any different in a high temperature superconducting system.

The second of the properties that we might want to apply is the ability to make high magnetic fields. The unit that most scientists use to measure magnetic fields is the gauss. (Actually, we're not supposed to use gauss any more; we're supposed to use a tesla, but most of us are old-fashioned and still use gauss.) The earth's field has a magnitude of about 0.5 gauss. The saturation field of an iron-core electromagnet is 20,000 gauss, and this was the strongest field



The Japanese MAGLEV train carries superconducting magnets that repel it above the track and propel the train forward. (Photo courtesy of Japan Railways Group.)

So what might we do with very large magnetic fields? My favorite by far is the magnetically levitated superconductor train.

you could get in the laboratory 20 years ago. There was perhaps one laboratory in the world that, by dedicating an enormous facility to that purpose, was able to create a field as high as 100,000 gauss for a scientific experiment. The great discovery in the early sixties of high field superconductors was that some of these can actually be used to create a field of 100,000 gauss, with the consequence that today you can just walk into your friendly neighborhood superconducting magnet store and buy one off the shelf, and you've got 100,000 gauss in your laboratory.

The new superconductors are also of the high field type. Furthermore, since the highest field you can get is related to the highest temperature you can get, the higher the temperature, the higher the field. Nobody knows yet how large a field will be possible with the new superconductors, but it's quite possible that it will be as big as half a million or even a million gauss. So when I say that we may have high fields available in the future, I mean very, very high fields.

So what might we do with very large magnetic fields? My favorite idea by far is the magnetically levitated superconductor train. The track on which this train rides is just an ordinary material—steel or some other ordinary metal, not a superconductor. But inside each car of the train there are powerful superconducting magnets. These magnets get turned on one after the other like the lights on a movie marquee. These fool the track into thinking that magnets are running backwards along the track. The track doesn't like that; it resists the motion of the magnets, and that gives the train an impulse to move forward. The track also repels the moving magnets, and so the whole train lifts up off the track by a few centimeters and rockets forward at a speed of 500 kilometers per hour. (That's an inch off the track at 300 miles per hour if you live in the U.S.)

If you've ever been in a truly high-speed train, such as the TGV in France or the Tokyo-Osaka bullet train in Japan, then you know how much fun it is to ride along in a train at ground level at 130 miles per hour. This thing will go more than twice that fast. It will put Disneyland out of business. If they ever build it, I will certainly be the first in line to buy a ticket, but I don't think we should start getting in line quite yet. There's no problem with the technology; the Japanese have had a few-kilometer, test-bed track running for many years to take VIPs on little rides to show them that it works. But there are a number of problems with building it, principally the expense. Among other things, the track must be very straight and very well maintained. When you're traveling at 300 miles per hour one inch off the track, you don't want any bumps and you don't want any hairpin curves. The capital investment for buying the right-of-way and building and maintaining the track and so on would be enormous, and because we already have ways of getting from one place to another—cars, airplanes, and so on—there's no driving economic force to build this thing.

Also, there's some concern about having 100,000-gauss magnets on a public conveyance. There's not a shred of evidence that large mag-

In projects such as a hypothetical manned mission to Mars, powerful magnets on board a spacecraft might be able to brake and steer it through the plasma created as the spacecraft enters the planet's atmosphere.

netic fields are dangerous to your health, but there's also not a shred of evidence that they aren't.

There are a number of other applications of high magnetic fields that are possible from these materials. One of them is the so-called superconducting supercollider. The SSC is to be the next generation of high energy particle accelerators, and it's barely small enough to fit in one state. Perhaps that's why Texas was picked as the site. As far as the designers and proponents of this $4.5 billion machine are concerned, the discovery of high temperature superconductivity was an acute embarrassment. The people who would like to slow down that very political project say, "Why build it now with obsolete technology? Why not just wait 10 years until the high temperature superconductors are ready and build it with them?" The last thing the proponents want to be told is to wait 10 years, so the plan is to build the SSC not with high temperature superconductors but with the old-fashioned low temperature kind.

Nuclear fusion, the promise of limitless energy from sea water or something, has been just around the corner ever since World War II and is still just around the corner. One of the schemes for performing this feat is called magnetic confinement. The plasma, the ionized material in which the fusion would take place, is contained in a powerful, shaped magnetic field, and it's conceivable that the magnetic fields available with the new high temperature superconductors could be strong enough to perform that trick and create magnetic confinement fusion. But there are some problems with that. One is that the new materials appear to be especially sensitive to radiation damage, and that's a property that you don't want to have in something that's going to be part of a nuclear reactor. The other problem is that magnetic confinement is no longer the system of choice. As a matter of fact, I don't think there is any major research group in the world now working on magnetic confinement. It's just not the way the problem is being approached these days.

If high temperature superconductivity is going to have an application, one of the most likely places is in space. For one thing, economics in space is different from economics on earth. If a communication satellite, for instance, costs $100 million to build, and you can save a little weight by using a component that costs $1,000 to replace a heavier component that costs $10, you do it. Weight is everything and cost means almost nothing. Also, there's a possibility that in a well-designed spacecraft, the ambient temperature will be low enough so that these materials will be superconducting without any active refrigeration at all.

Among the ideas that have been suggested for space applications is something called magnetohydrodynamic braking. When a spacecraft, a shuttle for example, reenters the atmosphere, there's so much heating that it creates a plasma (it ionizes the air through which it's passing), so what it's really doing is riding through a conducting medium. If you had a powerful magnet on board causing electric currents to flow through that medium, you might be able to

If high temperature superconductivity is going to have an application, one of the most likely places is in space.

direct those currents in such a way as to brake the craft and even guide its trajectory. When this idea was studied during the 1960s and 1970s, it was finally abandoned because there were no magnets strong enough to do the job. But it's just conceivable that these new materials will make magnets available that are strong enough.

With very powerful magnets you can accelerate charged particles, and it might be possible to come up with some exotic schemes for propulsion using these accelerated particles. People in the space business are always interested in exotic new schemes for propulsion. It's even conceivable that you might want to make ordinary electrical components such as motors and generators out of high temperature superconductors simply because this would substitute a lightweight ceramic coil for a heavy iron permanent magnet. Saving on weight makes the idea attractive. These are only a few of the possibilities; there is much potential application in space.

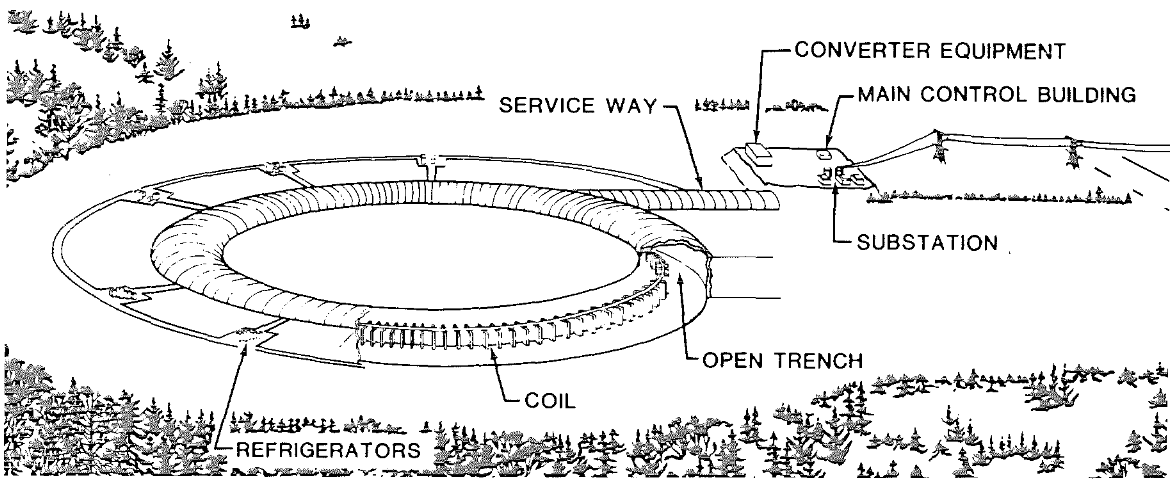
Finally, there's the possibility of using the high magnetic field properties of high temperature superconductors for energy storage. When the discovery was first announced, I started reading about it in the newspaper like everyone else. The newspapers said that all of this is going to change the way we live; we're going to have superconducting transmission lines, and magnetically levitated trains, and all sorts of things. And as I looked down the list of those other things, the one that seemed the least likely of all was energy storage. So I decided to look into it to see what that was all about. It turns out that it's not the least likely at all, and a project—SMES (for superconducting magnetic energy storage)—is already being planned by the Defense Nuclear Agency.

This project envisions the capability of releasing either 0.4 to 1 gigawatts (billion watts) of energy for a period of 100 seconds, or 10 to 25 megawatts for a period of 2 to 3 hours. You don't have to be a KGB agent to figure out what the first one is for; it's for Star Wars. The second one is to even out the peaks and valleys in the demand on the power grid for electric energy during the day and night. During the night, when people aren't using so much energy, you store it up in this thing, and during the day you release it for use.

An elementary calculation tells us that, if you're going to build this thing out of the old-fashioned high field superconductors and store the energy in a field of 100,000 gauss, then what you need is 2,500 cubic meters of high field volume. That's about an eighth of the volume of Beckman Auditorium. So we're not talking about the Grand Coulee Dam here, but we are talking about a fairly substantial engineering project, once you consider the coils and refrigerators and all the other stuff to go with them. I have seen the plans for one of these proposals, and the idea is to make a superconducting coil in the shape of a doughnut, 1 kilometer in diameter and buried underground.

The plan is to build it using conventional superconductors. Would there be an advantage in using these new high temperature superconductors? There is always a small savings to be had in the refrigeration. But as in all other big engineering projects, because we're really awfully good at making liquid helium and refrigerating things at those temperatures, the refrigeration is probably not a very serious problem. The question is, I believe, could we take advantage of the fact that we can make much stronger magnetic fields for the purpose of energy storage?

It turns out that the energy stored in a given volume is proportional to the square of the magnetic field. So if you can make a field 10 times stronger, which you may very well be able to do, you can store 100 times as much energy in the same volume. Or, conversely, you can store the same amount of energy in 100 times less volume. There's obviously a great advantage in doing that, but there's also a rather serious problem. The problem is that, if you have a coil carrying a current that creates the magnetic field, the field applies a force to the current that creates it. This is an outward force on the coil, as if it were trying to contain material under very



Bechtel's plan for a 5,000-megawatt SMES (superconducting magnetic energy storage) system places underground a superconducting coil in the shape of a doughnut 1 kilometer in diameter. (Drawing courtesy of Robert Lloyd, Bechtel Corp., and *Supercurrents* magazine.)

high pressure. That magnetic pressure, like the energy stored per unit volume, is proportional to the square of the field. So the magnetic pressure would also go up by a factor of 100 if you increased the energy density by a factor of 100. At 100,000 gauss the magnetic pressure in the system is about 400 times atmospheric pressure, or 400 atmospheres, which is a nice, well-known engineering pressure. It's the kind you might expect in a steam boiler, which engineers know how to handle with no problem. If we try to go up a factor of 10 in pressure from that—not 100, but just 10—we're talking about the kind of pressure generated in the barrel of a big artillery piece when it fires. That kind of pressure is contained for very short times by using special pre-stressed steel that is always under compression inside and not outside, so that the explosion just evens out the stresses and the barrel doesn't blow up. If you go up to 100 times this pressure, you're talking about a pressure that's never been contained before. If you ask engineers whether it's possible to contain that much pressure, they're reluctant to say that it's absolutely impossible but they will allow that it's never been done. And it's absolutely never been done using pottery.

Another problem associated with magnetic fields is a phenomenon you're familiar with if you've ever tried to open the switch on a circuit containing a big electromagnet. What happens is that the switch sparks over because the magnet doesn't like to be turned off quickly. If you do that with a very big magnetic field, the spark can be so violent that it vaporizes the switch itself. Since this would be the biggest magnetic field ever created, it seemed to me that there might just be some switching problems associated with such a thing. To find out whether or not that's true, I called up a friend of mine who is a knowledgeable and experienced power engineer and described the problem to him to get his opinion. I can't put in print exactly what he said, because these engineers can be pretty salty, but the gist of it was that "it's likely to be a challenging task."

The third property of high temperature superconductors is tunneling. If I put two pieces of superconductor very close together, some superconductivity can leak from one to the other, but the amount is acutely sensitive to such things in the environment as very weak magnetic fields or electromagnetic radiation. That means that you can use this property of tunneling as a detector of those things. Detecting infrared radiation is the one thing that superconductivity is now regularly used for outside the scientific laboratory. For example, in orbiting satellites superconducting tunnel junction detectors are used to detect infrared radiation, either in devices that look upward toward the sky for purposes of astronomy or downward toward the earth for purposes that are usually military secrets. (But not always—see page 24.)

The fact that the conducting state of one of these junctions is sensitive to small magnetic fields means that you can use small magnetic fields to manipulate it—to turn it on or off. This makes it possible to use these junctions for electronic logic and memory devices. In other

Human history starts with the Stone Age, when pottery was invented. It goes on to the Bronze Age, the Iron Age, modern times, and finally to the discovery of high temperature superconductivity —which is the second coming of the age of pottery.

words, it's possible to build a superconducting computer instead of the kinds we have now, which are based on semiconductors.

IBM, AT&T, and Sperry all abandoned their superconducting computer research projects in 1983. The reason was not that the superconducting technology was not advancing; it was. The reason was that the semiconducting technology was advancing much faster, and it seemed hopeless for superconductivity ever to catch up. The problem with superconductivity was not refrigeration; it was material fabrication. And, as I mentioned earlier, the fabrication problem with these new superconductors is even worse than with the old ones. In the long run, however, the superconducting computer will ultimately be the computer of choice. The reason is simple: The whole game in computers is to make them fast, and in order to make them fast, you have to make them small, because it takes time for the signal to travel any distance. So you want to pack the elements of the computer as tightly together as you can. When you pack a lot of semiconducting elements together, as is done in present computers, each of the elements is generating heat, because it's an electrical device, and devices using electrical conductors generate heat. When they're all packed together, they generate a lot of heat, and when too many of them are packed too closely together, the computer melts and that's no good. That's the ultimate physical limitation on how small, and therefore how fast, a computer can be. That limitation does not apply to superconducting circuit elements, because they don't dissipate heat the way semiconductor circuit elements do. So in the long run the superconducting computer will win—but it might take a very long time.

Let me end with a brief summary of human history. It starts with the Stone Age, when pottery was invented. It goes on to the Bronze Age, the Iron Age, modern times, and finally to the discovery of high temperature superconductivity —which is the second coming of the age of pottery.

This, of course, reminds me of a little story about the Second Coming and the Pope. I hope no one finds this offensive; I've spent quite a bit of time in Italy and consider the Pope to be sort of a friendly neighbor. The story takes place in the Pope's Vatican chambers, where he's talking with two of his assistants, who are both monsignors. One of the assistants notices a strange light coming from the window, so he goes to the window to investigate, and he sees the Second Coming. But he doesn't believe it at first because he's trained to be skeptical—not to accept things on first sight but to think about things and analyze them. So he does all those things and finally decides there's absolutely no doubt about it—what he's seeing is the Second Coming.

So he calls his colleague over to the window, and he looks out and says, "You're absolutely right. There's no doubt about it. This is the Second Coming." So the two of them spin around, fall to their knees, and say, "Your Holiness, it's the Second Coming."

The Pope races to his desk, sits down, and starts typing madly on his typewriter. One of the monsignors asks, "Your Holiness, what are you doing?" And the Pope says, "Well, I don't know about you, but I want to look busy."

I don't know whether high temperature superconductivity is really the second coming. But I do know that a lot of people are looking busy. □

This article was adapted from David Goodstein's Watson Lecture, which played to a standing-room-only crowd in October. Goodstein is no newcomer to show business; the prizewinning TV physics series, "The Mechanical Universe," in which he played a leading role, grew out of the witty freshman physics course Goodstein taught at Caltech from 1979 to 1982, a course that Richard Feynman had already made a legend (and a tough act to follow). Goodstein, whose BS is from Brooklyn College and PhD from the University of Washington, has been a member of the Caltech faculty since 1966. He is now vice provost and professor of physics and applied physics.

