California Institute of Technology

Engineering & Science

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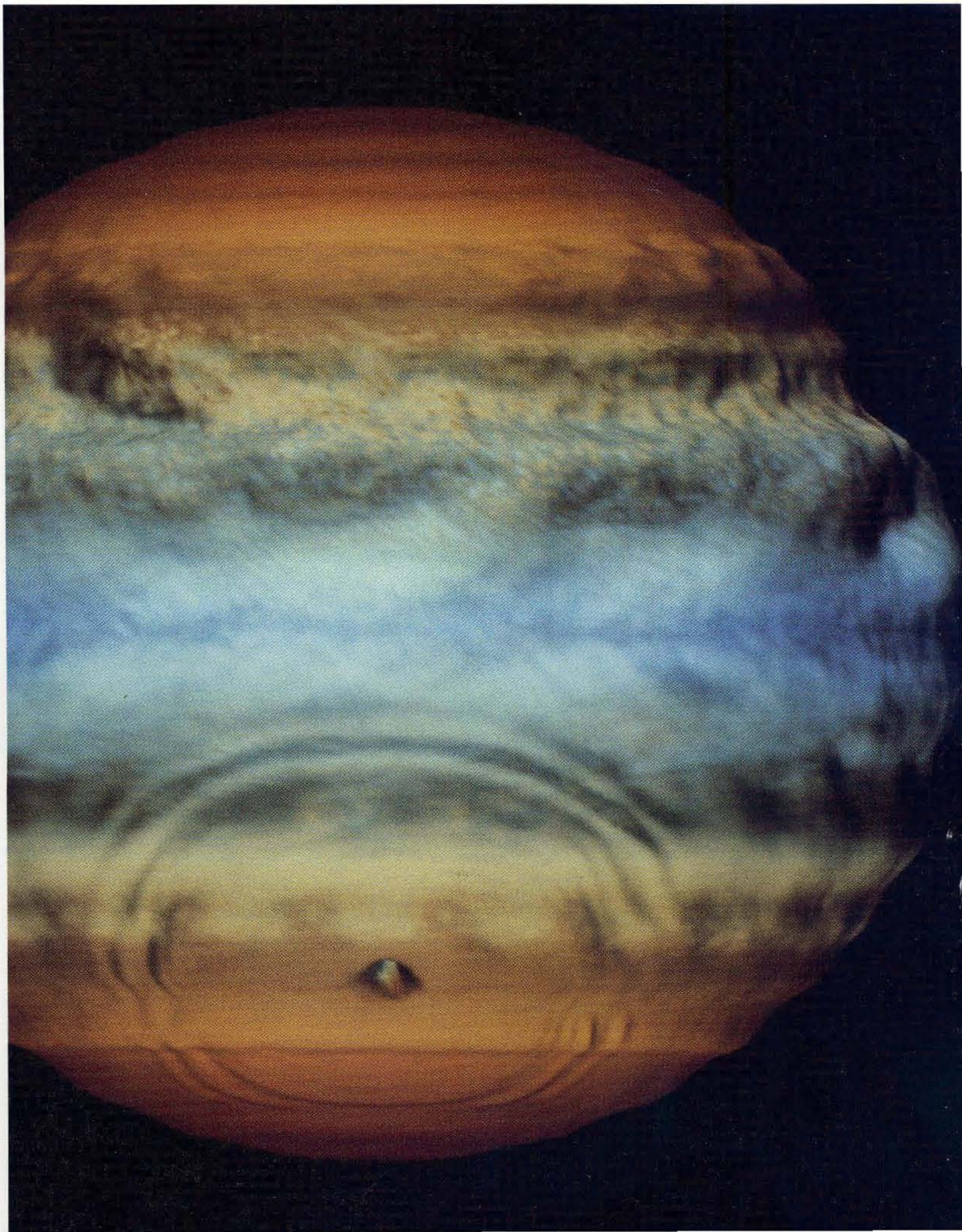

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Colliding Worlds

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Studying the rift system in Baja California demands "roughing it" in the desert for mapping expeditions. The Caltech geologists drive as far as the roads last, and then into accessible arroyos, to set up camp as close as possible to their destination. The rainy season is the optimum time for such expeditions, since there is no dependable groundwater to drink at other times, but camping in the rain, as here in the Arroyo El Canelo in 1992, is not exactly a vacation.

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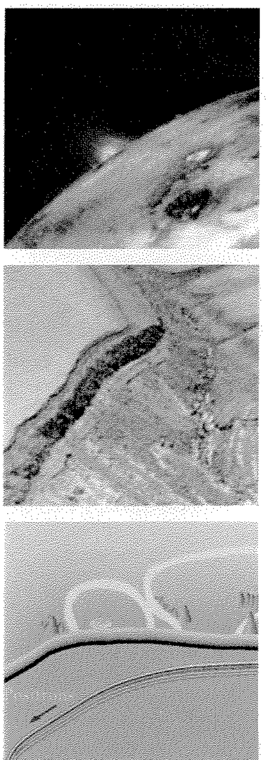

On the cover: A simulation of Jupiter's atmosphere two days after a comet fragment one kilometer in diameter hits it. The impact generates motions in Jupiter's atmosphere analagous to the ripples that spread from a rock thrown into a pond. In this image, created by a research group at MIT headed by Timothy Dowling (PhD '89), variations in height correspond to changes in pressure. What else planetary scientists hope to see when a comet hits Jupiter next summer is described in a story beginning on page 2.

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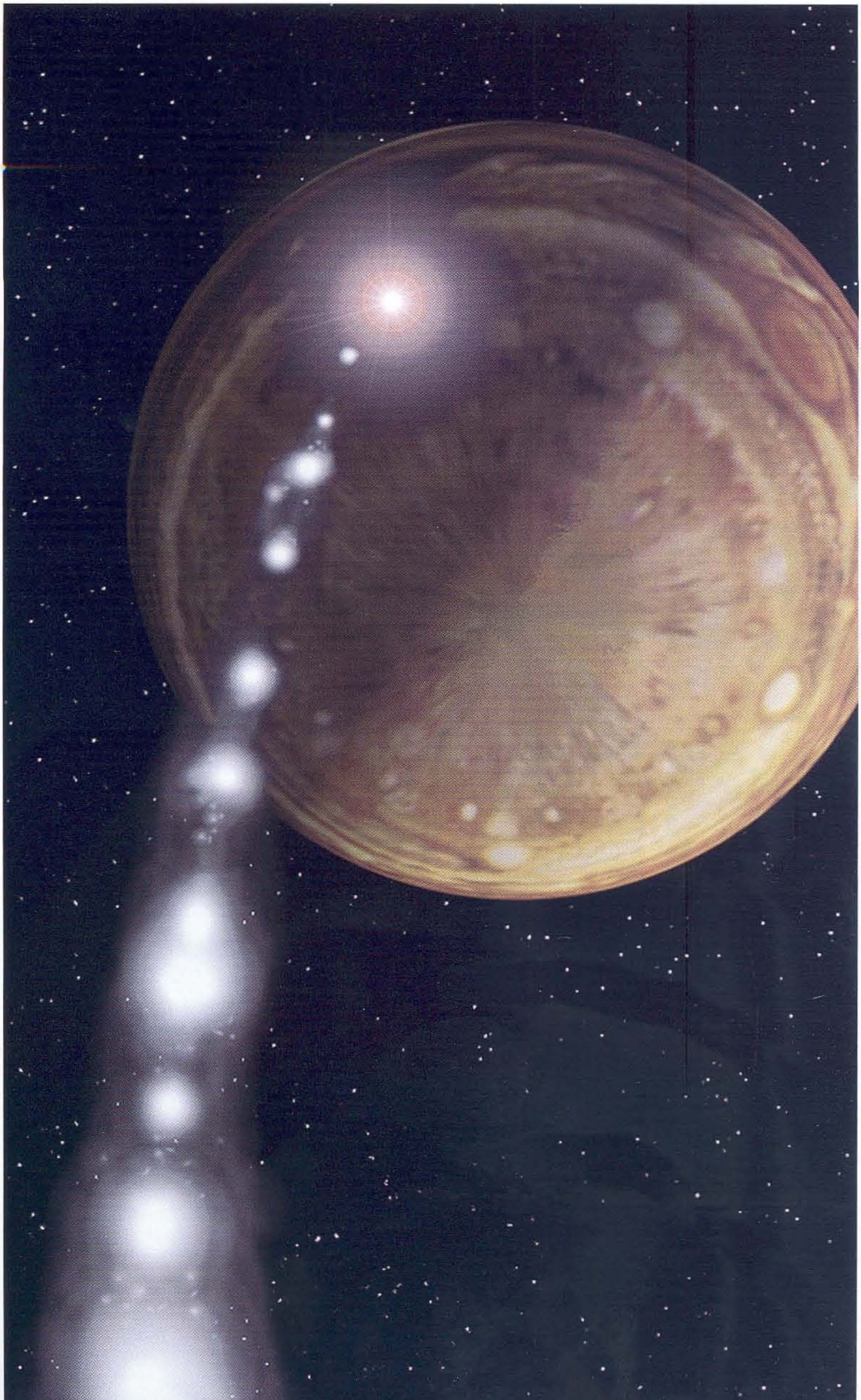


When a Body Hits a Body Comin' Through the Sky

Its fate was sealed on July 8, 1992, when the star-crossed snowball passed within 1.6 Jupiter radii (113,000 kilometers) from the center of the massive planet and was literally torn apart.

by Douglas L. Smith

Shoemaker-Levy 9's last moments, as they might appear to an observer over Jupiter's south pole. David Seal, a mission engineer on JPL's Cassini project, created this representation by wrapping Voyager data around a globe on which the impact point had been plotted. The image was generated using a computer-animation package designed by Caltech's James Blinn for the Voyagers' encounters with the outer planets, and off-the-shelf photo-editing software.

On or about July 21, 1994, a planetary hard-luck case named Periodic Comet Shoemaker-Levy 9 will perform the celestial equivalent of jumping off the Golden Gate Bridge, plunging headlong into Jupiter's atmosphere to a fiery finish. The comet had run afoul of the giant planet some time previously and been captured by Jove's gravitational field. A more fortunate prisoner might have taken up residence in a nice, regular orbit around Jupiter and started a new life as a minor moon, but this hapless hostage stumbled into a chaotic orbit, wandering footloose through the Jovian system.

In a sense, Shoemaker-Levy 9 is no more already. Its fate was sealed on July 8, 1992, when the star-crossed snowball passed within 1.6 Jupiter radii (113,000 kilometers) from the center of the massive planet and was literally torn apart. The strength of any body's gravitational attraction increases as one approaches the object, so Jupiter tugged harder at the comet's near side than at its far side. Within some distance—called the Roche limit—the difference between Jupiter's far-side pull and its near-side pull became stronger than the comet's own puny gravity. The tensile strength of the comet continued to hold it together a little while longer, but the stress soon overwhelmed the fragile comet, pulling it apart. Comets aren't put together very well—the differential acceleration that undid Shoemaker-Levy 9 was a mere 0.0016 meter per second squared. A snowball that loose would come apart in your hand. Truth to tell, it's not clear that this comet was really a snowball—the familiar periodic comets, such as Halley's, are best described as balls of dirty ice, but Shoemaker-Levy 9 could just as easily have been a ball of loose dirt and rock containing little or no ice. All we know for sure is that it was pretty shoddy construction, whatever it was made of.