Origami: Complexity Increasing

by Robert J. Lang

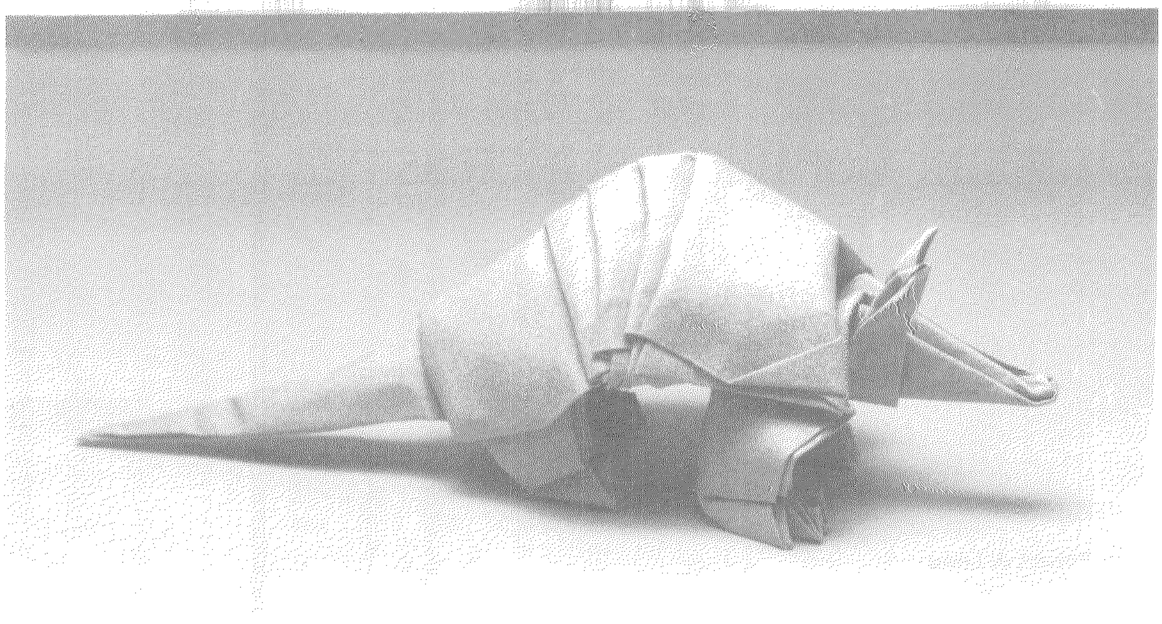
Lang's "Black Forest Cuckoo Clock" is made from a single sheet of paper—a 10:1 rectangle. The model contains about 200 meters of creases and takes 4 to 6 hours to fold.

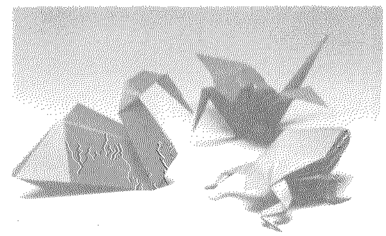
Sitting on the sill of a window at the Jet Propulsion Laboratory are three small figures. They look somewhat incongruous among the piles of journals, computer diskettes, books, and glassware scattered about; they are a man playing a violin, a man playing a string bass, and a man playing a grand piano. Each has been folded from a single sheet of paper. They are examples of an art called origami, which is a Japanese word meaning "folded paper." The art originated in Japan, where it has been an integral part of religious ceremonies for some 1,500 years. There, folded paper streamers, called *gohei*, and paper human figures, called *katashiro*, are placed in Shinto shrines to receive the temple deity. The three instrumentalists did not originate in Japan, however.

They are a result of the peculiar fascination origami has for at least one scientist, in this case, myself. The appeal is due to many things. Origami is a game; it includes topology, it requires visualization. There are pleasant symmetries involved in the transformation of a square of paper into a bird or flower, a transformation that may be very elegant. Within origami, we see the apparent creation of something from nothing, order from disorder, entropy reversed. These aspects of paperfolding have attracted thousands of people to the art in recent years. They have inspired explorations into many of the mathematical and physical properties of folded paper. They have drawn me into origami and held my interest for some 20 years, and they are ultimately responsible for the three instrumentalists I designed that now sit above my desk.

The trail that ends at a physicist's window sill began in China around the year 100 A.D. with the invention of paper. By the 4th century paper had traveled to Japan; in the centuries that followed, the secrets of its manufacture spread around the world. Somewhere along the way, someone discovered that paper could be folded into a variety of interesting shapes. This pastime was established in Japan by 600 A.D., and was called origami, from the Japanese words *ori*, meaning "folded," and *kami*, meaning "paper." It was, and still is, a folk art. Mothers teach simple folded designs to daughters as they have done over the centuries. The traditional origami designs encompass some 100 simple toys, abstract shapes, and representations of birds, animals, and flowers.

That description of the art would have been accurate 50 years ago. At that time, all of the different origami designs in the world could have been cataloged on a single typed sheet of paper, had anyone the inclination to do so. No model would have run over about 10 or 20 steps. Most could be folded in a few minutes, even by a novice. This is no longer the case. Today, in books, in journals, and in personal archives, the number of recorded origami designs runs well into the thousands, and many of the most sophisticated designs have more than a hundred steps and take over an hour for an experienced folder to produce. The growth in the number of models owes its existence to a burgeoning worldwide interest in paperfolding, but the growth in the complexity of designs is due to something else: 1,500 years after its invention,





Traditional Japanese origami designs included simple representations of birds and animals. More complex animal designs, such as Lang's "Armadillo" (top) evolved only in the last 25 years.

origami was discovered by science.

Science is attracted to a challenge, and the challenge of origami lies in its rules. Simply put, origami is the art of folding uncut squares of paper into decorative objects. That is the modern definition. Many traditional Japanese designs, both ceremonial and recreational, were quite liberal with cuts, however. Origami designs from the *Kayaragusa*, a collection of 49 examples of ceremonial and recreational origami dating from 1797, included many examples with cuts, and many other traditional Japanese designs use multiple sheets of paper. Modern folders are more conservative with cuts, more liberal with shapes. Some use rectangles, some triangles; some allow cuts that don't actually remove paper; others allow more than one sheet but no cutting at all. There is no agreement among the world practitioners on absolute rules about multiple pieces, or unusual shapes, or cutting, but there is widespread agreement that there is a purest form of origami, which is: one square, no cuts.

Cuts or not, for 1,500 years, the origami repertoire remained essentially static. Part of this lay in the way it was passed on. Word of mouth does not allow complex designs to survive more than a generation or two. Then, too, original designs were not encouraged. When, in the 1920s, a metalworker named Akira Yoshizawa began to invent new designs, he was not supported in his work. Fortunately, he persevered. Yoshizawa, now considered the father of modern origami, publicized his own work through exhibitions and books. Through his efforts, the art caught on around the world, and an era of new designs began that continues today. The designs and designers multiplied. English-language books began to be published, further accelerating the spread of knowledge. Then in the 1970s, a new breed of paperfolder began to appear. Mathematicians, scientists, and engineers were attracted to origami and began to approach it in a new way: not as a form of artistic expression, but as a source of technical challenge.

Before this time, the typical way for a person to invent a new design was to fold one of a handful of basic folds, or "bases," and play with it until it began to bear a resemblance to something. Throughout the first three-quarters of the 20th century, origami grew by trial and error. Unsuccessful attempts were discarded, successful ones recorded. The number of designs grew, but the sophistication of designs remained relatively steady.

The design of an origami model may be broken down into two parts; folding the "base," and folding "details." A base is a regular geometric shape that has a structure similar to that of the subject, although it may appear to bear very little resemblance to the subject. The detail folds, on the other hand, are those folds that transform the appearance of the base into the final model. The design of a base must take into account the entire sheet of paper. All the parts of a base are linked together and cannot be altered without affecting the rest of the paper. Detail folds, on the other hand, usually affect only a small part of the paper. These are the folds that turn a flap into a leg, a wing, or a head. Converting a base

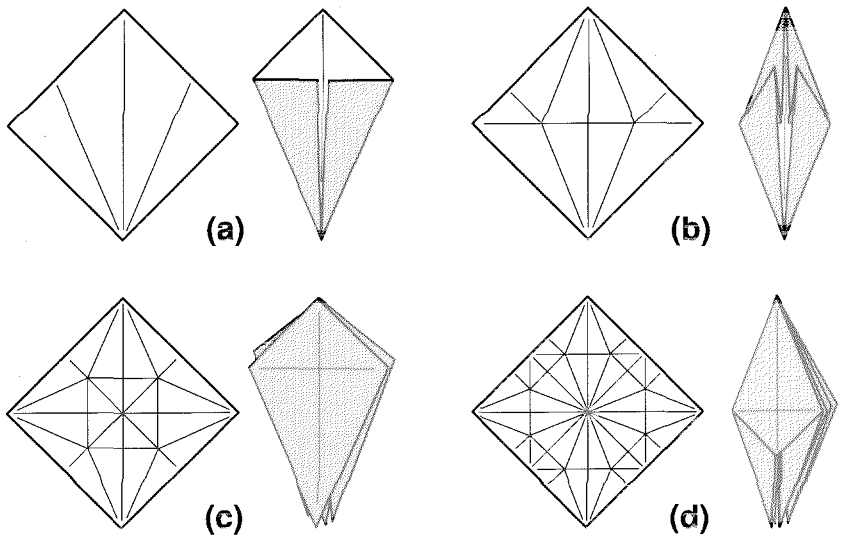


Figure 1: (right) The "classic" origami bases and their *crease patterns:* (a) Kite Base; (b) Fish Base; (c) Bird Base; (d) Frog Base. (Not to the same scale.)

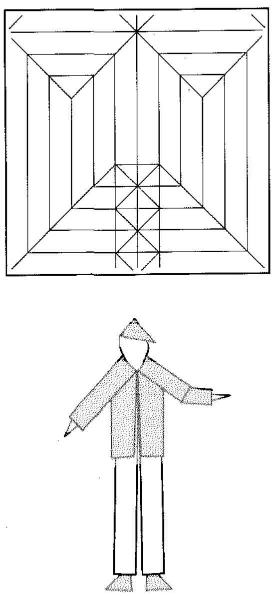


Figure 2: (below) Crease pattern and model of Neal Elias's "Man in Black and White." All creases in the base are either vertical, horizontal, or at 45°.

into an animal using detail folds requires tactical thinking. Developing the base to begin with requires strategy.

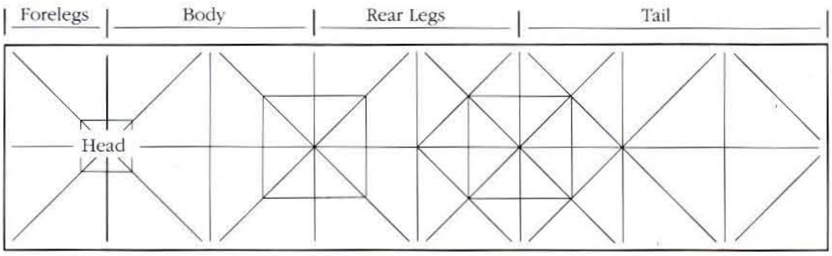
By the mid-1960s, four bases were in widespread use (Figure 1); in English-speaking countries, they are called the Kite Base, the Fish Base, the Bird Base, and the Frog Base. (In addition, there are two other shapes commonly called bases—the Preliminary Base and the Waterbomb Base—that are precursors to the Bird and Frog bases.) All four, dubbed the "classic" bases, were known to the Japanese for over a hundred years before origami made it to the West.

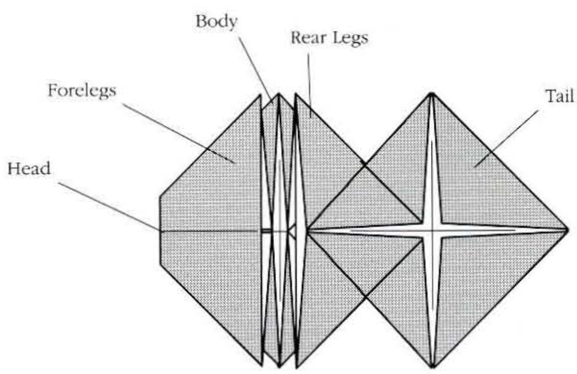
Major points on a base get turned into major appendages of a final model. The Kite, Fish, Bird, and Frog bases have, respectively, one, two, four, and five large points and one, two, one, and four smaller points. To fold an animal, you need to start with a base that has the same number of points as the animal has appendages. A simple fish has two large points (head and tail) and two small ones (pectoral fins), which is why the Fish Base is so appropriate and so named. The average land-dwelling vertebrate has five major points (four legs and a head), which pretty much stipulates the Frog Base and rules out a tail. The point on the Frog Base that is in a position to form a head is thick and difficult to work with, however. One of the four points of a Bird Base would be easier. But to use a Bird Base to fold a four-legged animal, you would have to represent two of the legs (usually the rear legs) with a single point. In the 1950s and 1960s, there were a lot of three-legged origami animals running around.

Not only were the four classic bases widely known by the mid-1960s, but their shortcomings were known as well. Brilliant advances in detail folds had been developed, techniques to give the appearance of separate legs, but no actual legs were forthcoming. Clever use of different colors (from opposite sides of the paper) gave the appearance of multiple subjects from the same sheet of paper, provided those subjects had no long appendages. There were isolated successes—an elephant with legs, ears, and tusks, made by folding the corners of a square to the center before folding a Bird Base—but in general, no systematic method existed for making complex subjects.

In 1963, an amateur magician and an engineer broke from the traditional bases. Neal Elias and Fred Rohm began their explorations on a challenge: to make a working Jack-in-the-box. They hit upon the technique of limiting all creases in the base to a series of parallel creases that divide the paper in one direction; a set perpendicular to those; and a set at 45° to the others (Figure 2). With the paper so creased, it may be collapsed on these creases into a variety of regular shapes with varying numbers of points and flaps. By this means, far more complicated structures were possible than with conventional folding techniques. Because the paper is initially pleated and intermediate steps in the formation of a base are assemblies of boxes, the techniques are collectively referred to as box-pleating.

Box-pleating may be used for models made from squares, but the techniques are especially





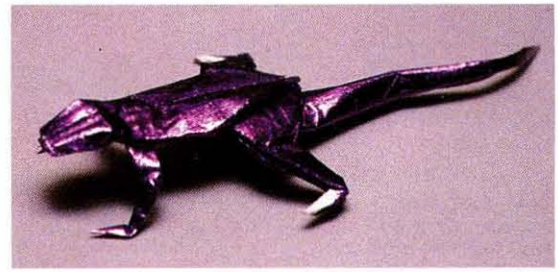


Figure 3: Crease pattern, base, and finished model of Max Hulme's "Lizard," a box- pleated design from a 4:1 rectangle. Below, Neal Elias's box-pleated masterpiece, "Llopio's Moment of Truth."

suited to rectangles. To design a new model, you may imagine yourself initially in possession of an infinitely long rectangle. You divide it up along the short side into twelfths or sixteenths. Each division is defined as one "unit." Beginning at one end of the rectangle, lay out the parts of the subject along the rectangle, allocating appropriate amounts of paper for each appendage (for example, a pair of points three units long requires six units of paper); when you've allocated all the parts, snip off the excess, and you have your starting rectangle. Crease on all the horizontal and vertical divisions; crease the diagonals; then starting from one end, collapse the paper on the pleats to form a base. Figure 3 shows the process for a lizard.

Some of the most fantastic structures origami has yet produced have resulted from box-pleating; a working Jack-in-the-box (several, actually), a steam locomotive, cars, trains, and planes. While the rectilinear lines of a box-pleated model are well-suited for man-made objects, and indeed, most box-pleated models are inanimate, there are a host of animals made using box-pleating, including one of the earliest: Elias's "Llopio's Moment of Truth," in which a bull, bullfighter, and cape are all folded from a single sheet (left). Box-pleated designs can get extremely involved. One of the most complex box-pleated models is my "Black Forest Cuckoo Clock" (shown on page 16); it is made from a 10:1 rectangle, contains about 200 meters of creases in a model 40 cm high, and takes 4 to 6 hours to fold.

Box-pleating brought complexity to rectangles, but the square remained inviolate until the

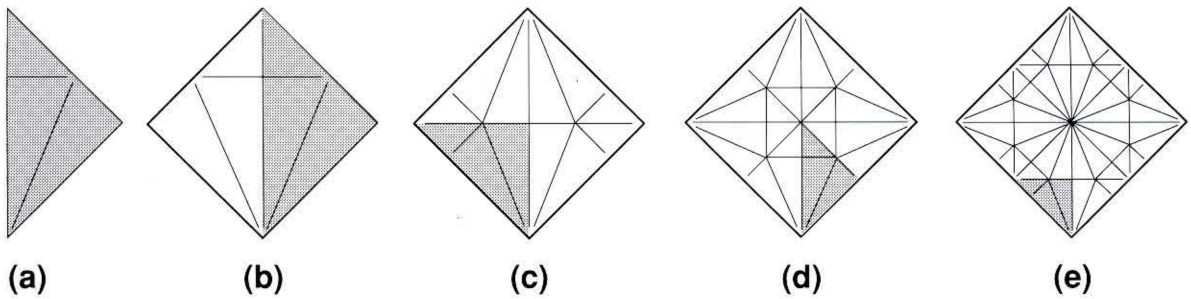


Figure 4: The basic shapes of technical folding. The triangle in (a) is found in the Kite Base (b), Fish Base (c), Bird Base (d), and Frog Base (e) in successively smaller sizes.

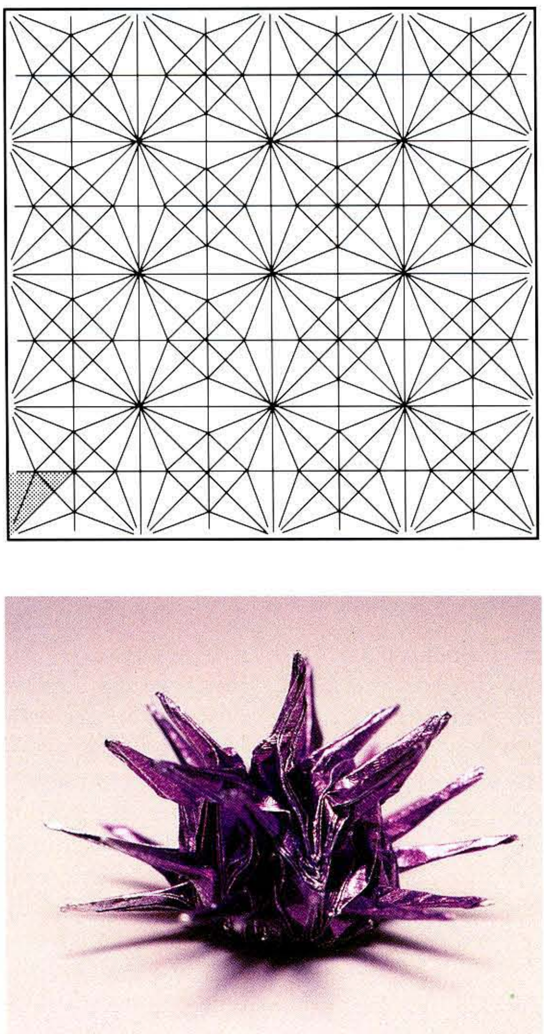


Figure 5: Crease pattern and model of Lang's "Sea Urchin," which contains 128 repetitions of the basic shape.

late 1970s and 1980s, when three Americans and a Japanese, working independently, hit upon a set of techniques and symmetries suitable for folding complex models from squares. They were John Montroll, a mathematician and computer scientist; Peter Engel, a science writer and architect; Jun Maekawa, a nuclear physicist; and myself. The techniques we developed have come to be called "technical" folding: origami composed of equal parts art and engineering.

The fundamentals of technical folding spring from the same geometric patterns present in the classic bases. The basic principle is quite simple. In the four classic bases, the same shape appears in multiples of two, four, eight, and sixteen. Technical folding simply expands upon that trend.

This reappearing shape is an isosceles right triangle with two creases in it; Figure 4 shows how it appears in each base in successively smaller sizes. Two of the basic triangles can be assembled into a square, yielding the Kite Base. Four give the Fish Base. Eight give the Bird Base. Sixteen give the Frog Base. The pattern is clear. We could easily go to thirty-two, in which case we would end up with a Blintzed Bird Base, the source of the previously mentioned elephant. As in box-pleated bases, the base may be formed from the creased square by collapsing the crease pattern on folds in alternate directions. Every source of radial creases becomes a point of the base. The more radial clusters of creases there are, the more appendages the final model may have. The crease pattern for my sea urchin (Figure 5), which incorporates 128 copies of this triangle, contains 25 equal-length points.

Figure 7: (right) Combining two A triangles and two B triangles gives a 1:$\sqrt{2}$ rectangle. Four of these gives another 1:$\sqrt{2}$ rectangle. Two of these, plus two Bird Bases gives the diagonal crease pattern shown, which is used in Engel's "Alligator," Montroll's "Shark," Maekawa's "Kangaroo," and Lang's "Triceratops."

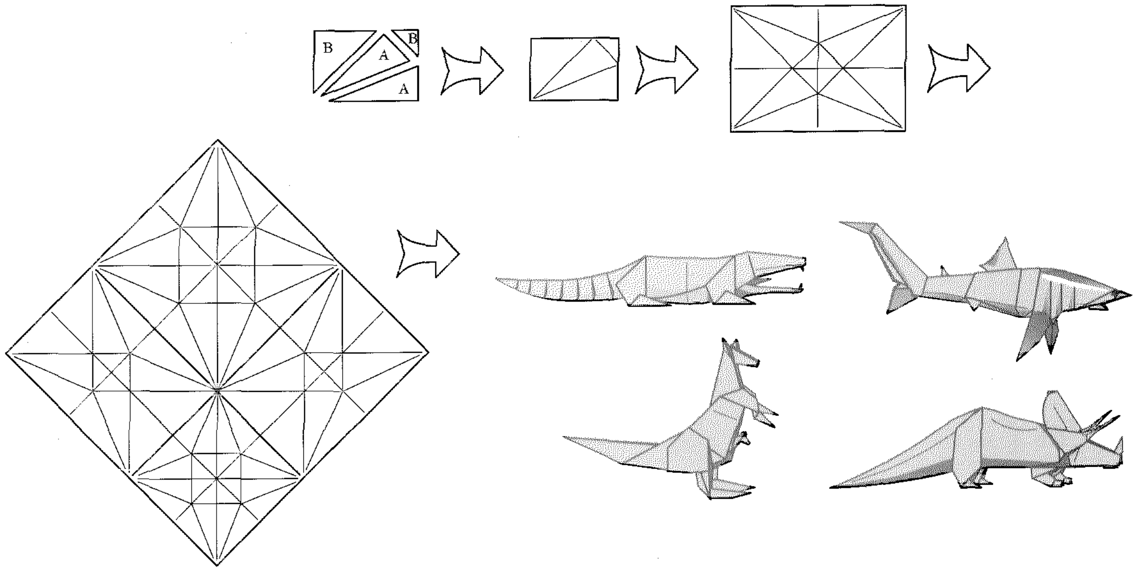
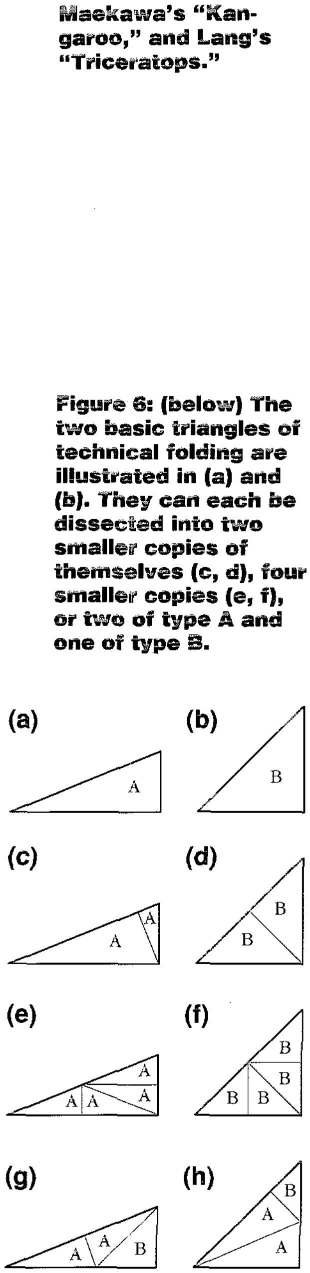


Figure 6: (below) The two basic triangles of technical folding are illustrated in (a) and (b). They can each be dissected into two smaller copies of themselves (c, d), four smaller copies (e, f), or two of type A and one of type B.



This triangle is not the most fundamental unit, however. It is composed of three smaller triangles: two identical scalene (1:1+$\sqrt{2}$) right triangles and one isosceles (1:1) right triangle that is a smaller copy of the original. We will call them type A and B triangles, respectively. These two triangles appear over and over in different sizes throughout the crease patterns in figures 4 and 5. They are the true building blocks of technical folding.

These two triangles have some interesting properties. They can each be dissected into two or four smaller copies of themselves, as shown in Figure 6(c-f). This property is not particularly unique, because any right triangle can be similarly dissected. What is interesting are the dissections shown in Figure 6(g-h); each triangle can be dissected into two triangles of type A and one of type B. By selectively applying these dissections to simple crease patterns, it is possible to get more complicated crease patterns, yielding more and more points.

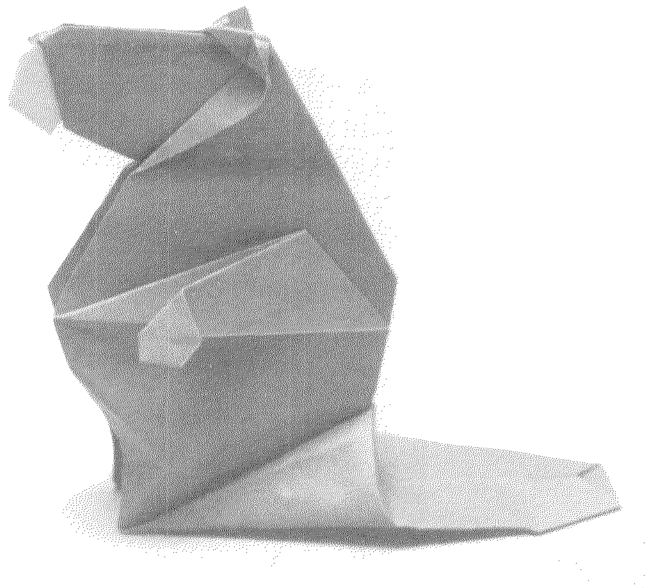
Alternatively, rather than breaking up a square into smaller and smaller triangles, we can assemble A and B triangles into larger and larger geometric patterns. By this means, we can create higher-order building blocks with which to generate bases. For example, two type As and two type Bs can be assembled into a 1:$\sqrt{2}$ rectangle. Four of these rectangles can be assembled into another 1:$\sqrt{2}$ rectangle with two axes of symmetry. Two of these rectangles can be combined with two Bird Bases to give the crease pattern in Figure 7, which yielded an alligator for Peter Engel, a shark for John Montroll, a kangaroo for Jun Maekawa, and a Triceratops for myself.

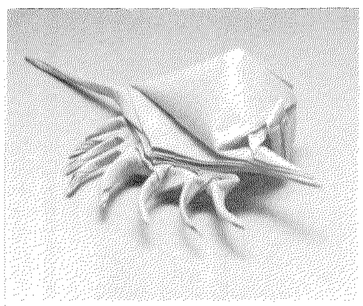
By combining ever larger assemblies of the basic modules, we can create ever more complicated bases, leading to ever more complex models. As we explore the different combinations of triangles, we can develop "libraries" of higher-order crease patterns; the 1:$\sqrt{2}$ rectangle is an example of one. The problem of designing an origami base thereby reduces to that of tiling a square with A and B triangles (or higher-order combinations of such) so that we get a radial pattern of creases for each appendage of the model.

The set of patterns possible with this set of triangles is fundamentally richer than the set possible with box pleating. The reason is that we have two basically different shapes—types A and B—with which to construct initial crease patterns. All box pleating crease patterns, by contrast, can be produced using a single shape: the type B triangle. Two shapes give more possibilities for tiling and, therefore, more possible designs than one. The patterns possible with these two basic shapes are a rich trove of origami designs that is only beginning to be discovered.

As the technology to design origami models has improved, there has been a shift in the subjects that are folded toward the more challenging end of the spectrum. As is often the case in the sciences, we find technology in search of a problem to solve. The ability to fold multipointed creations cries out for a multipointed subject. Insects, once considered all but impossible, are now commonplace. Legs are no longer a sign of a realistic arthropod; mandibles are. The ulti-

With care, you should end up with your very own Caltech beaver.





Lang's "Murex."

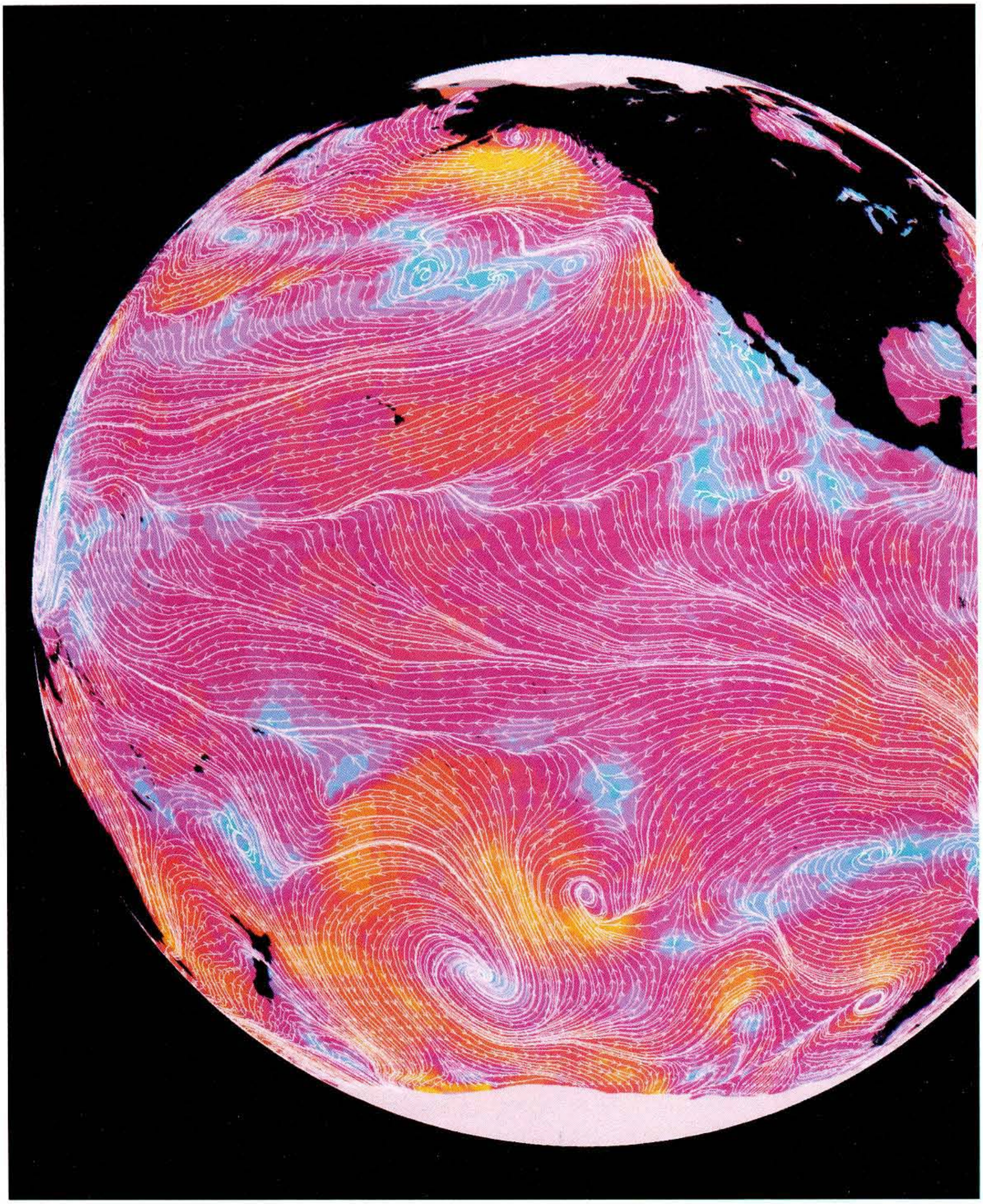
mate challenge to a designer was once thought to be a lobster, with its eight long, skinny legs, two split claws, antennae and segmented tail. In 1970, lobsters didn't exist. In 1988, there are recognizable species.

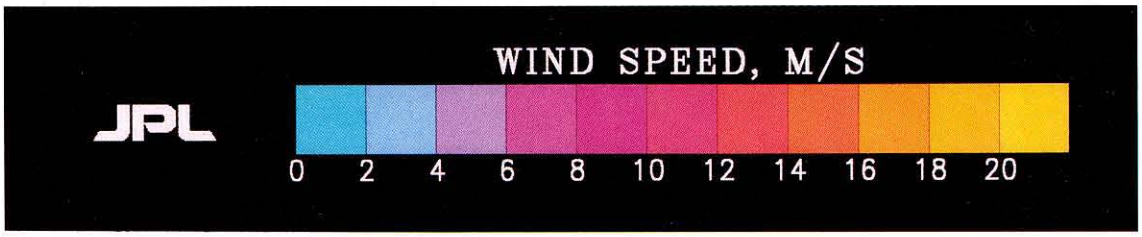
Origami as art and as science

Science, via geometry and tesselation, has brought origami into the modern age. We may ask, what can origami bring to science? Origami has always enjoyed an interest among recreational mathematicians, and achieved a prominent appearance in Martin Gardner's "Mathematical Games" column in *Scientific American* magazine in 1960. It made it to the world of engineering in 1969, when Jon Myers, a scientist at Hughes Research Labs, published an article showing how origami could be used to simulate optical systems. Computing succumbed to the appeal of folded paper when, in 1971, Arthur Appel programmed an IBM System 360 computer to print out simple geometric configurations at the rate of more than a hundred a minute. Ninety percent were considered unsuccessful, but it raises an interesting question: could a computer someday design a model deemed superior to that designed by man? Since so much of the process of design is geometric, the prospect is not as outrageous as it may seem. Still, technical folding can only take us so far. The architects of technical folding have begun to lay the groundwork for systematic design. To our great surprise, origami, the ancient Eastern art, may be a science after all.

Accompanying this article are a piece of paper and instructions for a simple origami model. Carefully cut the square out on the black lines and follow the attached step-by-step directions. The instructions are written for someone with no prior experience in origami, but the following tips may help. Folds occur on dashed or dot-dot-dash lines. If the line is dashed, fold the paper toward you; if it is a dot-dot-dash line, fold it away from you. As you work through each step, look at the drawing; read the text; look ahead to the next drawing to see what the result should be; then fold as directed. With care, you should end up with your very own Caltech beaver. □

Robert Lang, an internationally known expert on origami, has been folding paper figures since the age of six. His book, The Complete Book of Origami *(Dover Publications) is scheduled to appear in early January, and another work,* Origami Zoo *(co-authored with Stephen Weiss), is in progress. A Caltech alumnus, Lang received his BS in electrical engineering in 1982 and PhD in applied physics in 1986 (with an MS from Stanford in between). He's currently employed at the Jet Propulsion Laboratory in the Photonics Group, Advanced Electronic Materials and Devices Section, where he works with lasers, not paper.*




WIND SPEED, M/S
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Observing Earth From Space: The Greenhouse Effect

Surface winds on September 17, 1978, as measured by NASA's SEASAT scatterometer. Arrows show wind direction, colors indicate speed. Converging white lines generally correspond to cloud bands in weather photo opposite. Storms (counterclockwise swirls in the Northern Hemisphere, clockwise in the Southern) are visible off Alaska, Mexico, Chile, and in the mid–South Pacific. High-pressure regions (which swirl opposite to storms in each hemisphere) appear between Alaska and Hawaii, and north and east of New Zealand. Data from 7 orbits spanning 12 hours were interpolated and time-corrected to show the entire Pacific at 1800 hours Greenwich Mean Time. The meteorological analysis needed to produce this image was performed jointly by JPL, UCLA, and AES-Canada.