When discovered by Carolyn Shoemaker on March 24, 1993, the fragments of Shoemaker-Levy 9's dismembered body were already smeared out across some 160,000 kilometers—about one arc minute of sky as seen from Earth. (The photographic plate containing the comet was exposed by Carolyn and Eugene Shoemaker (BS '47, MS '48) and David Levy at Caltech's Palomar Observatory, using the 18-inch Schmidt telescope that the late Fritz Zwicky used for his pioneering cosmological studies.) The fragments—21 identifiable ones at last count—lie in a nearly perfect straight line, causing them to be widely likened to a string of pearls. Extending ahead and behind the fragments along essentially the same line are trails of rubble—particles ranging from perhaps the size of houses down to pebble-sized—that mark the abrupt edge of a vast sheet of diffuse material. The sheet is much thicker around the fragments. The ensemble looks rather like a stealth bomber seen from above and in front, with the thick part of the sheet being the cockpit. James Scotti of the University of Arizona has looked at the cockpit more closely and discovered that it's really a set of narrow, parallel tails, which he traced back to individual fragments.

By May, 1993, the object had been tracked long enough for scientists to begin calculating its current orbit. "Shoemaker-Levy 9 is only the

The "pearls" will plummet into the planet one by one, with all the slow-motion inevitability of a train going off the end of a dynamited bridge in an old Western.

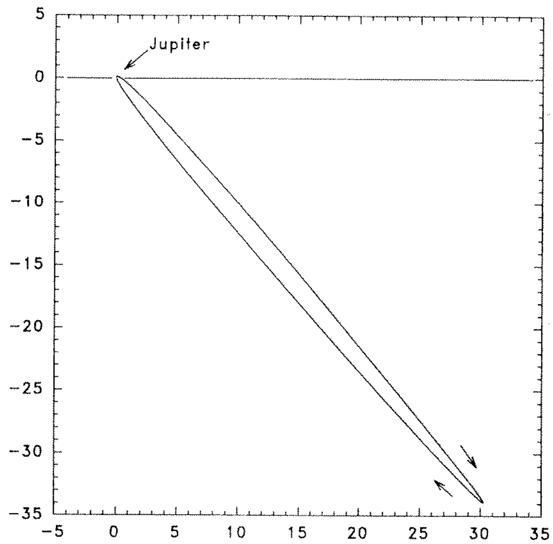
Below: Shoemaker-Levy 9 as photographed by JPL astronomers Eleanor Helin, Ray Bambery, and Donald Hamilton on March 31, 1993, using Palomar Observatory's 60-inch telescope. The inset is a close-up of the comet's fractured nuclei. Colors are keyed to the comet's brightness, with white being the brightest and red, yellow, and green regions being progressively dimmer.

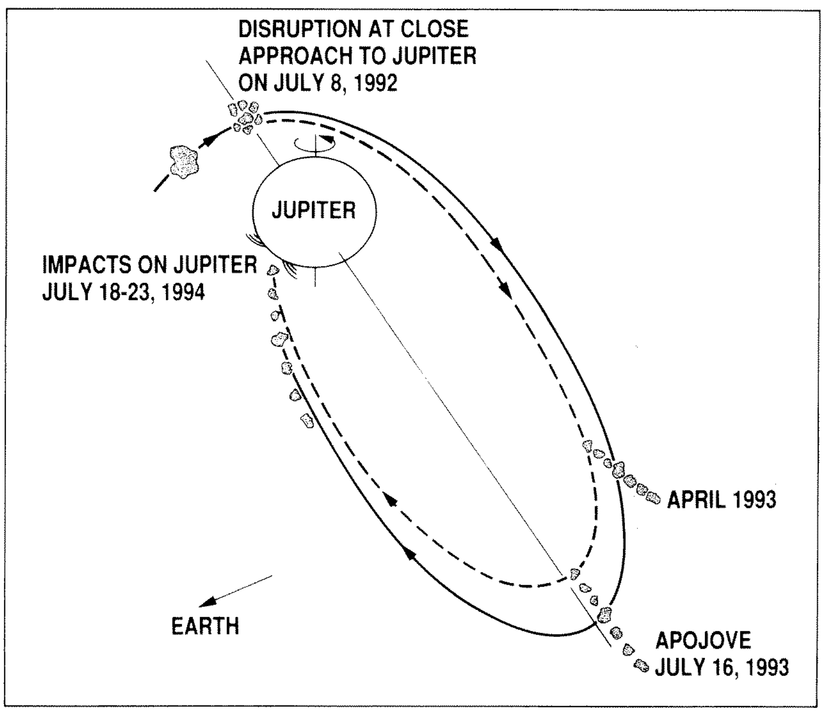
Right: What a "normal" comet looks like. This is Halley's comet, photographed by Helin on January 7, 1986, using Palomar's 18-inch Schmidt telescope. The comet has one nucleus, and a dust tail emanating from it.

second or third known comet to orbit a planet, Jupiter in all cases, and the others weren't discovered until after escaping," notes Paul Chodas of JPL's Solar System Dynamics Group. (Caltech manages the Jet Propulsion Laboratory, better known as JPL, for NASA.) And Shoemaker-Levy 9 nearly got away, too—its current orbital eccentricity is 0.996, according to Chodas. With an orbital eccentricity of 1.0, the comet would have escaped—flung from Jupiter's clutches after half an orbit. "The sun is a very strong perturber of this comet's orbit," says Chodas. "In fact, the sun's influence is about equal to Jupiter's at the far extent of the orbit." Chodas and coworkers Donald Yeomans, head of the Solar System Dynamics Group, and Zdenek Sekanina, a senior research scientist at JPL, have studied the comet's orbit in detail. This orbit, whose major axis is tilted about 50 degrees to the south of Jupiter's own orbital plane and takes a shade over two years to complete, will pass within 37,000 kilometers of Jupiter's center next summer, according to independent calculations by Chodas and Yeomans and by Brian Marsden of the Minor Planet Center in Cambridge, Massachusetts. Unfortunately for Shoemaker-Levy 9, Jupiter's equatorial radius is 71,400 kilometers. The orbital geometry is such that the "pearls" will plummet into the planet one by one, with all the slow-motion inevitability of a train going off the end of a dynamited bridge in an old Western. It should take about five days for all 21 fragments to go over the brink. (The leading rubble trail will arrive earlier, and dust and small particles will continue to shower down on Jupiter

Right: Shoemaker-Levy 9's current orbit, as it would appear from the sun on July 21, 1994. North is to the top, and the horizontal line at 0 is Jupiter's orbital plane; the axes are labeled in millions of kilometers. Jupiter is in the plane of the page, and the comet's orbit projects down and out from the page at an angle of about 40 degrees. The orbit isn't foreshortened, however—it really is that narrow!

Below: After the comet broke up, each fragment assumed its own orbit based on its point of origin. The fragments from the side farthest from Jupiter wound up in slightly larger orbits that take longer to complete, so the fragments from the comet's near side pull ahead and will hit Jupiter first. (The apojove is the point in the orbit farthest from Jupiter.)



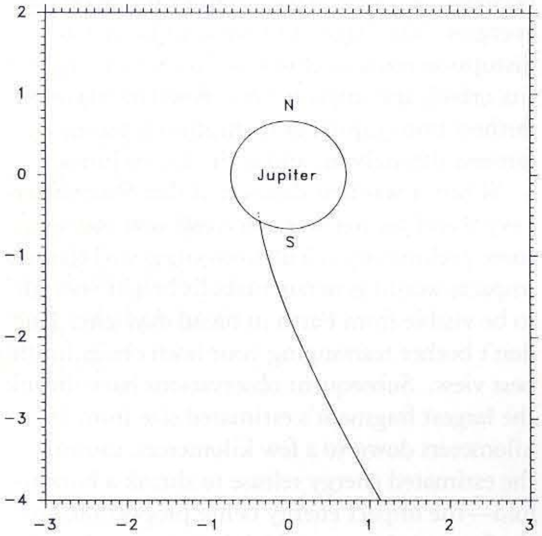


for weeks afterwards.) The fragments will roll to their fate in single file, Chodas explains, because "the pieces of the comet that were closer to Jupiter at break-up have less orbital energy than the pieces that were farther out. The pieces in between, of course, have a continuum of orbital energies. The fragment closest to Jupiter at disruption remains closest to Jupiter throughout [its orbit], and impacts first. And the fragment farthest from Jupiter at disruption remains farthest throughout, and is the last to impact."

When it was first discovered that Shoemaker-Levy 9 and Jupiter were on a collision course, some preliminary calculations suggested that the impacts would generate fireballs bright enough to be visible from Earth in broad daylight. But don't bother rearranging your lawn chairs for the best view. Subsequent observations have shrunk the largest fragment's estimated size from 10 kilometers down to a few kilometers, causing the estimated energy release to shrink a hundredfold—the impact energy being proportional to the fragment's mass, which increases as the cube of its radius. Worse, better orbit calculations show that the impacts will occur on Jupiter's far side 10 degrees beyond the limb, invisible to Earth in any case. The incoming pieces will disappear behind Jupiter a tantalizing five minutes before they hit. Even though the impacts will occur over a five-day span, we won't see any of them, because the point where the comet's path intersects Jupiter's surface remains fixed in space as the planet spins. Like a machine filling milk bottles on a conveyor belt, the orbit will dispense blobs of comet into parcels of Jovian airspace that the planet's rotation will carry into our sight some two hours later.

So is the entire episode a bust—the Comet Kohoutek of the '90s? (Remember Comet Kohoutek? Neither does anyone else.) Not exactly. JPL's spacecraft Galileo will be a mere 230 million kilometers from Jupiter, en route to a rendezvous on December 7, 1995. Galileo may be able to see just enough of Jupiter's night side so that the impacts will be on the planet's limb, giving us our only direct view of the crash site. Warns Chodas, "It is entirely possible that new orbit solutions for the comet will move the impact point back behind the limb as seen from Galileo. It's that close." The Hubble Space Telescope will have a look, too, but won't see anything any sooner than Earthbound observers. And it seems that every telescope on Earth will be watching as well.

This is, after all, the first time we have ever gotten advance notice of such a collision, giving scientists the chance to follow the process from



Above: Shoemaker-Levy 9's trajectory as seen from Earth on July 21, 1994. The dotted portion is behind Jupiter, out of sight. The axes are labeled in units of 10,000 kilometers.

Right: Hubble's Wide-Field and Planetary Camera took this close-up on July 1, 1993. The individual points of brightness are believed to represent individual comet fragments. Although shrouded in dust, they have retained their identities in every image with sufficient resolution to discern them. Two systems for naming these putative fragments have been proposed—Sekanina, Chodas, and Yeomans call the one that will be first to hit (and which is just barely visible at the very top of this image) A, with the final one (not visible) being W. (The letters I and O aren't used.) Q is the brightest fragment, while P is a double. G, H, K, L, P, Q, R, and S are bright enough to show up as white spots.

beginning to end. Wrecks of this magnitude are rare—an object this size might hit Earth once every 10 to 100 million years, according to Professor of Planetary Science David Stevenson. Jupiter is a much bigger target, of course. It also has a hundredfold larger sphere of gravitational influence that can pluck slow-moving stragglers out of nearby orbits, and lives in a more cluttered region of the solar system. Even so, Jupiter probably runs into something this big only once every hundred years. And cometary suicides are of considerable interest, as it's now generally agreed that an asteroid slamming into Earth 65 million years ago did in the dinosaurs. The remains of Shoemaker-Levy 9 are considerably smaller bodies, but their impact energies may be comparable to the blow that wiped out Barney and his kin. That's because, gram for gram, an object hitting Jupiter packs 36 times the wallop that it would on Earth, due to Jupiter's stronger gravity.