"Most scientists have always looked at the earth, our planet, through the eyes of their particular discipline—geology, oceanography, biology, or whatever," says Moustafa T. Chahine, Chief Scientist at Caltech's Jet Propulsion Laboratory. "But planetary exploration scientists are used to looking at planets as unified systems: Mars is polar caps and wind and dust storms all rolled together. This is just now happening in earth sciences, as the problems we face become more complex and interdependent."

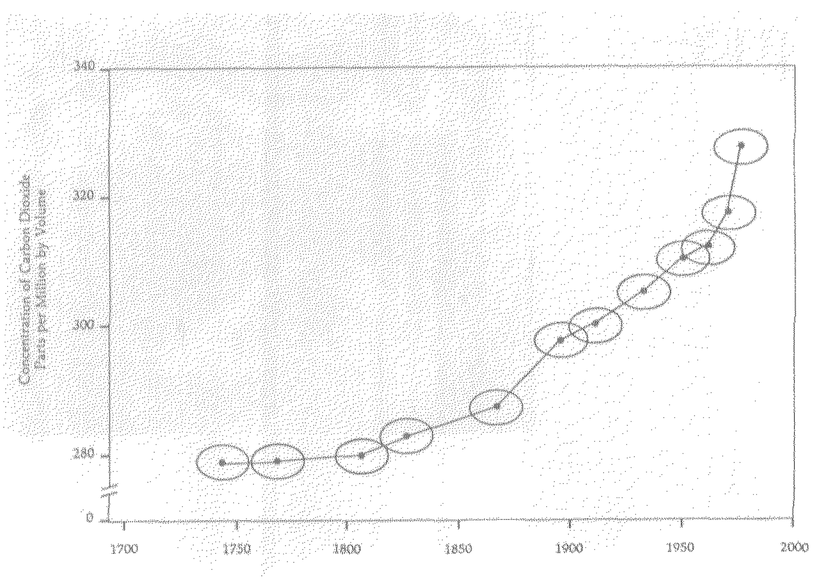
A case in point is the likely acceleration of the greenhouse effect—the predicted speedup of a process that naturally warms the earth's atmosphere. "Greenhouse gases" are transparent to visible light: like panes of glass in a greenhouse, they allow sunlight to warm the earth's surface but absorb the infrared (thermal) radiation given off by the warmed earth, keeping the heat trapped in the atmosphere. If the process went unchecked, it would change our climate on a planetary scale, but the greenhouse gases have been in equilibrium with the rest of the atmosphere until now. Man is pumping greenhouse gases into the atmosphere faster than nature removes them—carbon dioxide from burning fossil fuels (and from slash-and-burn farming, still practiced in parts of the Third World), chlorofluorocarbons from air conditioners and refrigerators, and methane from agriculture.

If these emissions continue at their present rate, computerized climate models predict that the earth could be an average of 3°C warmer by 2100. This hardly sounds like cause for alarm, but it means, among other things, a 100-foot rise in sea level. Richmond, Virginia, and Orlando, Florida, would become beachfront property, and much of New Jersey would only be visible at low tide. (Caltech, at about 765 feet above sea level, would still be on dry land.) Rainfall and vegetation patterns would change, making much of the Midwest a desert and shifting the grain belt north to Canada.

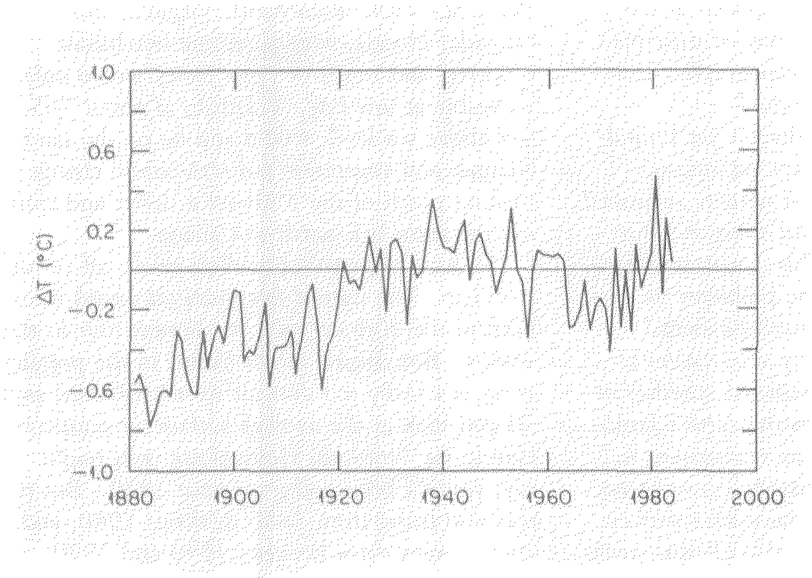
So has the greenhouse effect taken off yet or hasn't it? The hottest five years on record have been in the 20th century, the hottest four in the 1980s. But despite recent claims in the popular press, it's really too difficult to tell, Chahine says. "If you look at the average surface air temperature in the Northern Hemisphere, you might say, yes, it's been going up since 1970. But it was also rising from 1880 to about 1940, and then it went *down* between 1940 and 1970. Atmospheric CO_2 has been accumulating steadily since 1865, so why don't the temperature data match?"

The snag, according to Chahine, is that the onset of increased greenhouse warming will be very subtle. Global average temperature will climb less than one-tenth of a degree Centigrade per year, superimposed on background fluctuations of many times that amount. "Suppose the CO_2-related warming is superimposed on another warming–cooling cycle that's out of phase. The two will cancel each other for a while, but then they'll come back into phase and the temperature will suddenly take off."

Over the last 40,000 years, the earth's average temperature has fluctuated over a range of about 8°C, as recorded in the relative abundance



"It's like being a doctor before the days of x rays and CAT scans. . . . We could take the pulse, and listen to the heartbeat, but we really didn't know what was going on inside the body."

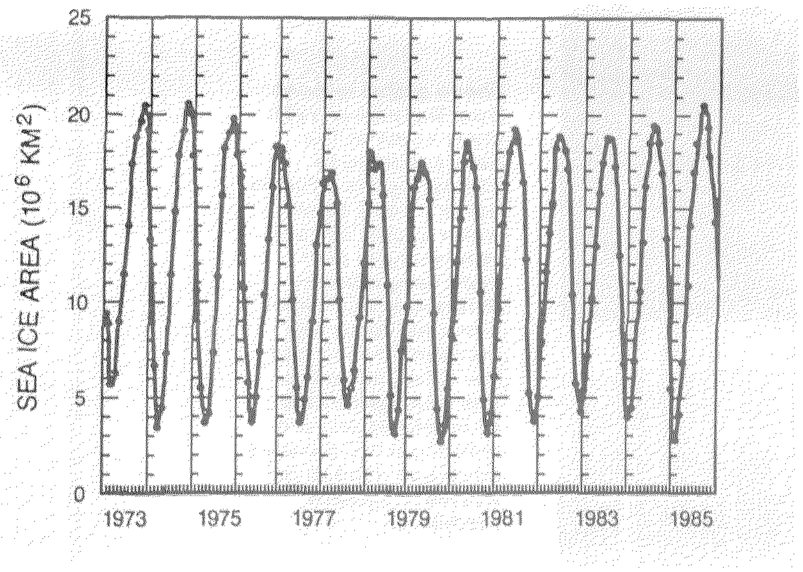


Top: Atmospheric CO_2 concentrations have increased steadily since 1865, as estimated from glacier ice cores. [Neftel et al., 1985]
Bottom: Changes in annual average surface air temperature for the Northern Hemisphere. [Wigley et al., 1984]

of shells from cold-water-dwelling foraminifera in deep-sea sediment cores taken west of the British Isles. And the changes have been abrupt, not gradual. About 15,000 years ago, the ocean warmed dramatically and has stayed warm ever since, except for two intensely cold periods of a few hundred years' duration each. So there have been cycles within cycles: hundred-year chills in a 15,000-year warming trend. But what's 15,000 out of 4.5 billion years? Are there still larger cycles undiscovered?

This leads to a related difficulty: the lack of a sufficiently accurate long-term baseline against which to compare today's measurements. Thermometers didn't come into use until after 1700, and much of the early data is of little value, due to difficulties in constructing accurate thermometers. But even if one takes the data from a given city since 1880, for example, and corrects for the different methods and instruments then in use, other subtle effects remain. Has the observing station been moved? Did what used to be a shady grove of trees become a sun-drenched rooftop, or an ovenlike asphalt parking lot?

But the central difficulty, Chahine says, is that "the problem is too big for our computer models, and many of the correlations and feedback processes aren't known. Everything is interrelated. Photosynthesis in trees is one of the primary ways to get carbon dioxide out of the atmosphere, by converting it into wood. So deforestation contributes to CO_2 buildup in two ways, by killing the tree and burning its wood. If the CO_2 level increases enough to melt some polar ice, the sea level rises. The smaller polar



Unfortunately, many of the observable effects aren't all that observable.

Sea ice in the Antarctic fluctuates in an annual cycle, with no apparent long-term trends. [Zwally et al., 1986]

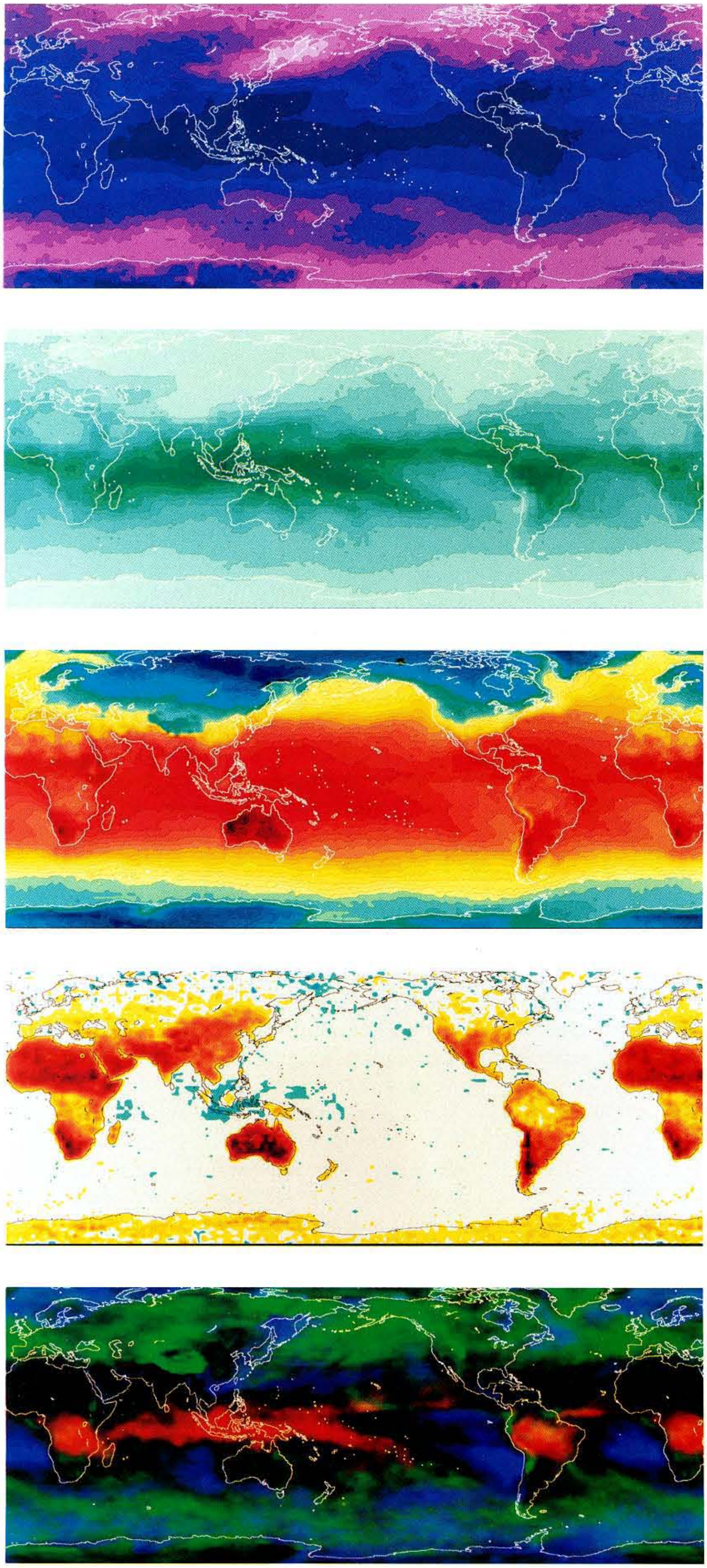
caps will reflect less sunlight back into space, amplifying the warming trend. But as the climate warms, there will be more evaporation from the oceans, and hence more cloud cover, and thus less sunlight warming the earth's surface. Which effects will predominate? No one knows. The air–surface interactions for the ocean have been modeled, for example, but the land really hasn't—it's too varied. The topography changes, the vegetation changes, heat capacity, albedo, everything varies. The oceans are much more homogeneous. A few variables suffice to describe most things. It's like being a doctor before the days of x rays and CAT scans and all these other diagnostic tools. We could take the pulse, and listen to the heartbeat, but we didn't really know what was going on inside the body."

But some of the correlations are known, and should have observable effects. "There are several different witnesses that can testify about increased global warming, so let's call the next witness." Polar cap size, and global snow and ice coverage, should shrink as the earth warms. So far this hasn't happened. Ditto for the predicted sea-level rise. The stratosphere should begin to cool, oddly enough, and this is, in fact, happening.

Unfortunately, many of the observable effects aren't all that observable. The required instruments either aren't in orbit (or are in the wrong orbit for global coverage), or weren't designed for this particular task. Global cloud cover should increase, for example, but current satellite data are only accurate to ±5 percent, and a mere 1 percent more cloudiness would nullify the current rate of increase of CO_2 concentration. Data accurate to better than 1 percent are needed. Rainfall patterns and the global moisture balance should change. These two items can be measured at ground stations, but there is no instrument in orbit today that can track these changes worldwide. (Furthermore, ground stations tend to be on land, but much of the data needed for the model must come from the oceans.) Atmospheric moisture data are incomplete, and are subject to sizeable errors in certain regions. Weather satellites record cloud cover around the world, but they don't provide detailed enough data. Wind data are not available for the whole planet, and what is available is of dubious accuracy. Nor is there any instrument aloft that can measure moisture in the soil. Vegetation distribution will change, and progress is being made in correlating ground-based plant inventories with satellite data, but much basic research needs to be done on the "inversion algorithms" that translate figures into fauna.

Not only are there several witnesses, but there is more than one defendant as well. Warming could be due to increased solar output, or to a change in the earth's albedo (the way it reflects light) or in the amount of aerosols in the atmosphere. Each of these defendants has its own set of correlations. But again, the testimony is inconclusive. The jury's still out.

"Our climate is a non-linear system with a large number of feedbacks," says Chahine. "It makes linear thinking impossible. The climate system will stay put at one spot for a long time,

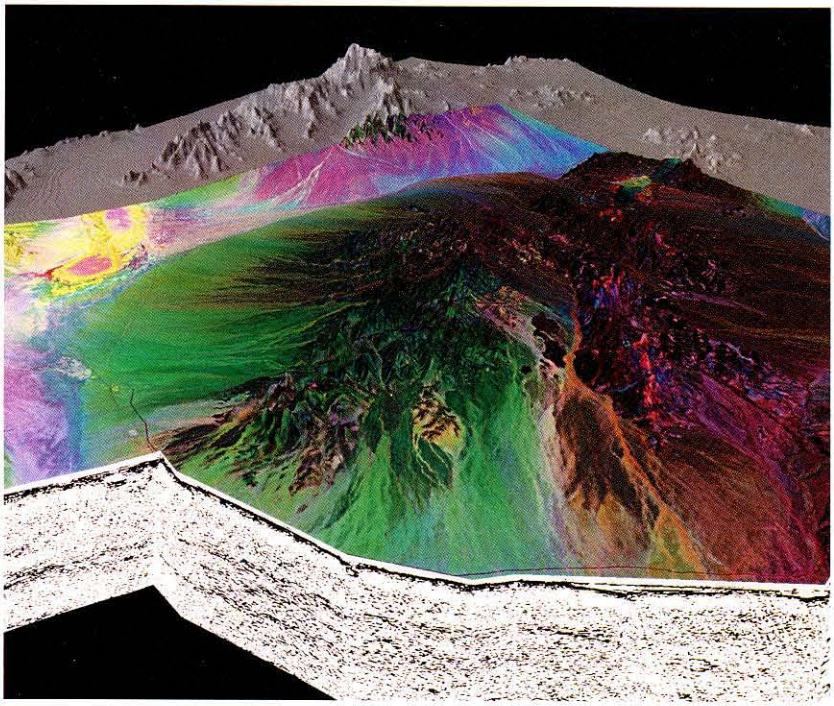


These global images from December 1978 show some of the data available to climatologists. Top to bottom: total ozone; water vapor; surface temperature; day/night temperature difference; and cloud cover at high (red), medium (green), and low (blue) altitudes. The next generation of satellites will provide the more detailed coverage needed for accurate climate modeling.

even though you're continually changing the input. Then it will suddenly change radically, leaping to a new quasi-stable state. It's like your body weight. You can eat everything in sight and nothing happens. Then you eat an ice cream cone and suddenly gain two pounds. Furthermore, climate models show what we call 'chaotic behavior.' If you start two computer simulations with almost identical initial conditions, they rapidly diverge to the point where they don't resemble each other at all."

There are two conclusions to be drawn. First, if we continue our present course, increased warming *is* coming. Carbon dioxide is increasing at the rate of 0.4 percent per year and, once in the atmosphere, each molecule stays there an average of 2 to 3 years. Methane is increasing at 1.1 percent per year, with a residence time of 11 years. Nitrous oxide (N_2O, emitted by nitrogen-based fertilizers, and by burning fossil fuels) is only increasing at 0.2 percent annually, but each molecule lingers on for an average of 150 years. So it's only a matter of time. Second, we will not know at the time the effect starts that it has, in fact, begun. The data are too fuzzy; the masking effects are too strong. The best we may be able to do is to look at the data several decades hence and say, "Ah, yes. The warming trend began back here."

But just because we can't see it yet doesn't mean there's time to waste, Chahine says. "We have got to protect our tropical forests. They are our first line of defense to get CO_2 out of the atmosphere. We need to stop using freons. We need to conserve energy, so that we get more



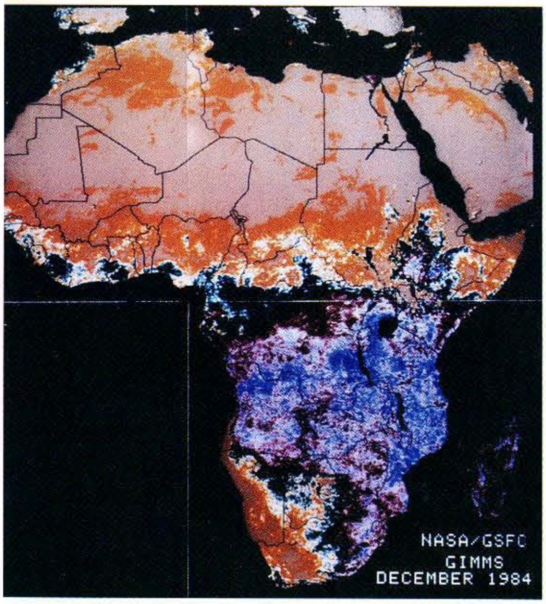
Left: This 3-D view of California's Turtle Mountains combines satellite and ground-based data—elevation data from the Shuttle Imaging Radar, false-color visible and near-infrared spectral data from the LANDSAT Thematic Mapper, and a seismic-reflection profile from CALCRUST showing subsurface features (white band at bottom). Colors reflect surface mineralogy and vegetation. Ferric iron is blue; ferrous iron, green; clays, carbonates, and vegetation are red. The area shown is about 50 km square.

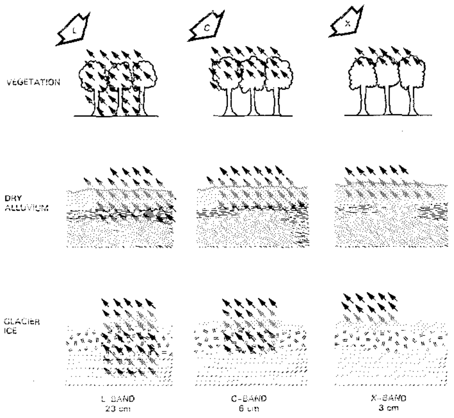
Below: Vegetation distribution in Africa from spectral analysis of light reflected from leaves. Desert is tan, grasslands are yellow and light green, woodlands (including rain forest and jungle) are dark green, red, and dark blue.

"We have got to protect our tropical forests. They are our first line of defense."

efficient use of the energy we do consume. And we have to start using cleaner fuels—natural gas instead of coal, for example—and we should move to nonfossil fuels such as solar energy as fast as possible. We have started on some of these things, but there is a long way to go on all of them. If we stopped emitting CO_2 today, and stopped cutting down forests, the damage we've already done would linger for a century, just because of the residence time of the gases."

We're not likely to stop chopping down trees tomorrow, much less quit burning coal and gasoline, so Chahine suggests a stopgap measure. "We should make a worldwide agreement to limit the man-made temperature rise to 1°C per century—0.1° per decade. [It could be 3°C hotter by 2100 otherwise.] I hope that 100 years would buy us enough time to learn how the climate system works, and how to undo the damage we have already done before it's too late." But to make such an agreement, we would need to determine what combination of activities would be tolerable under that level of increase, and how they would be distributed. How many tons of coal would the U.S. be allowed to burn per year? How many acres of rain forest could Brazil clear? Perhaps credits could be traded between nations—the U.S. might be allowed to burn an additional million tons of coal for every thousand acres of trees it planted in Brazil, for example. "Can we model our climate in such a way to specify how much greenhouse gas would limit the temperature rise to one degree? Not yet. Or if we set arbitrary limits, will we have enough data to know if





Microwave radars penetrate to different depths, depending on the wavelength.

"We should make a world-wide agreement to limit the man-made temperature rise to 1°C per century."

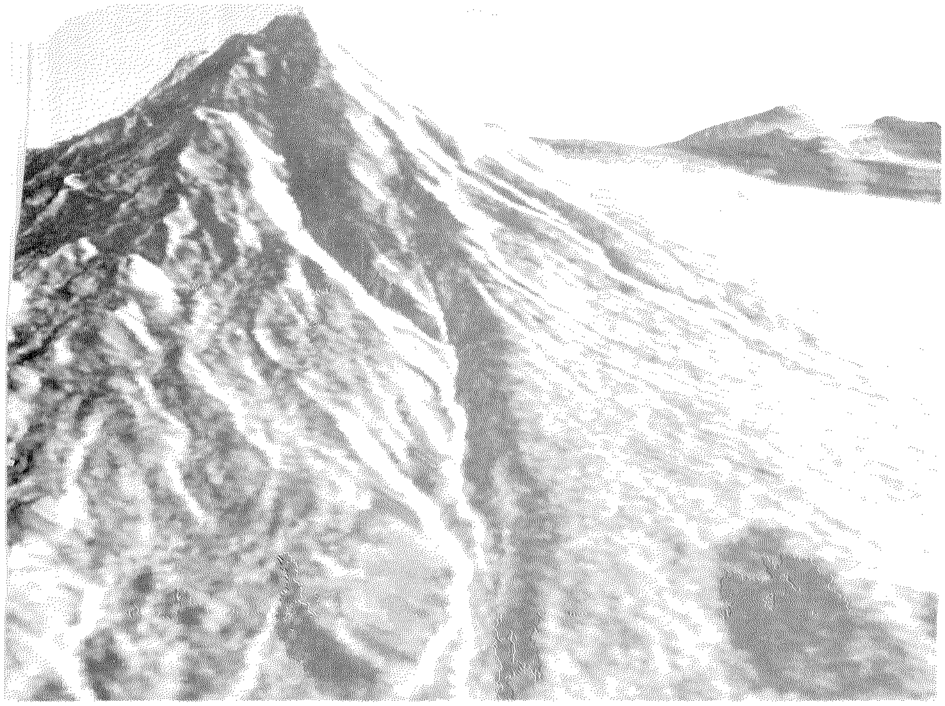
they're working? No. But we have to start somewhere. And I think this agreement would show that there's hope—that we'll be able to work together to solve the problem. The political ramifications would be great. It would change how nations deal with each other—forcing a depth of collaboration we have never tried before. Energy has been the foundation of civilization ever since the discovery of fire, and now we will have to put controls on its use. But I think a 1°C limit would be easier to work with than an attempt to cut all emissions by a set amount, because it has more flexibility to accommodate different needs. And I think people will accept that 1°C is a reasonable place to start until we know better."

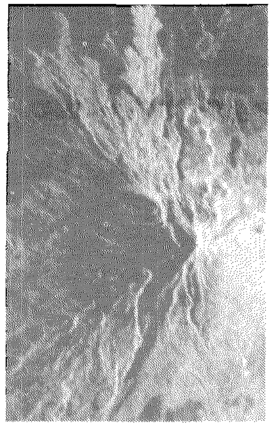
An international movement to address planetary environmental problems is taking shape. Officials from the national space agencies of Austria, Belgium, Brazil, Canada, China, France, Great Britain, Italy, Japan, the Netherlands, Norway, the Soviet Union, Sweden, the U.S., and West Germany met in April 1988 to design a Mission to Planet Earth as part of the International Space Year (ISY). Slated for 1992, the 500th anniversary of Columbus's discovery of the New World, the ISY will pool the resources of the spacefaring nations to begin a new era of exploration.

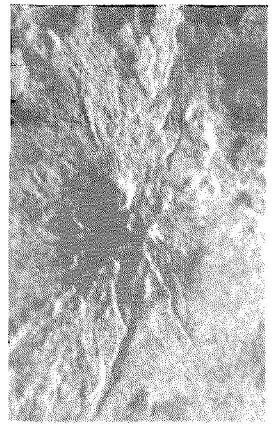
The Mission to Planet Earth will apply these resources to two specific projects—the detection of global and regional change due to an enhanced greenhouse effect, and monitoring the spread of deforestation. Says Chahine, "The ISY is only a start, a test case to see if we can take the pulse of the planet. It is the beginning of what must be done to solve the problem. Could the U.S. or JPL then propose a scheme where a one-degree limit would work? I don't know."

The greenhouse project, according to their report, will "require creating global datasets of atmospheric temperature, pressure, humidity, and wind velocity, both near the surface and throughout the atmosphere. Any long-term trends thus established will be compared against other indicators of global change, such as changing rainfall patterns, changing ecosystem patterns, changing oceanic cloud cover due to increasing sea-surface temperatures, polar warming and its consequences for permafrost and snow distribution and global sea-ice volume, stratospheric temperature changes, and coastal inundation." By collating all of this information, they hope to provide a mass of evidence sufficient to sway the jury one way or the other.

The mission's broader goal is to integrate the welter of satellite data, along with ground-based, airborne, and archived data, into a single "encyclopedia of the earth" that will be available to all researchers. The encyclopedia will serve as a baseline against which global changes, including greenhouse warming, can be measured. More importantly, using this detailed body of localized data in climate models instead of the world-wide-averaged data currently in use will make the models more sensitive, highlighting critical regional differences instead of obscuring them. The encyclopedia would also aid researchers working on more regional problems such as deforestation, desertification, acid rain, and







This 3-D view of Mt. Shasta was created from a pair of Shuttle Imaging Radar images taken at 29° from vertical (right) and 60° from vertical (far right).

the effects of air and water pollution.

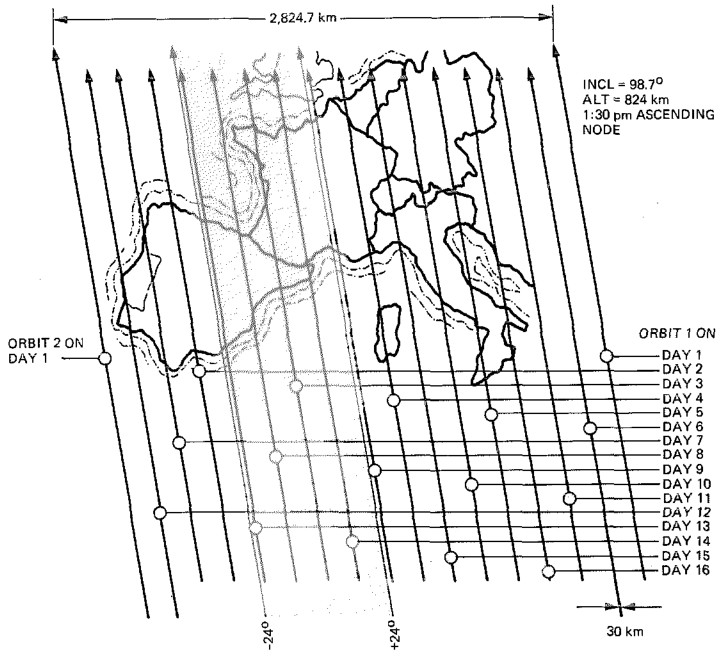
As a first step in that direction, the ISY committee circulated a questionnaire, asking the respondents to list their current and planned spaceborne instruments, along with such other pertinent information as the launch date, orbital trajectory, and sensor capabilities. This inventory will be circulated worldwide, and will be updated periodically. The inventory will allow planners to find where gaps in the current coverage exist, with an eye to filling those gaps with future launches.

This will be followed by a "global change directory"—a database, in a standardized, network-accessible format, of all satellite datasets available. The directory would include the satellite and sensor, areas and wavelengths covered, dates of coverage, data format, archive location and contact person, and so forth—the index volume to the encyclopedia of the earth, in other words.

A number of new satellites should be in orbit, or ready for launch, in time for the ISY. These will include TOPEX/Poseidon (a joint venture of the United States and France, to be managed by JPL), and NASA's Upper Atmosphere Research Satellite (UARS), as well as the European Space Agency's Earth Resources Satellite (ERS-1), and perhaps Japan's JERS-1. TOPEX/Poseidon will be able to make more accurate measurements of sea level, and will map surface ocean currents. UARS will take the first comprehensive look at the stratosphere's composition and dynamics. ERS-1 will have a scatterometer to determine wind stresses on the sea's surface, which permit energy transfer between atmosphere and ocean.

The next generation will be NASA's Earth Observing System (EOS) satellites, which grew out of the Earth Systems Science program NASA initiated in 1982. Two satellites are planned, both in polar orbits and carrying complementary instrument loads. Observations will be coordinated between instruments on the two satellites to provide near-simultaneous views of a given feature over a number of spectral regions. Thus correlations can be established for different aspects of a phenomenon studied simultaneously. EOS-1 should blast off in 1996, and will be managed by Goddard Space Flight Center; EOS-2, to be managed by JPL, is slated for launch in 1998. The EOS program is designed to monitor the earth continuously, in unprecedented detail, for at least two complete solar cycles—44 years. (The sun goes through a 22-year cycle of waxing and waning activity. The most visible effect of the solar cycle is the sunspot cycle, but the subtler effects of a brighter or dimmer sun have far-reaching consequences on the earth. It will take a couple of cycles' worth of data to sort them out.)

Forty-four years is probably longer than the lifetime of a single spacecraft, so maintaining continuity in the observations is a formidable task. One method under consideration is redundancy, i.e., placing duplicate instruments on board, but this runs into difficulty due to the great size and weight of some of the instruments. Another possibility is launching multiple satellites, but this would be expensive, and a delayed



An orbital coverage pattern for HIRIS. Shaded region shows the observable area during Orbit 1, Day 3.

launch could open a gap in the observations. Servicing the satellites in space from a robot vehicle is being considered, but the technical challenges this poses are truly enormous. (EOS couldn't be serviced by Space Shuttle–based astronauts, as the satellites are in polar orbit and the Shuttle is restricted to equatorial flights. Trying to catch the satellite as it crossed the Shuttle's path would be like firing perpendicular rifles 100 yards apart and expecting the bullets to hit each other. Re-orbiting the satellite afterwards would be even tougher.)

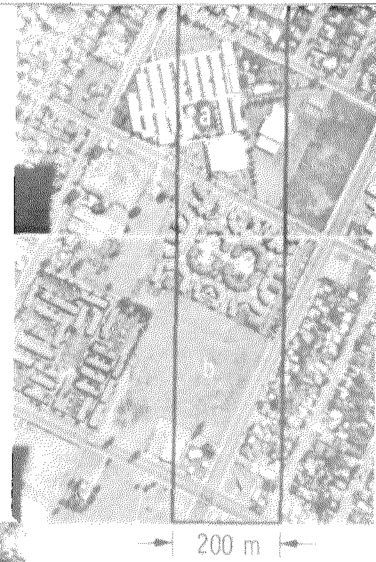
The EOS program is designed to monitor the earth continuously, in unprecedented detail, for at least two complete solar cycles—44 years.