When one of Shoemaker-Levy 9's main members hits, says Stevenson, "it will plunge through the upper atmosphere of Jupiter—the part above the clouds as seen from Earth—quite quickly, on a time scale of a second or two." Galileo may see a momentary flash like the one a meteor makes when it enters Earth's atmosphere, "due to the shock heating of the gas that passes the projectile, and also the heating and ablation of material on the surface of the body as it plunges through." The fragment will then tear through the opaque veil of clouds that forms Jupiter's visible surface, leaving no trace. But not for long.

Thomas Ahrens (MS '58), professor of geophysics; Toshiko Takata, graduate student in planetary science; John O'Keefe, visiting associate in planetary science; and Glenn Orton (PhD '75), a Jovian atmosphere specialist at JPL, have run computer simulations of what happens next. The simulation consists of three parts. The first part uses a technique called smoothed-particle hydrodynamics—invented by Joseph Monaghan, of Monash University in Australia, to simulate galaxy formation and evolution—to follow the fragment's dissolution as it plunges into Jupiter's atmosphere. In the second step, the same technique is used to let the trail of gas heated by the fragment's passage expand and rise. And finally, the team has calculated the thermal radiation spectrum from the temperature and internal-energy distribution of the resulting plume, to discover what it might actually look like.

The computational key to smoothed-particle hydrodynamics is that it breaks up the object being studied into a large number of particles, in this case "atoms" of Jovian atmosphere one-tenth

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to ten kilometers in diameter, depending on their location. "Each particle behaves as if it has a set of springs around it that looks like a sea urchin," Ahrens explains. If you try to squeeze two particles together, the springs provide an opposing force that represents the properties of the object. If the object is compressible, the springs have a lot of give, but if the object isn't, the springs are stiff. The "technique is used to mimic the behavior of real materials with finite particles," says Ahrens. "The term 'smoothed particle' comes from the fact that these springs give the particles spatial extent, so that they're not point particles, but particles that are smeared over space. You can think of them as fuzz balls. When they're far apart they don't interact. When you get them close together, they start interacting, and if you really push them together hard they become quite stiff and impenetrable."

Even with this simplification, the technique isn't cheap computationally. It took Ahrens and company "hundreds of hours" of time on JPL's Cray Y-MP supercomputer to run the simulations. Says Ahrens, "At any particular point in the calculation, we were keeping track of more than 50,000 pieces of Jupiter—their pressures, their temperatures, their coordinates in three dimensions, and their velocities. It's hard to do that kind of three-dimensional calculation with other numerical methods." Other researchers have also modeled the impacts, but "most of the other calculational methods set up an imaginary grid, which is imbedded in the material, and they study the deformation of the grid." Such a grid is only a cross section, from which the three-dimensional behavior must be extrapolated.

The calculations assumed that the comet fragment being simulated entered Jupiter's atmosphere at 60 kilometers per second—the planet's escape velocity—at an angle of 40 degrees from the vertical. This angle came not from the comet's predicted impact point, which is about 40 degrees south latitude, nor from the 50-degree difference between the comet's and Jupiter's orbital planes, but from "the flight path angle of the comet on impact," Chodas explains. The comet's orbit is such an extremely flat ellipse—practically a straight line—that the comet will hook into a hairpin turn as it reaches Jupiter. It's this wrapping around, plus Jupiter's oblateness that far south, that determines the angle of entry.

Ahrens's group did two sets of calculations, for bodies two and ten kilometers in diameter. There's still considerable uncertainty about the fragments' actual size. The visible "string of pearls" is actually a set of comae—clouds of dust surrounding much smaller nuclei. Astronomers assume that the brightness of a coma is a proxy for the size of the solid nucleus within it. Depending on what other assumptions an observer makes, however, the largest fragment's estimated diameter ranges from less than a kilometer to nearly four and a half kilometers. Assuming the comet is solid ice, a two-kilometer chunk would have a mass of more than four billion metric tons. Of course, the fragments aren't all of equal size—there appear to be half a dozen relatively large pieces (including one possible doubleton), a dozen medium-sized ones, and an assortment

As the simulation continued, the hot gas expanded with the force of a hundred million megatons of TNT. (In contrast, the atomic bomb that leveled Hiroshima was equivalent to a mere 20 kilotons of TNT.)

of smaller debris. Notes Stevenson, "When you take something and break it, by hitting it with a hammer or whatever, most of the mass is in the biggest fragments. You don't get an enormous amount of stuff in fine fragments. That's true in the asteroid belt itself, and it's true—we think—of how objects fragment and coagulate as planets form. It's a very common characteristic."

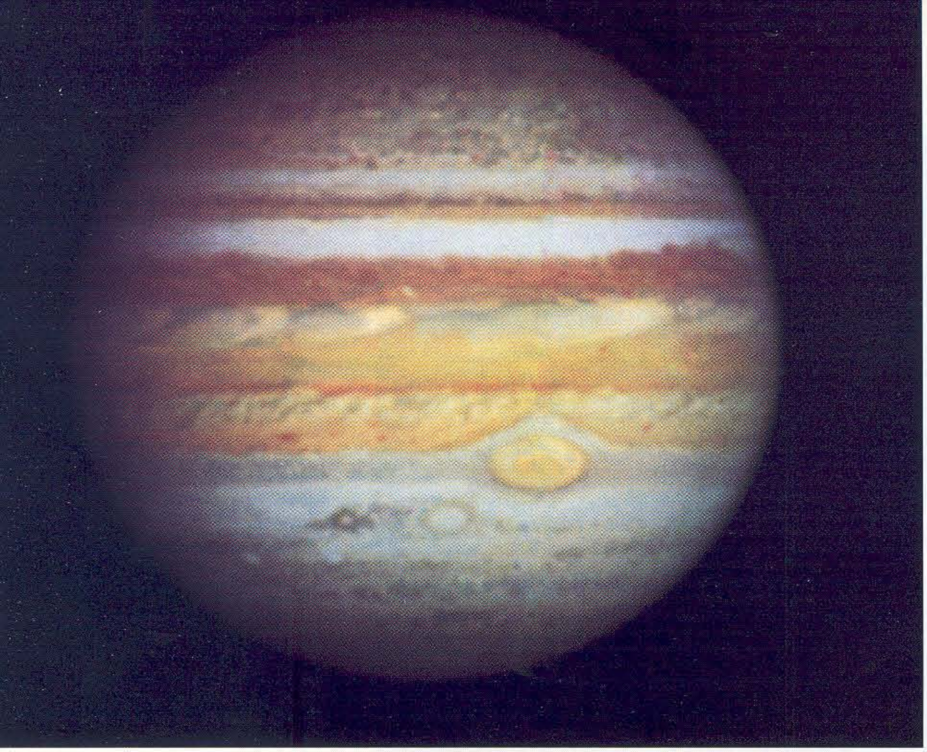
Thus the two-kilometer calculation should be about right for an average chunk o' comet. In the computer, such a fragment took about 10 seconds to disintegrate after whooshing through the cloud deck, and reached a depth of perhaps 350 kilometers before breaking up completely. (Since Jupiter has no solid surface, all depths are relative to the so-called one-bar level—the altitude where Jupiter's atmospheric pressure equals that on Earth's surface. The one-bar level is beneath Jupiter's visible surface, which is formed by ammonia-ice clouds at pressures of a few tenths of a bar.) The simulated fragment, says Ahrens, "basically kept on going at 60 kilometers per second as pieces break off, until there's nothing left. And that's how we define the depth of penetration. The reason it didn't slow down very much is that we assumed in our calculations that the comet has no strength... a high-speed drop of ice." Ice's properties under such conditions are described by an "equation of state," some of whose parameters, such as compressibility, were measured by Ahrens and O'Keefe in the 1980s. "Everything else in the calculations is just the laws of physics—conservation of mass, momentum, and energy. The equation of state is really the only ground truth that we put into these calculations, both for cometary ice and Jupiter's, mostly hydrocarbon, atmosphere. But it's a very important ground truth."

The simulated fragment punched a hole in the atmosphere—a thin, inverted cone like an upside-down wizard's hat that was perhaps 10 to 100 times less dense than the gas around it. The projectile's supersonic passage also piled up a tremendous shock wave—a sonic boom of deafening proportions, were anyone there to hear it. This and other processes converted roughly 60 percent of the fragment's kinetic energy into heat, most of which wound up in the atmosphere at depths between 125 and 225 kilometers. (The shock wave continued to propagate into Jupiter's interior, even after the fragment has vaporized.) The gas lining the hole was hot enough to emit a flash of white light—a continuation of the meteor streak Stevenson described, now diffused by the clouds overhead. "If you were in a position where you happen to be looking down the hole," says Ahrens, "which of course nobody will be, you'd see a very high-intensity source. If you were off to the side, you might see scattered light, like lightning in the clouds—you wouldn't actually see the lightning bolt, you'd see a glow." The nearby moons Io, Europa, and Ganymede may reflect a detectable bit of this glow to Earth.

As the simulation continued, the hot gas expanded with the force of a hundred million megatons of TNT. (In contrast, the atomic bomb that leveled Hiroshima was equivalent to a mere 20 kilotons of TNT.) Most of this explosion's oomph came from that sizzling 100-kilometer stretch where the bulk of the heating occurred. Says Ahrens, "It's not really a point-source explosion, it's more of a line source." This explosion created a balloon of hot, low-density gas analogous to the fireball from a nuclear blast. Most of the material from the fragment, now nothing but superheated hydrogen and steam, ended up in the balloon's skin. The fireball rose along the path of least resistance—the original entry wound—spewing out of a 200-kilometer-wide hole in the clouds as a plume containing some billion tons of gas. "That plume is really moving," Ahrens exclaims. "There's a lot of energy there! You wouldn't want to be in its way." The plume grew at a rate of perhaps 10 kilometers per second, exhausting its upward drive several minutes later some 3,000 kilometers above the cloud tops, creating an object that would easily be seen from Galileo.

The computer-generated plume gave off both infrared and visible light—its temperature was "on the order of 2,000 to 3,000 kelvins, which is hot, but not overwhelmingly hot," says Ahrens—but the brightest glow was in the infrared, in the 1–10 micron band. This glow radiated as much power—about 10^{24} ergs per second for several minutes—as the entire day side of Jupiter. In other words, this tiny plume—perhaps 700 kilometers wide at its top, compared to Jupiter's 143,000-kilometer equatorial diameter—packed a planet's worth of brightness. Furthermore, Jupiter's natural thermal radiation is in the 100 micron band, according to Ahrens, so the plume's light should be easy to distinguish. The glow began dimming immediately as the heat radiates off into space, but by the time the simulated impact point would roll into view from Earth some two hours later, the plume could still be 10 kelvins hotter than the surrounding atmosphere, a temperature difference readily detectable by terrestrial telescopes.