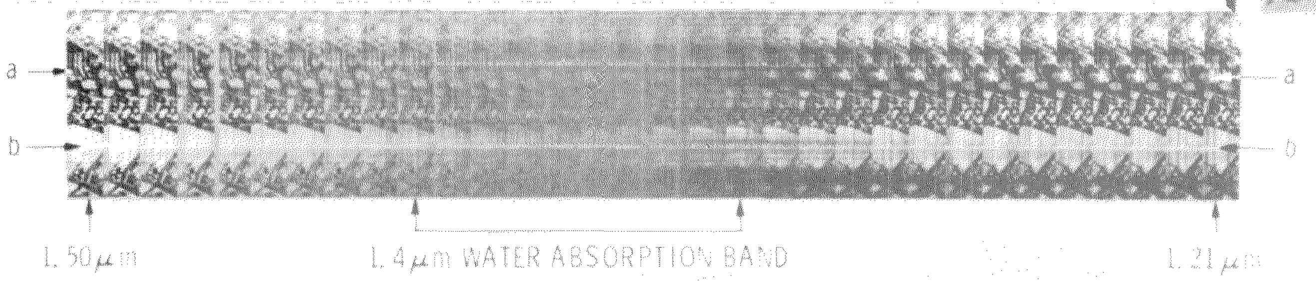
NASA issued the solicitation for EOS's instrument packages and experimental proposals in December, 1987. JPL responded with 16 instrument proposals. "JPL has been developing remote-sensing technologies for missions to other planets for over 25 years," Chahine says. "And we've been applying this expertise to earth since the 1970s. So when the EOS solicitation came out, we had a lot of ideas ready to go." Three of the 16 proposals have been approved as "facility instruments"—instruments available to the scientific community at large, so that any scientist from any institution could submit a proposal and be granted instrument time. Some of the other instruments will be approved as "principal investigator" instruments—designed for a specific experiment by a single scientist, the principal investigator, whose team will operate the instrument and be the primary recipients of its data. The PI instruments are still being chosen, with the selections to be announced in March 1989. In the meantime, prototypes of the facility instruments are being built, and models are being test-flown in aircraft.

Seven facility instruments have been chosen in all. JPL's three are the Atmospheric Infrared Sounder (AIRS), the Synthetic Aperture Radar (SAR), and the High-Resolution Imaging Spectrometer (HIRIS). HIRIS and AIRS will fly on EOS-1, while SAR will take up the bulk of EOS-2. HIRIS will weigh almost a ton, and SAR with its antennas will weigh over two tons. The satellites will be too massive to ride the Space Shuttle, and will be sent into orbit by Titan rockets.

The AIRS will be the lead NASA instrument for greenhouse research. It will give continuous, high-spectral-resolution coverage in the 3- to 17-micron (millionth of a meter) range, the near-infrared portion of the spectrum. AIRS will provide data on atmosphere–ocean coupling—how energy and matter are exchanged between the two bodies. It will study the atmosphere from the boundary layer up. The boundary layer is where the coupling actually occurs, and includes the ocean's "skin" (the topmost micron of water) and the lowest kilometer of air; AIRS will have a unique ability to study it in detail. It will monitor the ocean's (and the land's) surface temperature, the boundary-layer temperature, snow and ice cover, cloud distribution and elevations, and atmospheric humidity and temperature at 1-km vertical intervals up to an altitude of 50 kilometers. AIRS will also map sources of greenhouse gases through trace-gas analysis. This information will help define global energy and water cycles, as well as track climatic variations, and will aid efforts

HIRIS will acquire simultaneous images at 192 wavelengths, ranging from the visible to the near-infrared.



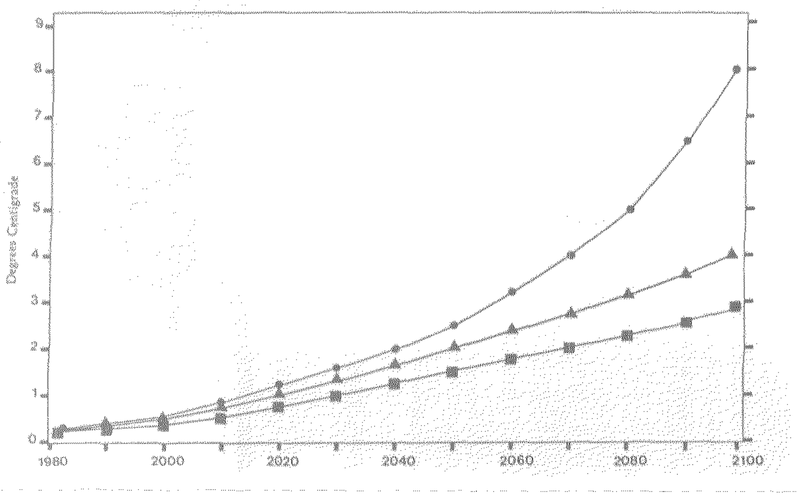


Air photo and spectral image showing (a) a school courtyard and (b) an open field in Van Nuys, California. The black rectangle outlines the area covered at 32 wavelengths between 1.5 and 1.21 microns. The well-watered courtyard shows a different reflectance pattern than the drier field. The gray blur at 1.4 microns is due to atmospheric water vapor.

at numerical weather prediction.

The SAR will map not only the earth's surface, but its vegetative cover and near subsurface (to a depth of 2 to 3 meters—see *E&S*, Sept. '83) as well. Like all radars, the SAR emits a radio beam and measures the portion of the beam reflected by the object being scanned. The SAR will operate on three frequencies in the microwave portion of the spectrum—1.25 GHz (the so-called L-band), 5.3 GHz (the C-band), and 9.6 GHz (the X-band). Microwaves can penetrate an object to some depth before being reflected. Since penetration decreases at higher frequencies, each band provides different information. Thus the L-band can penetrate up to six meters of desert sand. The intermediate C-band reflects strongly from surface features, and the X-band is very sensitive to vegetation. The way a substance reflects microwaves depends on its dielectric constant, which in turn depends on its moisture content. (There is also a marked difference between liquid water and ice.) The SAR will thus be able to map moisture at ground level (in ice and snow as well as standing water), below ground (in soil), and above ground (in leaves). Furthermore, the way in which microwaves scatter off foliage is very sensitive to the geometries of leaves, stems, and trunks. These properties are unique to every species, so it should be possible to identify types of vegetation when views of the same area at different angles and multiple polarizations are compared. SAR's transmitter and detector can be polarized in any direction, and the beam can be aimed to strike the surface at any angle from 15° to 55° from the vertical. Much calibration work remains to be done here, however, with airborne and truck-mounted instruments. The SAR will operate in three modes: a local, high-resolution mode that can resolve features as small as 25 meters over a swath 50 kilometers wide, an intermediate mode, and a global mode that covers the entire planet every three days, offering 500-meter resolution over a 700-km swath. The SAR will be the first orbital imaging radar to provide multifrequency, multipolarization, multiple-incidence-angle observations of the entire earth, and, in its global mode, will provide frequent enough observations to track fast-evolving phenomena like icebergs and volcanoes. It will also provide extensive coverage of the polar icepacks, which have been largely out-of-view to existing instruments.

The HIRIS will acquire simultaneous images at 192 wavelengths, ranging from the visible to the near-infrared portions of the spectrum. The images, taken at 10-nanometer (nm, billionths of a meter) intervals from 0.4 to 2.5 microns, extract virtually all the information contained in the incident light, and much more information than any other sensor yet envisioned. With a 30-meter resolution (the same as LANDSAT's) over a 30-km swath and the capacity to aim from +60° to −30° along its track and ±24° across its track, HIRIS is designed to zero in on specific sites rather than to map large areas. EOS-2's polar orbit will bring HIRIS back over the same spot every 16 days, but its ability to look sideways means it will be able to observe any given point more frequently than that—from every 3 to 4 days for a site at 40° north or south



Predicted surface warming effects if present emission trends continue. Squares = CO_2 + N_2O + CH_4. Triangles = squares + 1.5% annual increase in chlorofluorocarbons (CFCs). Circles = squares + 3% CFCs. [Ramanathan et al., 1985]

"For the first time, mankind is making changes on the same scale as natural changes, and the dynamic equilibrium is in jeopardy."

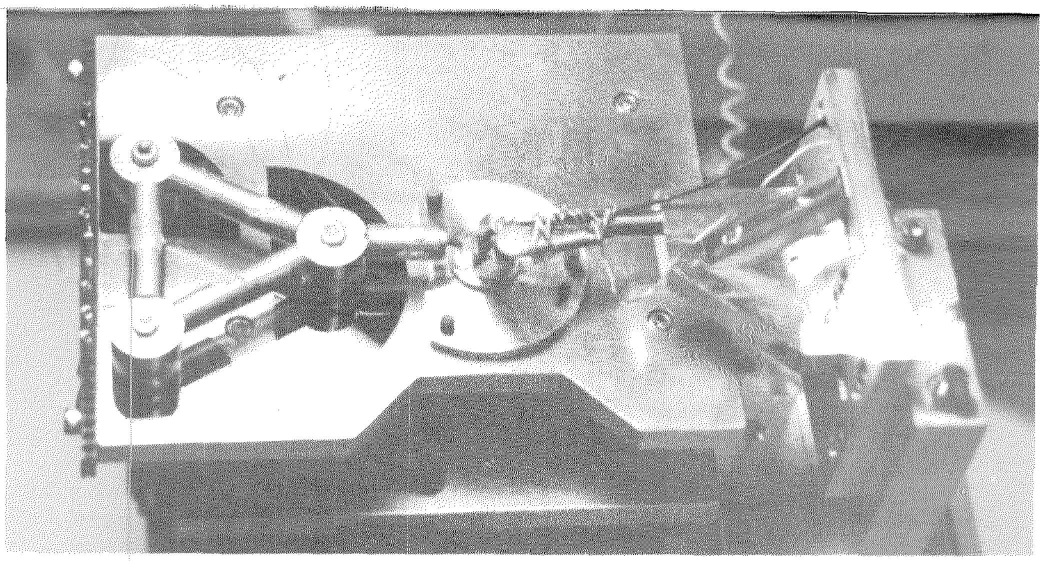
latitude to every 5 or 6 days for an equatorial site. Multiple views at different angles will make it possible to study albedo variations, which contain information on the health and distribution of vegetation, and the grain size and reflectivity of snow and ice fields. HIRIS will be able to identify over 1,000 minerals that have unique spectral signatures in the visible and near-infrared, including iron and magnesium compounds, carbonates, and sulfates. HIRIS will also be able to examine suspended sediments and phytoplankton in coastal and inland waters. In both applications, HIRIS's 192 spectral bands will allow discrimination between organic and inorganic matter, as well as providing the sensitivity to subtle spectral differences needed to distinguish between algal pigments or closely related minerals. (Even changing the bandwidth from 10 to 20 nm would lose much of this information.) HIRIS will also be able to study biochemical processes in vegetation by mapping environmental stresses that manifest themselves as subtle shifts in chlorophyll's absorption spectrum. Furthermore, nitrogen in leaves and lignin (related to cellulose) in stems and branches have detectable spectral signals, although they are not as well-defined as those for minerals. If the signals could be identified, however, it would refine estimates of the carbon and nitrogen balances in living and decomposing vegetation. None of the above functions can be done adequately with existing satellites.

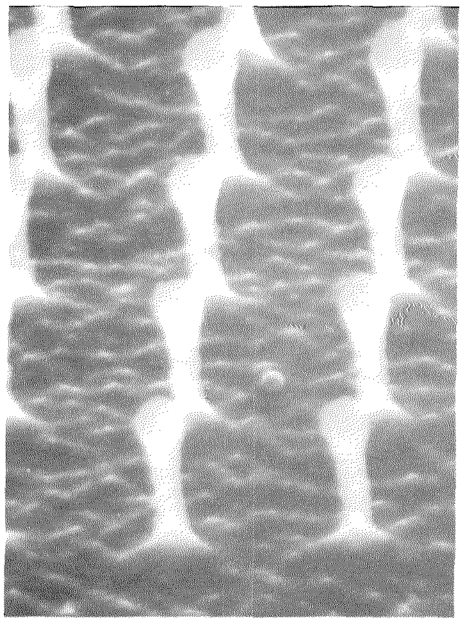
All of this data would be useless unless some way existed to get it to earth intelligibly. Tremendous strides in signal-processing technology have made it possible to send HIRIS's 192 images per view back to earth in almost real-time, at a rate of 300 million bits of information per second. But even after it reached the earth, most of the data would never have been looked at without comparable improvements in data visualization, a computerized function that combines image processing with sequence information. Concurrent- and parallel-processing systems developed at Caltech and JPL have made it possible to compress months' or years' worth of information from multiple sources into false-color "movies." Says Chahine, "How else can you look at, say, 10^{11} bits of information in six minutes? Now we can just archive all this data as it comes in, and the people who need specific parts of the data can take what they want. But when we're looking for trends or anomalies, we don't want to look at it all piece by piece. So we make a movie in the computer, and as we watch the movie, what we are looking for becomes very apparent. Then we can go back to that particular dataset and analyze it in greater detail.

"The earth's climate has always been changing. But the natural variations have always been over a limited range. One reason life was able to develop was that a steady-state climate existed for a long time. The oceans and the atmosphere have been in dynamic equilibrium for billions of years. But now we are drastically disturbing that equilibrium. For the first time, mankind is making changes on the same scale as natural changes, and the dynamic equilibrium is in jeopardy. Venus and Mars started much like Earth, but they never achieved a steady state in the habitable range. Venus got hotter from a runaway greenhouse effect, and Mars got colder as all its CO_2 got tied up as carbonates in rocks. And now look at them—they're dead planets. As we begin celebrating the 500th year of Columbus's discovery, one of our objectives is to work toward celebrating a second 500 years on a planet we can still enjoy."□—*DS*

Lab Notes

"In a sense, these dots are large man-made atoms."





Above: An orchard of quantum dots. The bulbous dots, 0.05 microns in diameter, sit on gallium arsenide stalks spaced 0.38 microns apart. Right: The piezoelectric walker. Each leg of the triangle is 1.5 inches long. The rod on the right apex carries the needle; the chip bearing the quantum dots is the tiny black square in the mounting to the walker's right. The optical fiber goes off to the right.

Eyeing the Dots

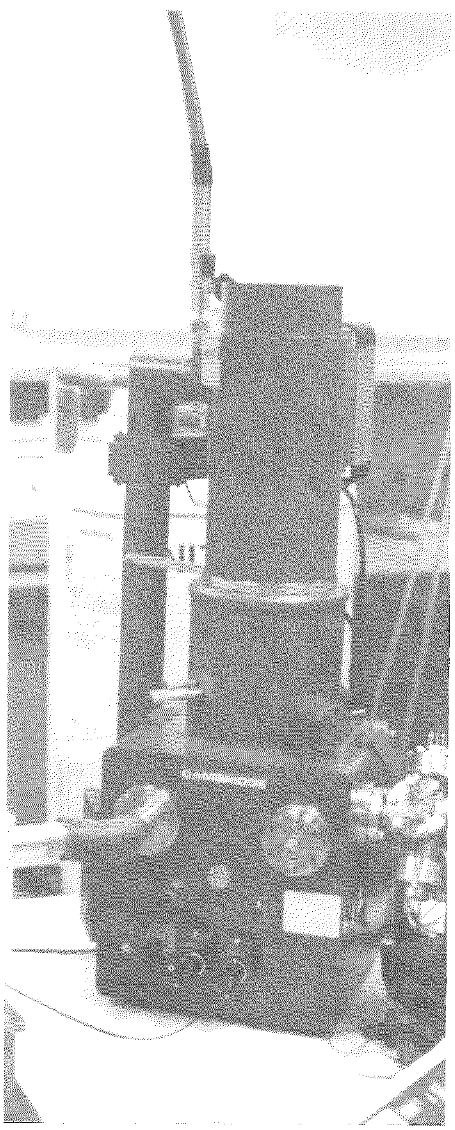
Electronic devices, even things as small as computer chips, use electrons in bulk to make things happen. Millions of electrons surge through any given circuit, as faceless as lemmings or commuters at rush hour. But as individual components get smaller and smaller, strange things begin to happen. An electron, looked at by itself, *does* have a personality—a property called a quantum state. And when there are few enough electrons in each component, the effects of these personalities begin to emerge.

According to quantum physics, an electron can behave like either a particle or a wave, depending on its circumstances. Quantum effects occur when the size of the component approaches the wavelength of an electron. In gallium arsenide crystals, this happens at slightly less than 0.1 microns—roughly 500 atomic widths. (A micron is one-millionth of a meter.) When it happens, the electron is no longer free to do as it pleases, but is confined to specific motions dictated by its quantum state. This behavior would give quantum devices very different properties from bigger components.

Physicists have been sneaking up on quantum devices in stages. The first step was the quantum well, where electrons can move in only two dimensions: length and width. A group led by Amnon Yariv, the Thomas G. Myers Professor of Electrical Engineering and Professor of Applied Physics, recently made a quantum-well laser 300 microns long by 1 micron wide by 0.005 microns—a mere 20 atoms—thick. The laser runs on 0.5 milliamps of power, a record low and close to the theoretical minimum threshold current for a quantum-well device. These lasers should become widely available in 4 to 5 years.

But that's only one step toward making ultimately small devices. Next comes the quantum wire, so small that electrons can only move lengthwise, and ultimately the quantum dot, where electrons essentially can't move at all. Quantum-wire lasers should have a threshold current 10 to 20 times lower than quantum wells, and the properties of quantum dots are a hot topic for theorists. Assistant Professor of Applied Physics Kerry J. Vahala's group is beginning to build and test these devices.

Building these devices is a formidable task, and there is no favorite technique yet. Vahala's group is experimenting with well-established chip-



The electron microscope sits on a tabletop in the lab. The sample chamber is behind the word "Cambridge."

manufacturing technology and other more esoteric approaches. In any case, the process usually begins with a crystal of alternating gallium arsenide and aluminum gallium arsenide layers on a gallium arsenide base. The upper layers are etched by various methods, leaving behind layered islands, each of which is a device. The finished crystal looks like a set of parallel lines or rows of dots.

Testing the completed devices is more daunting. Each line or dot must be tested individually. Standard chip components must also be tested, but they are much larger, and have leads running off to the chip's edges, where wires can be attached. But a dot, obviously, has no leads—if it did, it wouldn't be a dot.

The first challenge is simply *finding* the devices. The researchers can use electron microscopy to look at the crystal as a whole, but probing a specific dot isn't like a biologist chasing an amoeba around a microscope slide with a micropipet. For one thing, electron microscopy only works in a vacuum, so the sample chamber is sealed. Furthermore, much of the work must be done at liquid-nitrogen (77K or −196°C) or liquid-helium (4K or −269°C) temperatures.

"Our ability to see these effects is temperature-dependent," Vahala explains. "The effects are always there, but other phenomena tend to obscure them. If you make things cold enough, however, the quantum effects become noticeable."

The device is located by "cathodoluminescence." The crystal emits light when struck by an electron beam. Quantum dots (and wires) emit characteristic sets of frequencies that depend on their sizes—a quantum effect. By collecting and analyzing the emitted light, the researchers generate an image that locates the devices precisely. Graduate student Michael Hoenk has built a fiber-optic light-collection system that fits inside the electron microscope's sample chamber. As the microscope sweeps its beam across the crystal, the optical fiber hunts for patches of dots and wires. The team is currently using this system to study structures between 0.05 and 0.1 microns in size.

The next step is to combine the optical fiber with an electrical probe. The probe uses an 0.2-micron-diameter needle from a scanning tunneling electron microscope as the world's tiniest jumper cable. The needle pumps electricity to the dot, and the same fiber that found the dot collects any light it emits when zapped.

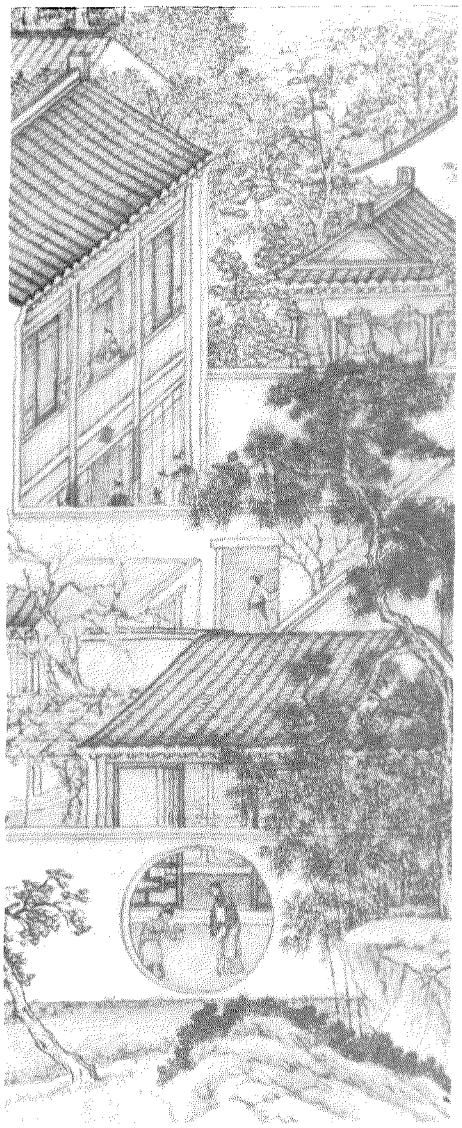
Graduate student Peter Sercel and Research Fellow John Lebens have built a triangular walker to guide the needle to the dot. Each side of the triangle is a piezoelectric rod that contracts in a very precise way in response to electricity. Each apex of the triangle has an electrostatic foot. Switching on two of the feet anchors them to a silicon plate. The free foot is moved left or right by applying current to the appropriate rod. Then that foot is switched on and another foot freed to move the walker in any direction.

The walker has not jump-started any dots yet, but Vahala expects to begin very shortly. "In a sense, these dots are large man-made atoms," Vahala says. "This system will allow us to probe the electrical and optical properties of these 'atoms' with an eye toward their potential application in new devices."□—*DS*

"This is the first time anyone has looked at patterns of criminality in China."

Like charity, murder begins at home. 25% of the manslaughters and 37% of the premeditated murders were committed in houses, more than in any other location.

Murder by the Numbers



In China's Qing Dynasty (1644–1911), all capital crimes went through an elaborate review system whose final step was the emperor himself. Like all good bureaucracies, the system kept copious records. The information included not only particulars on the criminal and victim, but a summary of the crime and the events leading up to it. At least 300,000 such case histories survive today in the Palace Archives at Taibei and Beijing.

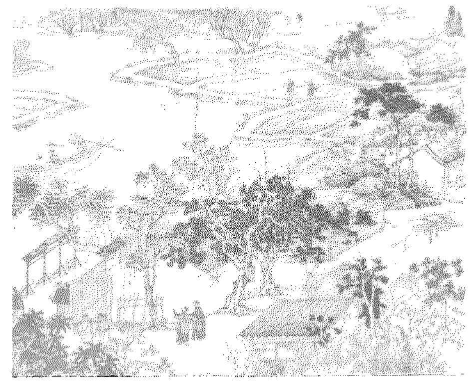
Associate Professor of History James Lee realized that a statistical analysis of these records to find out who was killing whom and why would reveal much about Qing society. "A similar technique has been applied to police blotters in Western countries, especially England and France," Lee says. "But this is the first time anyone has looked at patterns of criminality in China."

Then-sophomore physics major Xiaojian Yan began the work this past summer on a SURF grant, along with Research Assistants Shaoai Chi and Mei-chih Chang. They obtained microfilm copies of the Beijing records via the Genealogical Society of Utah. It took them eight weeks, translating from the Chinese as they went, to computerize the data from a single year—1738. The cases had to be input in a standardized format, but as the trio plowed through the records they found that the reporting methods kept changing. And each time they revised the format, all the previously entered cases had to be redone, a cycle that ultimately consumed nearly half of the available time. Once the data had finally been entered, it took Yan several more weeks to complete the preliminary analysis.

The statistics show men killing and being killed far more often than women. Of 1,500 homicides studied, about 95 percent of the criminals were male, as were 80 percent of the victims. More than 60 percent of these killings were manslaughter cases, often escalating from a domestic dispute or a quarrel with neighbors. By contrast, women were three times more likely to commit premeditated murder than men. Of the 77 female criminals, 52 killed their husbands, with their lover as an accomplice. According to Yan, "Women had no social position, and couldn't own property. They had no contact with the world, so the only people they could come into conflict with were relatives. In the coastal provinces of Jiangsu, Fujian, and Guangdong, however, we found a higher percentage of female criminals and victims than inland. This may be due to greater commercialization encouraging women to have more contacts outside the family, giving them more opportunities for conflict. We can also see commercialization's influence in

The illustrations for this article come from a Qing Dynasty scroll depicting Suzhou, a bustling commercial center near Shanghai. Painted by the court artist in 1749, the scroll is over 40 feet long, 15 inches wide, and includes some 4600 people.

Fields were the second most popular site for dirty deeds. 26% of all manslaughters and 22% of all premeditated murders occurred there.



another way. These three provinces had more property-related crimes."

Indeed, 51 percent of all murders were property crimes, often beginning as a dispute between neighbors over land, between acquaintances over unpaid loans, or between brothers over an inheritance. (The oldest son did not automatically inherit everything, and many quarrels arose when one brother felt slighted in the will, or decided to lessen the competition by removing a sibling while the father still lived.) Some of the fights about land escalated into clan wars, with hundreds of members of both extended families mixing it up throughout town and countryside. When this happened, the local militia (who acted as civil police) lay low until the dust settled, then emerged to arrest any survivors they could round up.

A few murders can be blamed on salt smugglers. Like drug trafficking today, smuggling salt was a lucrative profession, and it attracted ruthless, violent men. Several militiamen were killed trying to arrest salt runners who, like their modern counterparts, were better armed and organized. The smugglers had guns, but the militia usually had only spears.

Yan measured the strength of societal bonds and conflicts by finding how often two people in a given relationship were accomplices versus how often they killed each other. "No one has ever tried to quantify this before, as far as I know," says Lee. The larger the accomplice/victim ratio, the stronger the bond. A ratio near 1 is ambivalent, while a ratio less than 1 shows sources of conflict. Although the data are limited because only about 30 percent of the killers had accomplices, a pattern emerged. Not surprisingly, the father/son bond proved very strong, with a ratio greater than 10, namely 21 cases to 2. The brother/brother ratio was slightly less than 2, with 65 to 39 cases, as brothers fought together against outsiders but among themselves within the family. The uncle/nephew bond rated 0.5 (12 to 25), and more distant relatives behaved as total strangers. "We were a little surprised by this," Yan says. "We thought that the extended-family relationships would make the bond decline gradually, but it's more like an exponential decay." There was little love lost between husband and wife: while the lover/lover bond rated 8.4 (67 to 8), the husband/wife bond was less than 0.001 (1 to 124).

Some cases offer cultural insights even when taken in isolation. In a case from Henan Province, Hanying Liu's daughter was betrothed to Mao Yang. Then Liu's wife began an affair with Hei Tian. Yang's father found out, and demanded that Liu immediately surrender his daughter into Yang senior's keeping to protect her from further disgrace. Liu complied, and Mao married her as soon as the arrangements could be made, even though the wedding was supposed to be several months away. The Lius were not invited. Liu, furious, plotted with his wife and her lover, Tian, promising him that if they killed the Yangs, he could marry Liu's daughter. Tian agreed to an ambush. Liu's wife lured Mao and his father into a convenient field, where Liu and Tian set upon them with knife and spear, finishing them off with an axe they had brought for that very job.

In a case from Jiansu Province, Liu Gao was traveling around the country on business. He carried a lot of cash, perhaps as much as 1,000 taels (roughly equivalent to ounces) of silver. Gao stayed in Shicheng Wang's house for several months while conducting business in town, and had an affair with Wang's wife at the same time. Wang discovered her infidelity, but allowed it to continue until Gao, who was a lavish gift-giver, had spent his last tael on Wang's wife. (Wang, needless to say, took his share.) Once Gao had been bled dry, Wang threw him out into the street. Gao returned that night and broke into Wang's house, killing the larcenous couple as they slept. "There were many cases where a husband allowed his wife to have an affair if he stood to profit from it," Yan said. "Or a woman would be raped by a rich or powerful man, and a cash settlement would follow. Sometimes the husband would almost act as a pimp. But we see no cases of a husband allowing his mistress to do this. Usually, if a man knew his wife was having an affair, he would kill her. But if his mistress had an affair, he would kill the other man."

Although Yan's analysis has barely scratched the surface of the available data, Lee says his results offer a tantalizing glimpse of several facets of Qing society unexamined previously. Lee plans to continue the research with the assistance of future SURFers. "As we examine the records from other years, we hope to see trends as Qing society evolved," Lee says. "We are also looking for regional variations. And I'd like to look for correlations between the criminal-victim relationship and the criminal's eventual fate. Records are available for other kinds of crime, and I'd like to look at them, too."□—*DS*

Books

Delbrück's Phage Group at Caltech in 1949.

Thinking About Science
Max Delbrück and the Origins of Molecular Biology

by Ernst Peter Fischer and Carol Lipson

W. W. Norton & Company, 1988
$19.95
334 pages

Max Delbrück (1906-1981), professor of biology at Caltech from 1947 until his death, was one of the most influential biologists of our time, and also one of the most interesting. His career spanned two of the greatest achievements of 20th-century science, those of quantum mechanics and molecular biology. He played a minor role in the first, but a major one in the second. For the latter, he won the Nobel Prize in 1969 with Alfred Hershey and Salvadore Luria.

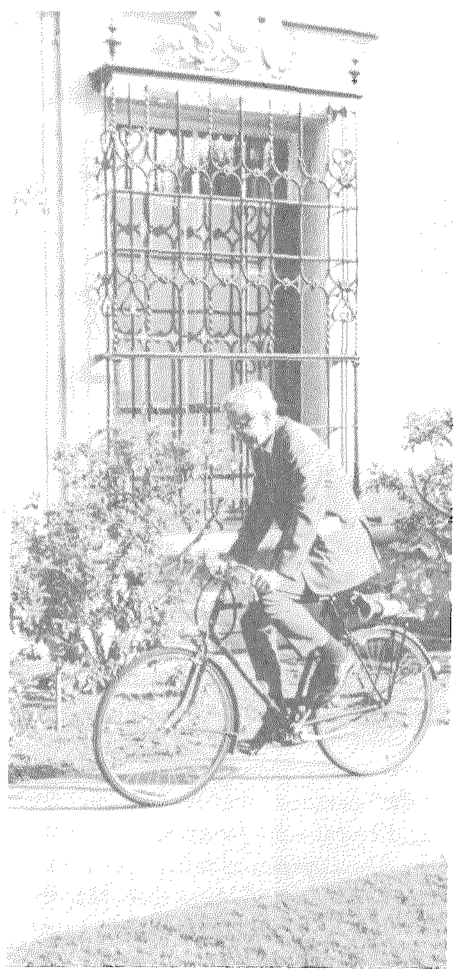
Peter Fischer, the principal author of this biography, has a special right to authorship. He was one of Max's last graduate students. When, near the end of his life, Max decided to write his autobiography, he asked Peter—who by that time had returned to his native Germany—to come to Pasadena to help him. Max died soon after their collaboration began, so the book is essentially Peter's. He, in turn, invited Carol Lipson, who also knew Max and who teaches writing at Syracuse University, to assist him with composing in a foreign language. The result is altogether admirable: an honest, witty, and sensitive book written in flowing English.

Max studied theoretical physics in Göttingen, Berlin, and Copenhagen during the late twenties and early thirties, in the early days of quantum mechanics. He obtained his PhD with Max Born at Göttingen and then took off on postdoctoral peregrinations that brought him to the Institute for Theoretical Physics in Copenhagen. There he came under the influence of Niels Bohr, with whom he developed a lifelong friendship. It was in Copenhagen, in 1932, that Bohr gave a lecture that turned Max into a biologist. In his lecture, Bohr proposed that life might not be reducible to atomic physics, but might stand in a complementary relation to it, analogous to the relation between the wave and particle aspects of light—contradictory, yet both necessary for understanding. Max was fascinated by epistemological questions, and Bohr's argument had a deep effect on him. He became interested in biology and within a few years left physics altogether.

One of the highlights of this book is its discussion of Bohr's complementarity argument, including its physical background, and of Max's unceasing search for the "paradox" that he was convinced would reveal complementarity in biology. The complementarity idea is explained more clearly here than Max ever explained it. The irony in the fact that Max's brilliant career was motivated by the pursuit of a mirage is not lost on the authors. Their treatment of this subject is brilliant.

Max's entry into biology is described by Fischer and Lipson as follows: "Max began his search for complementarity in biology by analyzing how ionizing radiation influenced the genetic material. Genes were stable elements; as a special feature, they could be shifted to a different form, which again was stable. Could the new quantum mechanics explain this, or did biology run into a paradox right here?" The result was a paper published in 1935 with Timoféeff-Ressovsky and Zimmer in which a quantum mechanical description of gene mutation is presented. It found that the stability and mutability of genes are explicable quantum mechanically if the gene is regarded as a macromolecule.

This paper made Max famous because it was quoted in Erwin Schrödinger's widely read little book, *What Is Life?*. The chapter entitled "Delbrück's Model" was read and admired by a number of people who later joined in the attack on the gene. These included Salvadore Luria, James Watson, Francis Crick, and Seymour Benzer.



By now the Nazis were in power, and Max gladly accepted the offer of a Rockefeller Fellowship to leave Germany. He chose to continue his studies of the gene by coming to what was the world center of genetics: T. H. Morgan's department at Caltech. Max wanted to learn how genes replicate—a goal he pursued singlemindedly until it was solved (by Watson and Crick) in 1953. At Caltech he found the organism—bacteriophage—that he hoped would lead him to that goal. These tiny viruses that prey on bacteria seemed to Max "beyond my wildest dreams of doing simple experiments on something like atoms in biology." Enthralled by phage and its possibilities, Max apprenticed himself to Emory Ellis, a Caltech biochemist who was working with phage at the time, and together—Ellis supplying the techniques and Max the theoretical framework—they founded modern phage genetics. Phage became one of the best understood of all organisms, thanks to Max and the bright group of collaborators and students he gathered around him.

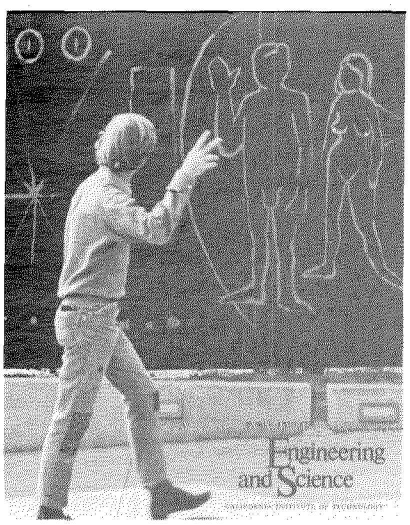
The largest section of *Thinking About Science* deals with the phage period of Max's life. It summarizes the major accomplishments, and it contains fine descriptions of Max's style as a leader. On a personal level, he was the most informal and relaxed of men. But in scientific matters he was a dragon of rigor and purity, standards he applied to himself and to others. He had his failings, too, and they are not whitewashed here. Most notable was his inability to appreciate the importance of chemistry—a failing not rare among physicists. He thought that the fundamental problems of biology could be solved by a combination of genetics and physics. He had no difficulty learning what biochemistry he needed to know, but his biochemical intuition was not strong. He thought Watson was wasting his time when, at Cambridge, he began modeling DNA with Francis Crick.