"It won't really be an impact," say Ahrens. "It'll be more like a soft catch, in the sense that there'll be great penetration, but not really any ejecta thrown out. If you had the same kind of



This photo of Jupiter was shot by Hubble's Wide-Field and Planetary Camera on May 28, 1991. The Great Red Spot is visible at lower right. To the left and below the Red Spot is one of three white ovals that were born about 1931. This white oval is roughly 7,000 kilometers wide, and may contain the same amount of kinetic energy as a two-kilometer-diameter comet fragment. Spots come in all sizes, including those too small to see in this image.

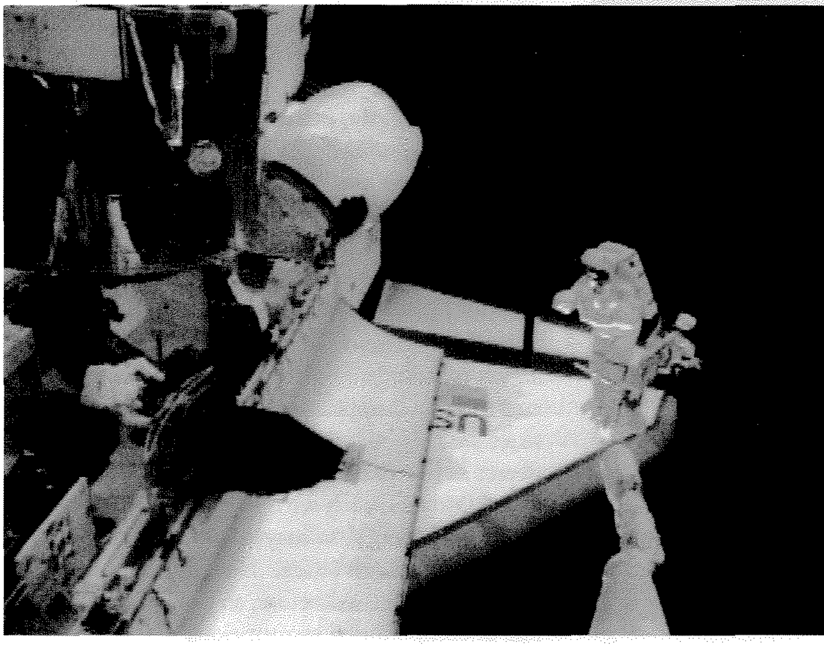
impact on Earth, it would be an erosive impact, meaning that there would be more material thrown off Earth than put on. The material would reach escape velocity." But Earth's escape velocity is a mere 11 kilometers per second to Jupiter's 60. And struggling free of Jupiter's dense, bottomless atmosphere would be like swimming up to the surface of a swimming pool filled with Jell-O.

The infrared welt shouldn't be the only phenomenon visible from Earth. Says Professor of Planetary Science Andrew Ingersoll, four billion tons of water "could cover a band of Jovian latitude 10 degrees wide with a layer of ice crystals one micron thick. And that's enough to make an opaque layer. But in addition to the mass of the comet, you can dredge up a lot of water vapor and stuff from Jupiter's deep atmosphere." The layer would probably be white. "Most of the things that you condense from a comet, like water, are white crystals. The colors on Jupiter are caused by more complex reactions that take some time." How much water is deep within Jupiter is one thing scientists hope to learn from this event, but it will be a difficult number to extract from the observations—you have to subtract the water contributed to the plume by the comet, whose size and composition is uncertain. "That's the reason for doing all this modeling."

When you toss a rock in a pond, you see a splash, followed by spreading ripples. The comet's splash will be out of sight from Earth, but Timothy Dowling (PhD '89) at MIT, his graduate students Joseph Harrington, Raymond LeBeau, and undergrad Kari Backes have concluded that we may see the ripples. The ripples would extend vertically through the stratosphere, which is clear, and the troposphere, where the visible cloud surface lies. These waves wouldn't be visible directly, but as a subtle temperature difference—about half a kelvin—between a wave's peak and its trough. Such temperature changes may be observable in the stratosphere's thermal-infrared emissions, showing up as parcels of gas that register as hotter or colder than their surroundings. But the ripples should be easiest to see in the cloud layer, where disrupted condensation patterns may alter the clouds' reflectivity, and thus their appearance. "The wave temperatures we're predicting are going to be hard to detect at best," Harrington warns. "We do have over 20 nuclei, each with a different detonation depth and energy, so maybe a few will make waves big enough to see. Needless to say, this has never happened before, so predictions are full of compounded assumptions."

The speed at which the ripples spread through the narrow cloud layer will depend on the temperature difference between the tops and the bottoms of the clouds, and on their thermodynamic properties. This, in turn, will allow scientists to derive the radius of deformation, a parameter that describes how the atmosphere's density increases with depth. Ingersoll is skeptical that the waves will actually be visible, but "if we can see 'em, it will provide information about the thermal structure down in the clouds. And that's something we'd love to know. All our models of the Red Spot and the long-lived ovals depend on this parameter. In fact, that temperature structure is the big unknown that prevents us from doing a definitive model of the dynamics of the atmosphere. We argue about what that structure is, and construct models where we vary that structure, but it would sure be nice to measure it."

Since Jupiter is not only a fluid planet but a rapidly spinning one, the gas displaced by the comet's splash will get a twist from the planet's rotation and become a whirlpool. If a vortex forms, it will almost certainly linger long enough for Jupiter's rotation to bring it into Earth's field of view, says Ingersoll. Its size will depend on the atmosphere's density structure, which is determined by that radius of deformation that Ingersoll hopes to derive, but it could be 1,000 kilometers in diameter. (A feature this size would be below the atmospheric distortion limit for ground-based telescopes, but could be seen by the Hubble, which orbits above Earth's atmosphere.) "Then what happens is not so clear, because of the shear zones on Jupiter—the alternating jet streams. Vortices with the wrong spin



Since there could be as many as 21 such vortices, we may be treated to the sight of them playing Pac-Man with one another, eventually forming one or more semipermanent bruises on Jupiter's face.

You may close now, Doctor. The white panel at upper left is the back end of the new Wide-Field and Planetary Camera, which has just been installed in the Hubble Space Telescope. Payload Commander Story Musgrave balances the old camera on the edge of the cargo bay, while Mission Specialist Jeffrey Hoffman rides the shuttle *Endeavour's* robot arm.

for the shear zone they're in get ripped apart very quickly. If they have the right spin, then they tend to roll like ball bearings and can last as long as the Red Spot, in principle, although they tend to get swallowed up by each other. They merge." And since there could be as many as 21 such vortices, we may be treated to the sight of them playing Pac-Man with one another, eventually forming one or more semipermanent bruises on Jupiter's face. After all, four billion tons hitting at 60 kilometers per second has got to hurt!

Such blemishes are common features on Jupiter. In addition to the Great Red Spot, which has graced the planet in one form or another since at least 1665, when Giovanni Cassini saw it, Jupiter boasts hundreds of smaller ovals that live for months or years before merging or disappearing in Jove's roiling atmosphere. Smaller is a relative term here, as the ovals range from 700 to 7,000 kilometers in diameter, the latter being about one-third the diameter of the Great Red Spot. (By comparison, Earth is slightly less than 13,000 kilometers in diameter.) According to Ingersoll, assuming that these twisters run from the top to the bottom of the cloud layer like a knot in a plank, then one of the larger white ovals has approximately as much kinetic energy as a two-kilometer comet fragment, while the Great Red Spot has about as much as a five-kilometer piece. "That doesn't mean that you can convert all the energy of the comet into a steady, standing vortex. That's too much to ask. It could be like one of those champion divers who just slips into the water without making a ripple."

Something else that's apparently too much to ask is to be able to look down the eye of the hurricane and get a direct glimpse of the atmosphere beneath the clouds. The vortex will probably be filled with clouds of its own—the water vapor and whatever other warm gases get dredged up from below will condense out in the colder stratosphere. The vortex will be a high-pressure region, or anticyclone, says Ingersoll, because it was produced by hot, expanding gas. The Great Red Spot and the white ovals are also anticyclones, and their cloud-filled centers give them their color.

So, although lawn-chair astronomers will be disappointed, the planetary-science community is mobilizing for the show. Jupiter will be in the evening sky, and at Palomar's latitude, will set around 10:30 p.m. Pacific Daylight Time. Ground-based observers will get the best view of the infrared and microwave regions of the spectrum. Aloft, the Hubble Space Telescope's replacement Wide-Field and Planetary Camera will see Jupiter unblurred by Earth's distorting atmosphere—assuming the space shuttle's service call was as successful as it appears to have been. WFPC2, designed and built by a Caltech/JPL collaboration, has optics to compensate for Hubble's misground mirror. Ground controllers will need "several weeks" after the repair mission to restart the telescope's instruments and check out the new optics, according to Professor of Planetary Science James Westphal, a member of the collaboration.

JPL's Glenn Orton is organizing part of a worldwide network of infrared astronomers who will keep Jupiter under 24-hour watch during

Two of the three radiotelescopes that make up the Owens Valley Radio Observatory's millimeter-wave array.

the impacts, and a less frenetic eye on it before and afterwards. The infrared is a good place to look for a number of phenomena. The ripples predicted by Dowling and Harrington might show up in several ways. The thermal-infrared differences between the waves and troughs should be visible at wavelengths greater than 16 microns (millionths of a meter), with different wavelengths corresponding to different pressures and thus altitudes. The waves could also be visible in the troposphere above the clouds as perturbations in the 13-micron radiation emitted by colliding hydrogen molecules, says Orton. And although Jupiter's cloud layers are very reflective, they're normally hard to see at certain wavelengths between 1 and 4 microns in the near infrared, because the methane and hydrogen gas above them strongly absorbs those wavelengths. "Thus, the 'background' clouds are barely detectable [at those wavelengths]," says Orton. "However, the deposition of sufficient amounts of reflecting particles in the upper atmosphere will produce a bright spot with respect to the rest of the planet... There may also be perturbations of deep cloud properties, as observable through Jupiter's best atmospheric window at 5 microns." Hydrogen (Jupiter's stratosphere and troposphere are more than 90 percent hydrogen) and methane don't absorb at 5 microns, allowing the clouds below to be seen. Infrared astronomers can also detect water directly, as well as enhanced amounts of ammonia from the lower atmosphere. If the impact is sufficiently penetrating, it might even launch detectable amounts of "H_2S or other trace constituents such as SiH_4 or AsH_3 from the *very* deep atmosphere." The mixing ratios of stratospheric hydrocarbons may be disrupted as well. All of the above are detectable between 5 and 14 microns, according to Orton.

Palomar's 200-inch Hale telescope will also dedicate 11 or 12 evenings to watching Jupiter, says Keith Matthews (BS '62), a member of the professional staff in physics. "We can actually see Jupiter in the afternoon in the infrared, but you do have to worry about the sun's glare." The Hale will be outfitted with two instruments, the Cornell Spectrocam 10, an imaging spectrometer that covers the 10–20 micron range, and a Matthews-built imager that sees in the 1–5 micron range.

Professor of Planetary Science Duane Muhleman and Tony Phillips, research fellow in astronomy, will be using Caltech's Owens Valley Radio Observatory to follow the action in the microwave band. They will be mapping Jupiter's emissions at 3 millimeters. "There is so much [gaseous] ammonia in Jupiter that nearly all the radiation from below is absorbed between 1 millimeter and 10 centimeters," forming an opaque surface at those wavelengths, says Muhleman. "If the ammonia weren't there, we could see deep in, but we only see down to one bar. When the comet explodes at about 10 bars' pressure, it will make a great disturbance in the ammonia gas." The gas molecules will re-emit some radiation at 3 millimeters, with the intensity of the emission proportional to their temperature. The impact could register as a cold region, marking where upwelling ammonia has been cooled to a temperature below the background temperature emitted at the altitude where the gas originally was. (Ammonia thrown too high freezes, and ammonia ice doesn't absorb these wavelengths.) Alternatively, the impact might show up as a hot spot if the ammonia ionizes or decomposes, revealing warmer radiation sources below. Either way, the temperature distribution will reveal the size of the explosion, and help elucidate its physics. "We will be checking the theorists' calculations," says Muhleman, "and looking for things nobody predicted. Because you never see what's predicted—it's always something else." Muhleman's team will also be using the Very Large Array in Socorro, New Mexico to look at the 6-centimeter band, another handy wavelength for ammonia, in cooperation with Arie Grossman (MS '87, PhD '90), now at the University of Maryland.

JPL's Galileo, Ulysses, and Voyagers will also attend from their vantage points in space. Ulysses doesn't carry a camera, but all four spacecraft will listen for radio signals. During the fragment's last few hours of life, it will traverse the inner reaches of Jupiter's magnetosphere—the region of space dominated by the planet's magnetic field—where lurk belts of intense radiation similar to, but thousands of times stronger than, Earth's Van Allen belts. Both sets of belts contain high-energy protons and electrons trapped and accelerated by the planet's magnetic field. Interactions between the fragment and these particles should generate radio waves at frequencies below and in the AM radio band, as well as electrostatic waves. These waves could be detectable by an assortment of instruments on board the various spacecraft. "There's so much energy involved that it doesn't take a very high degree of conversion efficiency to see an effect," says Torrence Johnson (PhD '70), Galileo's project scientist.

Of the paparazzi spacecraft, Voyager 2 has the best viewing angle, being on Jupiter's night side and south of the ecliptic plane. Unfortunately, Voyager 2 is also 6.3 billion kilometers away, heading in the general direction of Proxima Centauri after having taken a close look at Neptune in August 1989. The spacecraft's cameras were turned off soon after, as no one thought there was anything more to see for the next several thousand years. The camera software was then deleted from onboard and ground computers in order to streamline spacecraft operations and save money, according to Voyager Project Manager George Textor. Re-creating that software and making the other modifications needed to turn the cameras back on would take considerable effort and expense at a time of very tight budgets, and it isn't going to happen. However, the spacecraft's ultraviolet spectrometer is still running, and will be watching Jupiter.

"It's like a sports photographer with a manual frame advance taking a bunch of pictures at a game, and hoping to catch someone scoring in one of them."

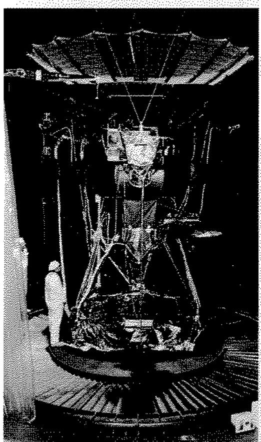
Thus Galileo will have the only working camera with a direct view—albeit in profile—of the comet's last moments, assuming the point of impact doesn't move beyond the horizon as orbital calculations improve. The spacecraft will take several dozen pictures bracketing the predicted impact times of the brightest fragments. The exact moment of each fragment's impact won't be known until an hour or two beforehand, and command sequences, including camera instructions, will have to be finalized well in advance. (In fact, the flight team is going to start writing them in March.) Remarks Johnson, "It's like a sports photographer with a manual frame advance taking a bunch of pictures at a game, and hoping to catch someone scoring in one of them. I've tried to do this at my daughter's soccer games, and it's tough." At its fastest speed, Galileo can take one picture every $2^1/_3$ seconds. The second-fastest speed is one every eight seconds.

Because Galileo's main antenna is stuck, the pictures will go on a tape recorder for playback to Earth over the much smaller low-gain antenna. But each image contains 5,000,000 data bits, according to Project Manager William O'Neil, and playing back just one at the low-gain antenna rate of 10 bits per second would take "nearly a week of near-continuous downloading." The Galileo project has requested three months of near-continuous tracking time on the Deep Space Network, which NASA uses to communicate with all its spacecraft, in order to download the equivalent of seven to ten full-frame images. In fact, most of each image will be blackness, as Jupiter will fill only about one-eighth of the frame at that range. So the flight team plans to play back just the Jupiter-containing portions of the images, which is relatively easy because Jupiter's exact position in each frame will be known in advance. And since tracking time will be limited, the engineers want to transmit to Earth only those frames containing impacts. Enter Galileo's Near-Infrared Mapping Spectrometer (NIMS) and Photopolarimeter Radiometer (PPR), which take data much faster than the camera. Jupiter will barely fill a single pixel in NIMS and cover a mere one-sixth of the PPR field of view, but if any of the impacts are as bright as Jupiter's day side, as advertised, the flare-up(s) will be obvious. So by looking at the NIMS and PPR data (which are encoded in much smaller numbers of bits) first, the flight team will know which frames to play back. The PPR has a 0.25 to 0.5 second time resolution, adds Orton, who is a co-investigator on the instrument, so if the fragment's meteoric career is bright enough, it may be resolvable into a time sequence.

At Galileo's range, one camera pixel will cover a square of Jovian real estate 2500 kilometers on a side, comparable to a medium-quality telescopic image from Earth. A plume would just about fill a single pixel from top to bottom, so there's no chance of resolving detail. But Galileo's camera should be sensitive enough to see the lightning-in-the-clouds glow predicted by Ahrens, as well as the above-cloud flash (if the frame-advance timing is lucky) and the plume. The spacecraft will see Jupiter in three-quarter view with a dark limb, says Johnson, and the impact will look like "a bright star right on the limb. We'll measure how bright it is, and see how the brightness changes with time. This will tell us about the physics of the impact—how deep it went, which will tell us the size of the comet." Galileo might also see a glint from material spattered high enough above the planet's night side to catch the sun.

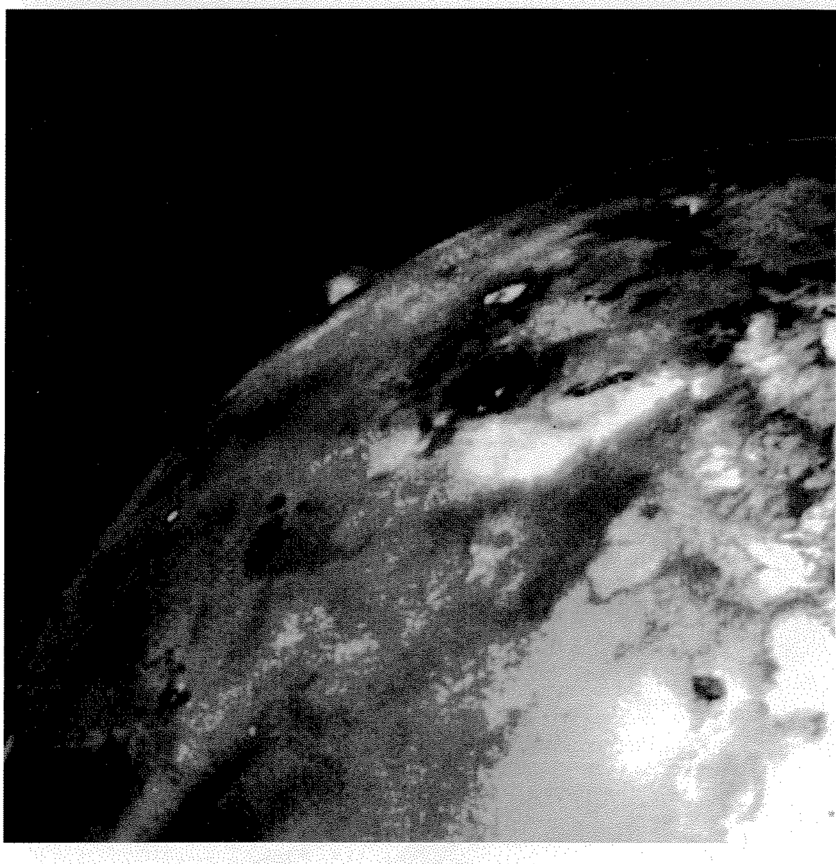
Galileo could also use its ultraviolet spectrometer to look at the ring of plasma surrounding Io, Jupiter's volcanic moon. The volcanoes spew sulfur dioxide, which Jupiter's magnetosphere promptly ionizes to create the ring. These sulfur and oxygen ions glow brightly in the ultraviolet, so a comet-induced change in the magnetosphere could noticeably affect the plasma glow.

Combining all these observations will enable theorists to practice forensic planetology and work out the details of the comet fragments' lemming-like demise. Remarks Johnson, "Comet impacts are a very-big-ticket item right now in the theory of the evolution of planetary atmospheres—it's a way to blow off layers of atmosphere—but all these theories depend on whether we have the right fairy story about the physics of impacts."



Left: Galileo being tested at JPL.

Below: Io, Jupiter's volcanic moon, as seen from Voyager 1. A volcanic plume rising some 300 kilometers above the Ionian surface is clearly visible in profile on the moon's limb. Galileo should see Shoemaker-Levy 9's impacts from a similar perspective, although unfortunately not in such detail.



Jupiter and its comet disappeared behind the sun late in July. But on December 9, the University of Arizona's Scotti and T. Gehrels found it again "under difficult conditions in the dawn." And JPL's Yeomans is coordinating a campaign of observations to hone the orbit estimates and reduce the uncertainties in the impact-time predictions. Says Chodas, "Right now, the uncertainties are a fair fraction of a day, and we're trying to get them down to minutes, which is a challenging problem. We're five AU from Jupiter, so our angular observations are not that accurate. [An AU, or Astronomical Unit, is the average distance from Earth to the sun—150 million kilometers.] We're seeing this on a single orbit, so we don't have the benefit of a long data arc to fit an orbit through. And finally, what do you measure? We were measuring the center of the train of fragments, and that's a very ill-defined point. But observers are now measuring the positions of individual fragments. That, of course, is 21 times more work for us. So it's a formidable problem." And ultimately, as Ingersoll says, "We are very much at the mercy of the size of the comet. You can't just go out and measure the size, because comets are surrounded by little clouds of dust, and you might be measuring the size of the dust cloud. And the dust cloud is so low-density that having a great big dust cloud doesn't mean very much."

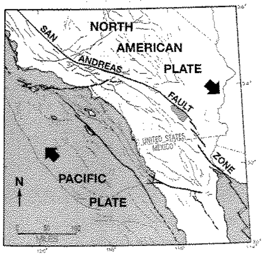
What with uncertainties in the fragments' orbits, compositions, diameters, and masses, everything is still very much up in the air. We won't know what's going to happen when Shoemaker-Levy 9 buys the farm until it happens. But whatever happens in the wake of the dear departed's passage, it's a wake that a lot of scientists are planning to attend. □

Baja California: The Geology of Rifting

by Joann M. Stock

You can think of Baja California as a fragment that used to be firmly attached to North America, but that has been pulled away along with everything else west of the San Andreas fault.