For Max, the structure of DNA was a disappointment—there was no paradox there. DNA was a simple molecule, and gene replication—the mystery of mysteries—was "a ludicrously simple trick." Max did not avoid the truth, but neither did he give up the search for complementarity. Calling the search one of his "private fantasies," he continued it at higher levels of biological organization. After briefly considering other possibilities, he settled on the light-responses of the fungus *Phycomyces* as the focus of a new research program. He entered the new field with enthusiasm and before long had attracted another group of bright collaborators; but *Phycomyces* never took wing as phage had. Max was interrupted repeatedly by visits to postwar Germany for the purpose, among other things, of helping found research institutes in the image of Caltech at the universities of Cologne and Konstanz. Although Max referred to *Phycomyces* as "the most intelligent primitive eucaryote," it proved to be more intelligent than primitive. It gave up some secrets, but no breakthroughs were made during Max's lifetime. Despite this, these years were not without interest, and Fischer and Lipson record both the science of this period and the personalities with their usual insight and humor.

This is a superlative biography. It is a fine memorial to Max Delbrück, who was my old friend and one of Caltech's great men.

Norman Horowitz
Professor of Biology, Emeritus

Letters



EDITOR:

I have been meaning to write *Engineering & Science* about this for some time now, but haven't gotten around to it. A while back, that revered alumni magazine published a special anniversary issue. In an array of covers reproduced therein, there was one of an unidentified undergraduate waving goodby to the two human figures on the space-bound Pioneer 10 plaque that someone had caricatured on a construction wall near the Beckman Auditorium (volume 35, number 5, March-April 1972).

I am proud to have been that cordial undergraduate. It all happened late one sunny afternoon a week or two before the issue came out. I had just driven onto the campus when the *E&S* photographer, Floyd Clark, who happened to be an acquaintance of mine because of my involvement with the Caltech Y, strolled by and recruited me for the task. I'd like to take credit for the idea, but I can't; it was hatched entirely in the mind of Floyd Clark (except for my use of the peace sign instead of a conventional wave). A couple of passes along the sidewalk and I had done my first (and so far, alas, my only) cover! Coincidentally, I had just driven in from JPL where, under the supervision of JPL Historian R. Cargill Hall, I had been working on a paper on the history of solid propellant rocketry, so it was only appropriate that I should have paused after such space-oriented work to bid farewell to the two soon-to-be space travelers. That assignment finished, I then proceeded to a session in Baxter Hall with my advisor, Daniel J. Kevles, whose good counsel helped launch me (ahem!) on my own unusual trajectory as a historian of science and technology.

P. Thomas Carroll, BS '72
Assistant Professor of History
Rensselaer Polytechnic Institute

EDITOR:

Your paragraph on the death of W. R. Smythe at age 95 was, perhaps inevitably, a too perfunctory notice of a career of the greatest significance for Caltech. Professor Smythe set the standards, and maintained the continuity of quality, of the Physics Department from the era of Uncle Bobbie through the fifties. He was friend, mentor and judge of all the graduate students, not just those whose research he supervised. His famous required course in electromagnetism, and successive editions of his splendid text, were our essential introduction to an intuitive, physical, understanding of field physics, and to the analytical methods of mathematical physics. His personal encouragement meant much to me.

Professor Smythe was inflexibly honest, rational, decent, and both scientifically and physically tough. A proper biography will mention his military service in the Philippines, his long association with R. A. Millikan, his tennis matches with the Athenaeum houseboys. In later years many noticed his noontime laps in the swimming pool. He will still be long remembered.

Frank B. Estabrook, PhD '50
Jet Propulsion Laboratory

Random Walk

NSF Sites Named

Caltech will be the site of one of 11 Science and Technology Centers supported by the National Science Foundation and will be a partner in another. The Center for the Development of an Integrated Protein and Nucleic Acid Biotechnology and the Center for Research on Parallel Computation (based at Rice University) represent 2 of 323 proposals submitted nationwide.

The NSF will provide first-year funding of more than $3 million for the Center for the Development of an Integrated Protein and Nucleic Acid Biotechnology, which will be a cooperative effort by scientists at Caltech and JPL, led by Leroy Hood, the Bowles Professor of Biology and chairman of the Division of Biology. Further funding of the centers for the first five years will depend on available funds and the center's progress, and a review will determine funding for an additional five years after that.

Scientists at this center intend to improve on and integrate the most advanced techniques in genetic engineering, protein chemistry, and data analysis in order to develop new technology to speed research in protein and gene regulation. Their efforts should ultimately open up new possibilities for understanding, diagnosing, and treating diseases at a molecular level.

First-year funding of more than $4 million will support a joint proposal of Caltech and Rice University for the Center for Research on Parallel Computation, based in Houston. This center will focus on the development of the next generation of supercomputers, which will depend on parallel processing—breaking up computations into smaller problems that can be solved more quickly by computer subsystems working simultaneously rather than in sequence. The principal Caltech participants will be Geoffrey Fox, professor of theoretical physics and associate provost for computing; Herbert Keller, professor of applied mathematics (who will represent Caltech in the center's administration); and Charles Seitz, professor of computer science.

Time-Share Telescope

The cost of looking at the cosmos has risen astronomically, causing researchers to pool their resources. As of January 1990, Cornell University astronomers will be allotted 25 percent of the observing time on Palomar Observatory's 200-inch Hale Telescope. In return, Cornell will cover one-fourth of the operating costs of the telescope and provide new, ultra-sensitive detectors for it. Cornell's total contribution is expected to be about $500,000 annually.

The first instruments Cornell will contribute are infrared detectors. Cornell astronomers have led the way in developing high-sensitivity technology for such devices. Infrared, or thermal, radiation, is an important astronomical resource because many interesting objects that aren't hot enough to emit visible light, or whose light is obscured by intervening dust, shine brightly in the infrared.

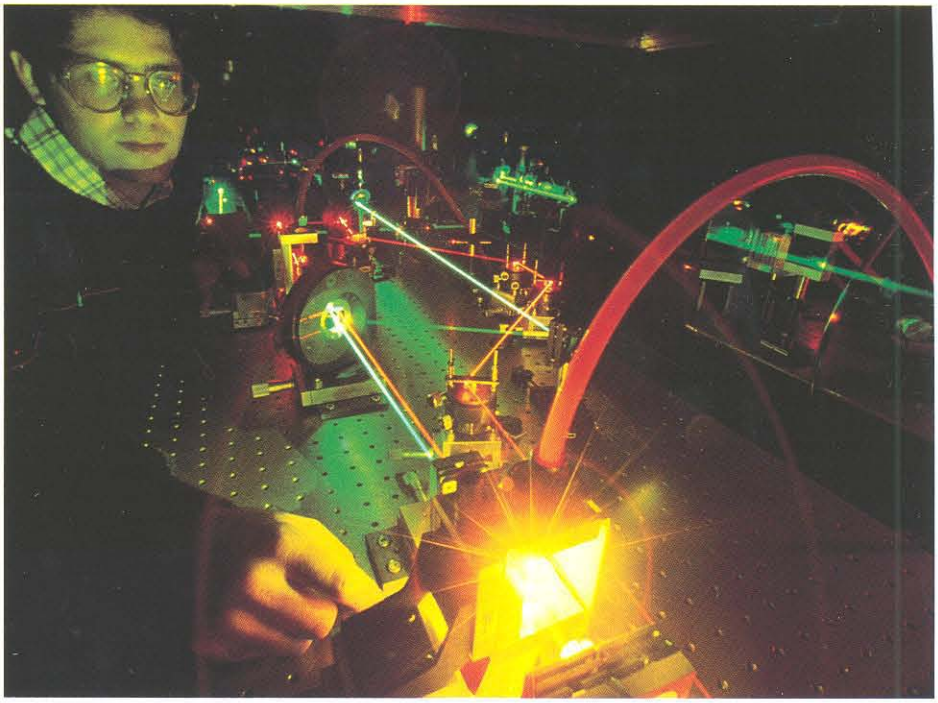
New Appointments

Edward Stone, Jr., professor of physics, has been named vice president for astronomical facilities. In this capacity Stone will be responsible for Caltech's involvement in the design, construction, and start-up phases (as well as the policy-making and negotiating aspects) of the W. M. Keck Observatory, which, when completed in Hawaii in 1992, will house the world's largest optical telescope. Stone is already chairman of the board of directors of the California Association for Research in Astronomy, which was formed in 1985 to oversee the 10-meter-telescope joint project with the University of California.

Stone has worked principally in cosmic ray research and was the project scientist for JPL's Voyager missions to Jupiter, Saturn, Uranus, (and coming next August, Neptune). He joined the Caltech faculty in 1964 and has been chairman of the Division of Physics, Mathematics and Astronomy since 1983.

Succeeding Stone as division chairman is Gerry Neugebauer, the Howard Hughes Professor and professor of physics, as well as director of Palomar Observatory. Neugebauer, who has been a member of the Caltech faculty since 1962, is known for his pioneering work in infrared astronomy. He has played a leading role in infrared studies of the planets—developing instrumentation for the Mariner, Pioneer, and Viking missions at JPL—and was the principal U.S. scientist for the Infrared Astronomical Satellite (IRAS).

On the evening of April 28, 1988, 100 photographers fanned out across the State of California. Starting at midnight, and for the next 24 hours, they shot nearly 115,000 photographs. The fruits of their labor, *A Day in the Life of California*, **contains only a few hundred pictures. This shot of Graduate Student Marcos Dantus in Professor of Chemical Physics Ahmed Zewail's laser lab appears on page 96.**



Honors and Awards

Harry A. Atwater, assistant professor of applied physics, has been elected to the Cornell University–based Böhmische Physical Society "for his studies of ion-beam-enhanced grain growth in thin-film systems."

Assistant Professor of Computer Science Alan H. Barr has won the 1988 Computer Graphics Achievement Award from the Association of Computing Machinery's Special Interest Group on Computer Graphics (SIGGRAPH) for developing the technique of "dynamic constraints," a shortcut method which imparts realistic motion to computer animations.

Assistant Professor of Cosmochemistry Geoffrey A. Blake is one of 20 outstanding young faculty nationwide to be awarded the first David and Lucile Packard Fellowships in Science and Engineering, which includes an unrestricted research grant of $100,000 annually for the next five years.

Harry B. Gray, Beckman Professor of Chemistry and director of the Beckman Institute, has been elected an Honorary Member of the *Societa Chimica Italiana* (the Italian Chemical Society), "in recognition of the many fundamental contributions he has given to modern inorganic and bio-inorganic chemistry."

J. Harold Wayland, professor of engineering science, emeritus, has received the 1988 Malphigi Award, the European Society for Microcirculation's highest honor. The award honored his research in blood flow and his development of quantitative measurements of fundamental life processes on the microscopic level.

Rhodes Scholar

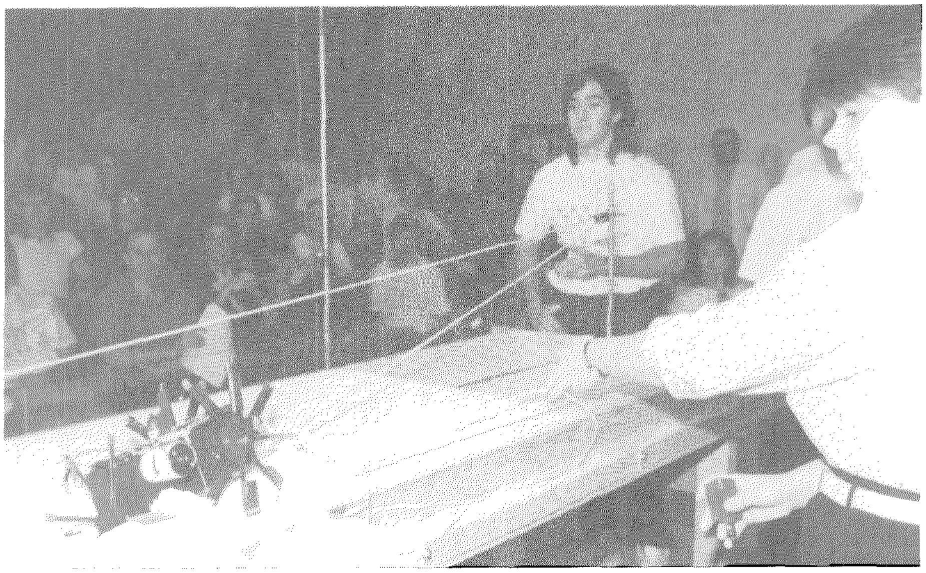
Gregory P. Dubois, a doctoral candidate in high-energy physics, has been named a Rhodes Scholar. The Rhodes Trust will give Dubois a two-year postdoctoral fellowship at Oxford University in Oxford, England. Dubois is one of 32 American college students to be selected as Rhodes Scholars this year. Dubois will head for Oxford this fall, where he will study the interaction of science, technology, and public policy.

Sternberg Dies

Eli Sternberg, professor of mechanics, emeritus, died October 8 in Pasadena. He was 70 years old. Sternberg was known for his theoretical work in structural elasticity, which found numerous applications in both mechanical and civil engineering.

Born in Vienna, Sternberg left there in 1938. He earned his BCE from the University of North Carolina in 1941 and his MS (1942) and PhD (1945) from the Illinois Institute of Technology. After teaching at I.I.T. and Brown, he joined the Caltech faculty as professor of applied mechanics in 1964. He became professor of mechanics in 1970 and emeritus just this past year.

Sternberg was a fellow of the American Academy of Arts and Sciences and a member of the National Academy of Engineering; he was awarded honorary doctorates from the University of North Carolina and the Israel Institute of Technology, and in 1985 won the Timoshenko Medal of the American Society of Mechanical Engineers, considered the nation's most prestigious award in applied mechanics.



Assistant Professor of Mechanical Engineering Erik Antonsson's ME 72 final played to a packed house once again. The challenge was the same as last year's— pitting devices students built from identical "bags of junk" in a tug-of-war over a bed of plastic "sand"—but this year's motors were 20 times more powerful. In the final round, Philip Lee's paddle-wheel crawler flailed doggedly down the track, but lost to Steve Errea (left), whose tank-treaded juggernaut went undefeated. Leslie McCaffree (right), who placed second last year, officiated.

Carlson Stamp

Separated by more than 600 years, Thomas Blanket of Bristol and Chester Carlson of Caltech have this in common: They both introduced popular, durable, even revolutionary products. However, Blanket, being a simple fellow, called his commodity after himself, while Carlson—an educated man, a scientist, and a graduate of Caltech (BS '30)— named his invention after the Greek word for dry writing: xerography. The result? Today, Blanket is a household word, not to mention a household item. As for the inventor of Xeroxing, who died in 1968, the ink has long since run dry on his memory.

But now Carlson's name—and face— may finally get some recognition. On October 21, the U.S. Post Office issued a stamp commemorating the man who 50 years earlier to the day had used a silk handkerchief, a sulfur-coated aluminum plate, and ideas borrowed from a library book in ways that would ultimately alter the lives of millions of office workers. (The commercial Xerox copier made its debut in 1960.)

The purple-gray stamp— the postage needed to mail a postcard to Canada— is largely the result of an 11-year campaign by Frank Horton, congressional representative from Rochester, New York, where Carlson lived as a citizen-philanthropist, after his invention made him rich but never famous.

Carlson's generosity was also extended to his alma mater. In the 1960s he made an anonymous gift to Caltech that, with funding from the National Science Foundation, made possible the building of Noyes Laboratory of Chemical Physics, completed in 1967— a year before his death. In accordance with Carlson's wishes, his role remained a secret until 1977, when, at the request of his widow, Doris Carlson, the identity of the donor was announced and a plaque to that effect placed in the foyer of Noyes.

Carlson also served for a brief period before his death on the Caltech Board of Trustees.

According to the Caltech Archives, Carlson is the first alumnus ever to grace a postage stamp— an honor incidentally that was never accorded Thomas Blanket. (Caltech's first president, Robert A. Millikan, was honored with a 37-cent stamp in 1982.) It may not have quite the force of "Can you Carlson me a dozen copies?" but at least it stamps as worthy of notice the man who, in the words of *American Heritage* magazine, "satisfied the reproductive urges of office workers everywhere."

Heidi Aspaturian

Reprinted from *On Campus.*

Math Show Award

Project *MATHEMATICS!*'s pilot videotape, "The Theorom of Pythagoras," won the gold medal in the Mathematics and Computer Science category at the 1988 International Film & TV Festival of New York. The tape is the first in a series that is designed to use computer animation to teach basic mathematics. Additional episodes will be produced as funding becomes available. The project, which involves 32 states as well as professional mathematics organizations, is based at Caltech and headed by Professor of Mathematics Tom M. Apostol and JPL's James F. Blinn, one of the world's leading computer animators. The two were also part of the collaboration that produced *The Mechanical Universe*, the award-winning physics telecourse developed at Caltech.