Left: Blocks cut by a series of faults have tilted over like dominoes as the Pacific plate pulled away from the North America plate in Baja California, stretching and deforming the surface. At lower left, white ash overlies the edge of a darker volcano, the same volcano shown on page 19. (Photo by John Shelton)
Below: The Pacific plate and the North America plate meet at a complicated boundary; they are sliding past each other along the San Andreas fault system in California, but farther south are moving apart.



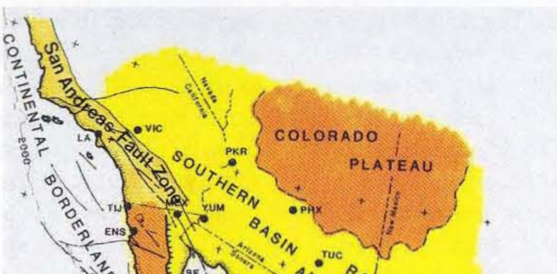
Those of us who live in the Los Angeles region know that this is an area of active tectonics. We have earthquakes; we have many large mountains nearby that are testimony to the great power of the forces that are moving and deforming the surface of the earth here; and we have the San Andreas fault as our local tourist attraction. But this great fault is not just local. Besides extending northward it also continues south toward the Gulf of California, where a series of structures represents its continuation under water. All of these structures are part of the major boundary between the Pacific plate and the North America plate. So even though we don't think of Los Angeles and the Gulf of California as being similar in many ways, they're tectonically connected because they sit on the same plate boundary and suffer many of the same kinds of deformation due to motions between these two plates.

The Pacific plate and the North America plate are two of many plates that are moving relative to each other on the surface of the earth. As these plates move, they control the main zones of active deformation, including volcanism, faulting, folding of rocks, and earthquakes. These plates are very thin—about 100 kilometers thick—in relation to the radius of the earth, which is about 6,400 kilometers. This thin skin of rigid material (the lithosphere) floats on top of a separate system of convecting mantle, which surrounds the earth's core. Deformation on the surface is mostly concentrated along the boundaries where these rigid plates are bumping up against each other or drifting apart. Because the plates are moving on the surface of a sphere, the geometry of the boundary is usually complicated, and the regions where the plates meet often look quite different from one another, even along the same boundary. There are places, for example, where the Pacific plate is just sliding by the North America plate sideways. This is characteristic of the San Andreas fault system in California; we think of North America holding still and the Pacific plate sliding northward. In Alaska, however, the Pacific plate is bending down and pushing underneath North America, where these two plates collide in what we call a zone of compression or convergence, or a subduction zone. Zones of compression typically form chains of volcanoes, such as the Cascades in Oregon and Washington or the volcanoes along the Aleutian islands in Alaska. But in the Gulf of California, where the boundary between the Pacific and North America plates is at a slightly different angle, the plates are actually moving apart. This rift has opened up the gulf itself.

The moving plates form a self-consistent system of rigid caps, so that while some lithosphere is getting pushed down under overriding plates, new lithosphere is constantly forming where the plates are moving apart. This usually occurs between oceanic plates, at midocean spreading centers, where new magma circulates up through the crack. As the plates move apart, at rates of typically a few centimeters per year, new undersea volcanism freezes onto the edge of the plates, making them bigger and adding a zone of new ocean floor in the middle of the existing ocean.

In the Gulf of California, the relative plate movement is about five centimeters annually.

Below: The San Andreas fault system continues into the Gulf of California creating strike-slip faulting through the extensional province. Yellow indicates land that has undergone extension, while the orange areas to the west and east have remained relatively stable. The region of Baja California discussed here is near the northwest corner of the gulf, roughly between San Felipe (SF) and Puertecitos (P). The Landsat image at upper right shows that area (San Felipe is in the top right corner bordering the gulf). In this false-color image, blue (band 1) represents blue visible light, green (band 4) is near infrared, and red (band 7) is middle infrared. The escarpment runs diagonally down from top left. The red volcanic rocks just below the center are a series of volcanoes about 6 million years old, aligned along normal faults parallel to the escarpment. (Image processing was done at JPL by R. Crippen, L. Barge, M. M. Miller, and J. M. Stock.)



Where the faults of the San Andreas system begin to plunge into the gulf, we expect to see, in addition to strike-slip faults, extensional faulting caused by the stretching of the plate as it pulls away and by the uneven geometry of the edges of the plates, which opens up extensional basins as the irregular pieces slide past each other. The Salton Sea is in one such extensional basin. What's happening under the waters of the gulf is a bit hard to map because of all the sediment that has spilled in from the Colorado River. But geophysics has played a useful role in locating the earthquakes that demarcate some of the active faults within the gulf, and from the seismicity it appears that this end of the San Andreas system continues to be a very complicated boundary.

My work has focused on a region in the northeast corner of Baja California, which has in particular suffered extensional faulting and deformation due to the gulf's opening. This area is dominated by a high mountain range, part of the Peninsular Ranges running from Mount San Jacinto to San Diego, crossing the international border, and continuing down into northern Baja California. There's a very abrupt topographic escarpment on the eastern side of the Peninsular Ranges, which in general coincides with a set of active faults. Many of the faults in this region are seismically hazardous, as are most of the faults of the San Andreas system; a magnitude 6.8 earthquake occurred on the San Miguel fault in northern Baja California in the 1950s, but most haven't been active very recently. Basically, everything to the east of that escarpment has been extended due to gulf-related faulting, while

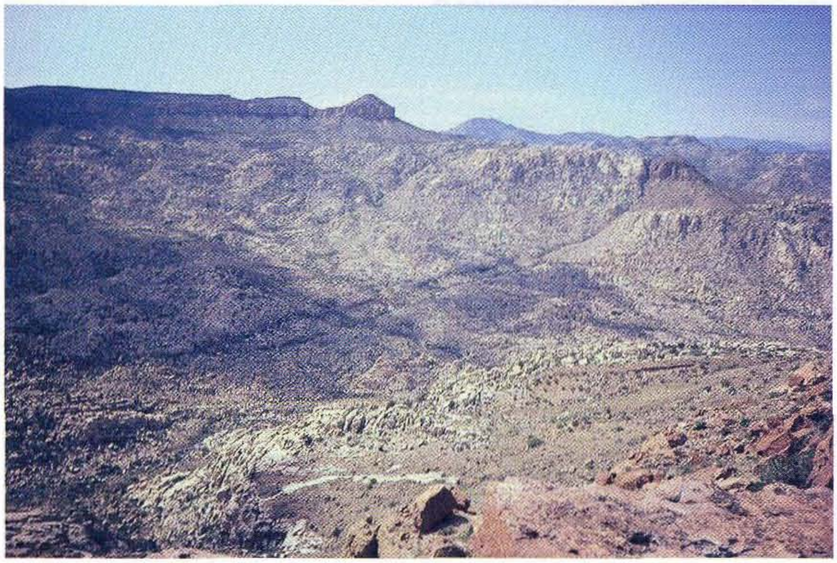
Left: The view east over the extensional province from the edge of the escarpment is a bleak landscape of desert basins and ranges. Below (top to bottom): View north along the escarpment near Valle Chico; grad student Tim Melbourne collecting paleomagnetic cores; and Arturo Martín of CICESE measuring striations on a fault plane.

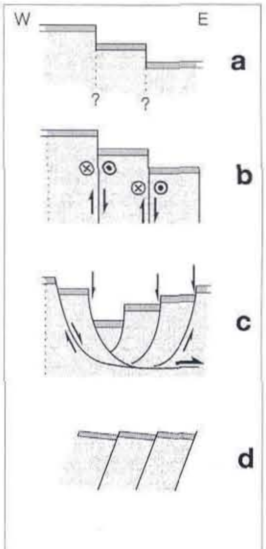
material to the west is relatively unextended and geologically stable (not deforming). On the map on the opposite page, yellow indicates all the areas that have been extended. The orange region has been relatively stable in recent geologic time; that is, there are not a lot of faults or tilting or earthquakes. This rift system is very asymmetric: it's much wider east of the gulf, on mainland Mexico, than west of the gulf, in Baja California; but on the western edge it's well exposed, while on the mainland much of it is buried under sand; the geology of that region still has much to tell us that hasn't yet been discovered.

The landscape of this northern corner of Baja California resembles a combination of the Sierra Nevada and the Mojave Desert. Looking out from the edge of the escarpment to the east over the extensional province, you see a series of basins and ranges, much like the Mojave or other desert regions in California. And like those deserts, it's full of rattlesnakes and cactus, but that doesn't stop us from mapping there.

When my students and I (along with our Mexican colleagues from the Centro de Investigación Cientifica y de Educación Superior de Ensenada—CICESE) go on mapping expeditions, we generally drive as far as we can if there are roads at all or arroyos we can drive in; then we camp for about a week and just hike out from the main campsite. If there are no roads where we want to go, we backpack in. For those excursions we have to wait until rainy times of the year so that there's water to drink; much of this region has no year-round groundwater. On our trips we spend our days walking around, mapping the rocks, making detailed geologic maps, and collecting samples to take back home to date and do lab work on. We pay particularly close attention to the faults that cut the rocks. By studying fault planes—measuring their orientation in map view, studying how they're inclined, and looking at the directions of the striations that formed as the two sides slid by each other—we can determine how much displacement has occurred on the fault and in what direction. And if we know the age of the rocks we can tell when it happened.

Two other kinds of geological research—studies of the magnetization directions of volcanic rocks, and remote-sensing data—have helped us put together the picture of this region's geologic evolution. Professor of Geobiology Joe Kirschvink and his Caltech paleomagnetics class have collected a lot of data that's been very useful to us. They drill cores in the volcanic rocks and then take them back to the lab to analyze the direction of the magnetization. (Because the direction of the magnetization is locked in when the rock cools, it reflects the direction of the earth's magnetic field at the time of the volcanic eruption. Since the direction of the earth's magnetic field lines is always slowly varying, and completely reverses every few hundred thousand years or so, each volcanic layer, or unit, acquires a direction that should be constant from place to place within the unit, but that might be different from the direction of magnetization of units that are older or younger.) We can use this information to determine whether in some regions the rock has been rotated about vertical axes since it was deposited, and we can also use it to tell





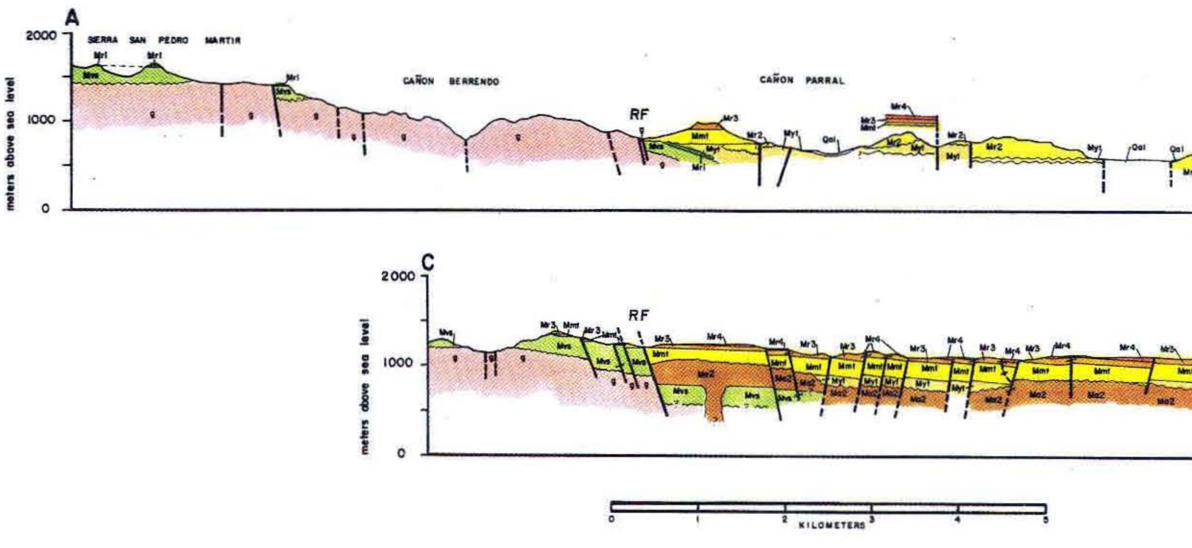
Observation of stairstep blocks (a) could mean that the blocks are sliding past each other with strike-slip motion (perpendicular to the plane of the page) (b); or that they become curved at depth and flatten out (c). Faulting and extension in originally flat layers (d) might have caused blocks to fall over like dominoes during extension (e).

something about the age of the rock. Remote-sensing data, such as the combination of visible and infrared reflectance of various rock units, helps us to distinguish different kinds of rocks, especially different compositions of volcanic rocks, and also to search for evidence of young faulting by looking at differences in soil development in valleys containing the active faults.

So, armed with information from these kinds of techniques, we look at the rocks that we can see and try to interpret their history. And then we can build structural models for how the blocks between the faults might have been moving in order to have created the landscape that we see. One example would be a series of steep faults along which a single layer has been stepped down progressively from west to east like a staircase, where the displaced layer corresponds to the steps and the faults correspond to the risers —(a) at left. There are a couple of possible interpretations for this. Perhaps these are mostly strike-slip movements, as the blocks slide past each other (b). If the layer was slightly tilted to start with, then sliding bits of it sideways along vertical faults could create this kind of pattern. Or perhaps, and this seems to be more consistent with what we've seen in Baja California, what we see represents just the uppermost surface of a series of steep normal faults (with slip up and down, rather than sideways in the fault plane) that are curved at depth and become flat. Then they might end up in a flat surface of detachment—what we call a detachment fault (c). In that case, the whole block on the left moves away from the block on the far right and everything else above the detachment fault falls into the hole created by this extension. This is what we think is happening along the topographic escarpment controlled by those big normal faults in Baja California. Another structural example might be a series of faults that are associated with tilting in the originally flat-lying rock layers (d). Such a scenario might have started off as a set of upright fault-bounded blocks that tilted over like a set of dominoes during the extension (e). Or perhaps the base surface became detached, allowing them to slide and fall over. This also represents extension.

The narrow zones on earth where extensional faulting occurs are known as rift systems. In the evolution of rift systems in general, where an ocean basin develops, it would start with some high-angle faulting, accommodating a little bit of extension as the two sides of the rift move apart, and some volcanism. This stage corresponds to a continental rift something like the East African rift valleys or the Rio Grande rift. Then as the two sides move farther apart, the rift subsides below sea level. New magma starts to come in and form real ocean floor, as along a typical mid-ocean ridge, with underwater volcanism all the way along the rift. As it subsides below sea level, the submarine volcanic rocks get covered with sediment that might have marine fossils in it. The Red Sea is usually given as an example of a rift that's in this state of evolution. The Gulf of California is similar to the Red Sea in many ways but with one big difference: the Red Sea is already forming true oceanic crust at its center. In the Gulf of California we have a pro-

Left: Along the escarpment seen from Berrendo Canyon one can see 11-million-year-old stratified rocks (dark colored) on top of granite. One dark-colored piece to the right is the same age but has slid down along the fault that is visible running down diagonally from right to left.
Right: The top cross section, going from west (left) to east shows the same scene. The 11-million-year-old rocks are in green, and the slipped piece can be seen along one of the high-angle faults cutting the escarpment. These older rocks exhibit more displacement than the younger ones (6 million years old) shown in yellow, orange, and brown. Going farther to the east, the faulting increases and involves the younger rocks, seen clearly in the lower cross section, farther south along the same axis.
Below: A 6-million-year-old volcano is covered with ash.

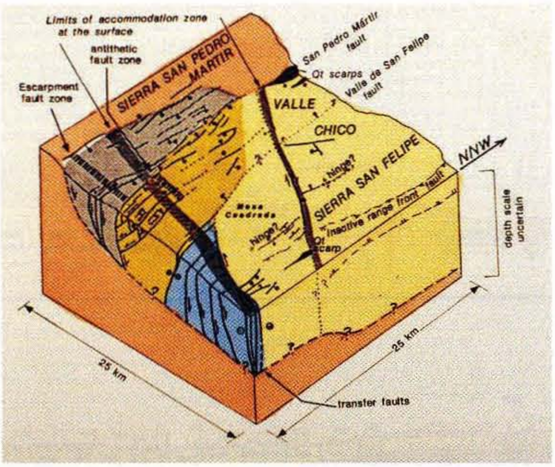


gression from true sea floor with underwater lavas forming in the very southernmost gulf to an area that's still largely extending by faulting and receiving continental sediments in the north. If we took an underwater sample from the seafloor in the northern gulf, we would probably just get sediment, not fresh lava. There is fresh lava coming in, but it's beneath the sediment; it's not poking all the way up to the surface. So within the gulf we have a transition from real ocean floor in the south to what is still a region of continental extension in the north. If this rifting continues, we expect to end up eventually with something like the Atlantic Ocean; in other words, a really big ocean basin with an active plate boundary in the middle—a spreading center with underwater volcanoes. But neither the Red Sea nor the Gulf of California has progressed that far.

What does this extensional faulting actually look like on land, where we can see the effects? The escarpment, a big normal-fault system, has experienced extension, and everything to the east has slid toward the Gulf of California. But the western side of Baja California is still high country, the continuation of the Peninsular ranges; one mountain, Picacho del Diablo, is over 3,000 meters, or 10,000 feet, high. This escarpment has played a big role in the history of Baja California's settlement, because it forms a daunting topographic barrier. It's still a challenge for humans; no roads cross it anywhere in the region where we've been working. Since there are no reliable sources of water in most of the region, there haven't been many settlements. Some people live in the high country—nice piñon pine country—and this is where the Spanish missionaries founded their missions. They didn't settle down in the desert where there are rattlesnakes and no water.

Unfortunately, the region with rattlesnakes and no water—the extensional province—is the one that interests us. And actually the desert is a great place to study geology because you can see everything; there aren't a lot of bushes covering up the rocks. What are the most important features that a geologist looks for? We see old volcanoes, such as the one at left, which is draped with ash layers, either from its own eruption or that of a volcano nearby. All of the rocks in this picture are about 6 million years old. The aerial photo on page 14 shows some rocks that form the edge of small cliffs next to some small faults. Rocks are being dropped down along the fault systems, similar to the "domino" fault system in the schematic drawing on the opposite page.

In another example we see stratified rocks on top of granite, cut by a fault (above, opposite page). The rocks on either side of the fault are the same sequence but the right (east) side has slid down along the fault. Combining all the observations of the faulting along the escarpment in this region, we can draw some cross sections going from west to east (above). These show high-angle faults near the escarpment's edge on the west (left); going east the faulting seems to get more pervasive and involve younger rock units. Knowing the ages of the rocks is key to understanding this picture; for example, we know that these are 11-million-year-old and older rocks. And we know from comparing them with



Above: This model illustrates what geologists *think* is going on on the western edge of the extensional province. East-sloping extensional fault systems (gray) and west-sloping ones (gold) both feed into a flatter fault below. Pink represents areas of unextended granite, while strike-slip faulting (perpendicular to the plane of the page) is occurring at the edges of the blue region.
Above right: Six-million-year-old rocks in "domino" blocks, dropped by a series of faults and then rotated, create the zigzag pattern here. Unfaulted 3-million-year-old rocks on top of them indicate that extension here had stopped by then.
Below: Young faulting is evident in the tilted fossil beds visible in road cuts near the coast.

the 6-million-year-old rocks in the picture on the previous page that they exhibit more displacement than their younger counterparts. This tells us that faulting in this region started before 6 million years ago, and, in fact, about half the faulting along the escarpment here had occurred between 11 and 6 million years ago.

We can combine this information to build a structural model of the western edge of the extensional province (above, left). We think the escarpment fault systems that slope steeply eastward probably feed into a flatter fault at depth. Then there's a series of westward-sloping faults that may "sole," or bottom out, into the same flatter fault. There are also some examples of strike-slip faulting within this region. Moving toward the east one sees more and more evidence of extensional faulting. As we go east, we can see that some of the same rock layers high on a hill to the west have dropped down into a valley—a relative vertical displacement of about 800 meters. And it just gets worse—or more geologically exciting, depending on your perspective—the farther east you go.

Driving along the east coast of Baja California from San Felipe to Puertecitos, you pass by outcrops where you can pick fossils out of young (2 million years old or younger) marine sediments and continental sediments near the beach (left). These are also cut by faults. And up a nearby canyon we can see a set of layers that have been dropped by a series of faults (above, right)—a nice example of a set of fault-bounded "domino" blocks that have rotated, tilting the layers about 50 degrees. These 6-million-year-old rocks are overlain by a cap of 3-million-year-old volcanic rocks that are not faulted. So in this place we can conclude that there was a lot of early extension between 6 and 3 million years ago that then stopped.

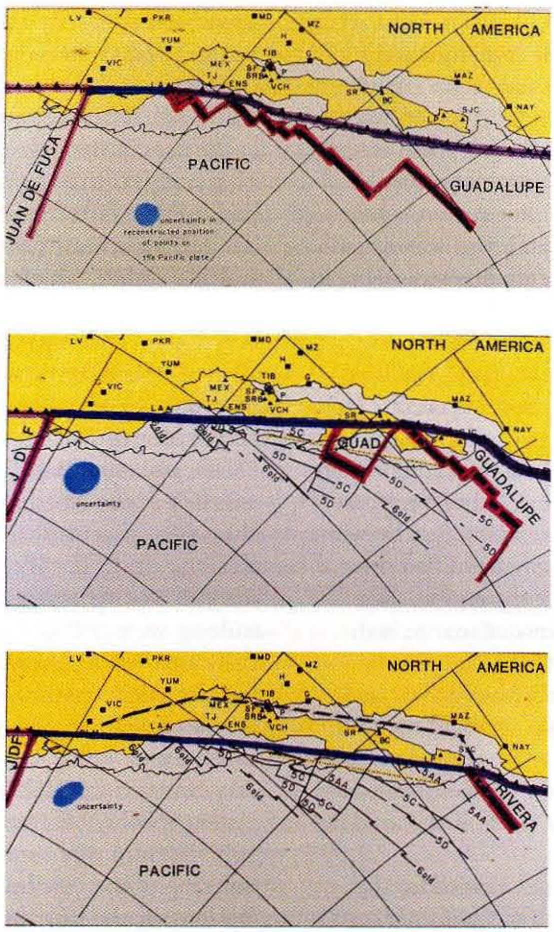
Other evidence for young faulting comes from the highly tilted fossiliferous beds close to the coast. Little closed drainage basins up on the mesas also indicate active strike-slip faulting stepping from one fault strand over to another and pulling apart a little basin in between. We can see evidence of disruption of drainages occurring along some young faults, and we can find lines of bushes, and even palm tree oases, along some of the faults, suggesting that they may be extremely young. So that tells us that there has been a history of motion from at least 6 million years up to the present in the area we have been studying.

If we make a very simple assumption that all of the Pacific–North America plate motion had gone through the Gulf of California, we come up with a problem. Calculating backward, the amount of slip needed to close up the gulf is about 300 kilometers, which would take us back 6 million years, moving at 50 millimeters per year or 50 kilometers per million years. (The value of 50 millimeters per year is the average rate for the last 3 million years, determined from the fault systems in California and also from other global data on plate motions.) But if we close the gulf up that much, we run into several problems. First, the continental margin isn't well aligned, so it leaves a big hole at the south end and too much overlap at the north. Second, we have

So while the strike-slip faulting zone was short originally, between 20 and 10 million years ago it grew longer, developing eventually into the San Andreas fault and the plate boundary within the Gulf of California.

evidence of extensional faulting as early as 12 million years ago (in marine deposits actually as early as 15 million years), and we know that the San Andreas fault system in California, which should connect down into the northern gulf, started moving long before 6 million years ago. So we think that there was a significant amount of tectonism or deformation occurring in this region before 6 million years ago, and therefore we need a more complicated story to explain the gulf's opening.

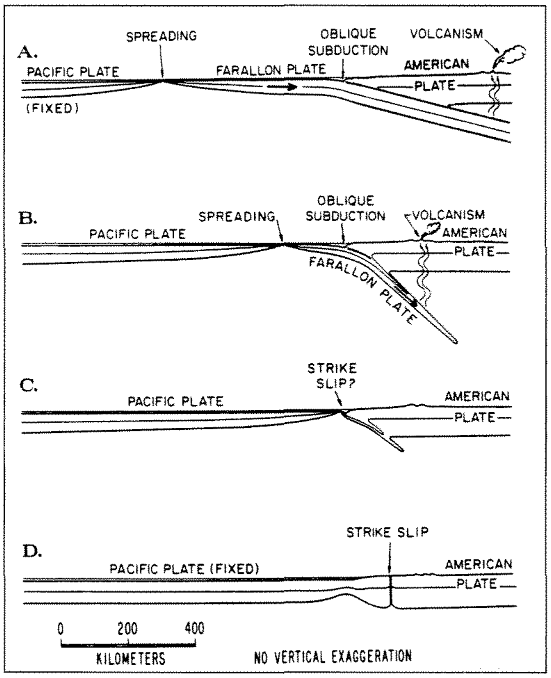
If we go back to the maps of the plate motions and use global plate reconstructions to figure out where the plates would have been, what we see is that 20 million years ago Baja California would be closed back up to mainland Mexico, and we would have a spreading ridge between the Pacific plate and the Guadalupe plate (which was originally a small fragment of the Farallon plate, which has now disappeared). The ridge would have been offshore, and so in between Guadalupe and North America there would have been a zone of convergence or collision, where the Guadalupe plate was going underneath North America. South of the Guadalupe plate, the Cocos plate (which still exists) would have also been subducting underneath North America. But by 10 or 11 million years ago the Pacific-Guadalupe ridge stopped spreading, and the Guadalupe plate got stuck onto the Pacific plate. The spreading center between the Pacific and Cocos plates kept moving farther to the south. We end up with a picture like that at left, with a new plate boundary being created at the western North American margin, creating a big zone of strike-slip faulting representing the motion between the Pacific and North America plates. So while the strike-slip faulting zone was short originally, between 20 and 10 million years ago it grew longer, developing eventually into the San Andreas fault and the plate boundary within the Gulf of California.



Twenty million years ago (top), with Baja California squashed back up against Mexico (it's unclear how that might have looked), the Guadalupe plate would have been subducting under North America in a collision zone (purple) with a spreading ridge (red) between Guadalupe and the Pacific plate offshore. By 12 million years ago, this spreading center moved southward (center), the Guadalupe plate stuck onto the Pacific plate, and the strike-slip boundary (blue) between North America and the Pacific plate lengthened. By 10 million years ago this boundary had started to relocate into what is now the Gulf of California (black dashed line). In all these pictures North America is held fixed, but in reality all of the plates in the picture are moving relative to the other plates.

There should have been a volcano chain inland from where the Guadalupe plate was being compressed against North America. And we do, in fact, see evidence for those volcanoes having existed in Baja California. They are 23 to 16 million years old in northern Baja California and as young as 11 million years old in southern Baja California. Although they're blanketed by a lot of younger rocks in the extensional province, we find the cores of these volcanoes still preserved, and we can date them. So it's reasonable to assume that before the gulf opened, eastern Baja California, including the area of the present gulf, might have looked like Alaska or the Cascades.

After volcanism stopped and extensional faulting began, the early gulf might have looked

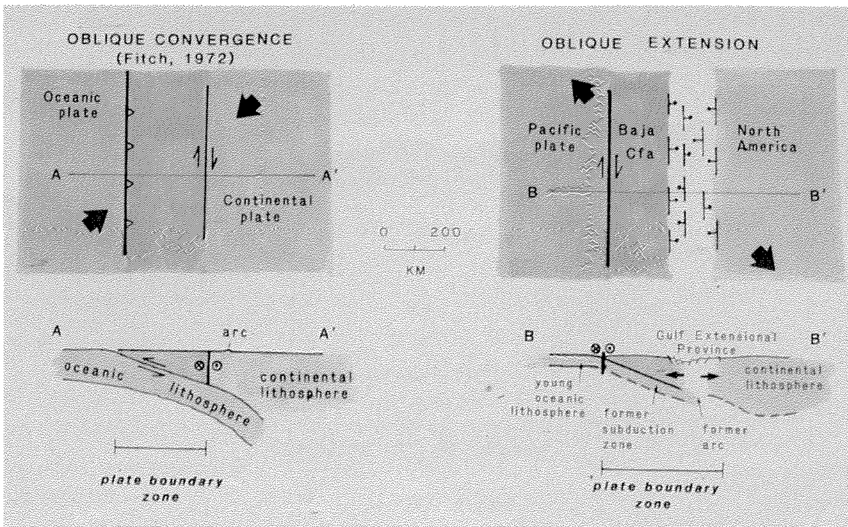


In a west-to-east cross-section view of plate activity near Baja California, the Farallon plate (of which the Guadalupe plate was part) subducts under North America, creating volcanism, while the Farallon and Pacific plates meet in a spreading ridge offshore. The spreading ridge moves in as the Farallon plate disappears under the American continent, and the Pacific and North America plates abut and begin to slide past each other in a strike-slip boundary. (Tanya Atwater in *The Geology of North America*, The Geological Society of America, 1989.)

We infer that this extension in the gulf was occurring at the same time as the faulting west of Baja California, so that Baja California was a peninsula that had faulting on the east side (extension) and faulting on the west side (strike-slip) going on simultaneously.

something like Death Valley—which is also a big extensional basin bounded by high mountain ranges and controlled by normal faults. As the extension continued, the early gulf region would have been sporadically flooded with ocean waters, so it would have started looking more like the Salton Sea or the Imperial Valley region, where water periodically comes in and then leaves again for awhile. The fossils in the marine sediments in the extensional basins around the margins of the gulf and ages on overlying lava flows indicate that there are marine rocks as old as 13 million years on Isla Tiburon off the Sonoran coast. This matches up to the region between San Felipe and Puertecitos in northeastern Baja California, where we find marine rocks at least as old as 6 million years and maybe older. So we know that between 13 and 6 million years ago seawater filled the basins in the northern part of the region. We haven't found exposed evidence of marine sediments of this age in the southern gulf, but it seems likely that the sea probably filled in some of the southern gulf then also. Around the gulf there are numerous regions with exposed marine fossils younger than 6 million years old, but we think a lot of the opening of the gulf occurred far earlier.

The scenario we have come up with for the tectonic evolution of the Gulf of California includes extension in the northern gulf starting at about 15 to 12 million years ago, while subduction- or convergence-related volcanism continued in the southern gulf. This is consistent with the disappearance of the Guadalupe plate, which shrank considerably starting from the north at about that time. By about 15 million years ago it was gone from the west side of northern Baja California, but it was still west of southern Baja California, a fact we see reflected in the difference in the ages of the volcanic rocks on the peninsula. This suggests that the northern half of the gulf might have started to open earlier than the southern gulf, or at least started to suffer extensional faulting earlier, which is consistent with what we see in the structures and the marine sedimentation there. Then by about 12 million years ago all of the plate convergence west of Baja California would have stopped, and there would have been a zone of strike-slip faulting between the Pacific plate and Baja California, which was still attached to the North America plate. And this is also when it seems that extension was occurring all along the gulf. We infer that this extension in the gulf was occurring at the same time as the faulting west of Baja California, so that Baja California was a peninsula that had faulting on the east side (extension) and faulting on the west side (strike-slip) going on simultaneously. Between 6 and 4 million years ago the plate boundary between the North America and the Pacific plates probably became more localized within the gulf. So from that time on is when we start thinking of the gulf being the center of the plate motions, or the location of most of the plate-boundary deformation. Around this time, 4 million years ago, the modern faults within the gulf evolved, faulting that is still continuing within the extensional province, although probably at a slower rate than initially. And even though we think that most of the plate-boundary



We think there are other places on the earth where similar fragmentation has happened earlier and other places where it is still happening.

Shown schematically in map view and cross section, the scenario (above right) represents what probably happened during the change in plate boundaries in between stages C and D of the cross sections on the opposite page. Baja California starts to pull obliquely away from North America before it is firmly attached to the Pacific plate. Thus, strike-slip faulting still occurs on the west, while extensional faulting develops on the east. This separation of oblique motion into two parallel zones with different kinds of movement is analogous to the separation often seen at oblique convergent boundaries (left).

deformation has been concentrated within the gulf for the past few million years, we still don't see a well-developed ocean basin. That's still in the process of formation in the gulf.

In another way of looking at it, as the Guadalupe plate was being pushed down under North America, forming a little chain of volcanoes at the convergence zone, the seafloor spreading axis between Pacific and Guadalupe was located quite a ways offshore to the west of Baja California. As the seafloor spreading axis moved closer and closer to North America, the Guadalupe plate got smaller and smaller till it reached a limit where it was no longer dense enough to sink. Then it probably just got stuck onto the Pacific plate, creating a zone of strike-slip faulting offshore. At some point the strike-slip motion might have jumped inland to form what is now the Gulf of California.

But what we think *really* occurred is illustrated in the final model above, in which Baja California is a small, independent plate, with motion on the west and east at the same time. With strike-slip motion offshore to the west, the Gulf of California is extending on the right (to the east), not exactly perpendicular to the plate boundary, but rather at an oblique angle. A series of extensional basins develops in the gulf, initially continental extension that later turns into what now starts to be real seafloor spreading. You can think of Baja California as a fragment that used to be firmly attached to North America, but that has been pulled away along with everything else west of the San Andreas fault. (And we in Los Angeles are sitting on the northern extension of this same fragment, which is now mostly attached quite firmly to the Pacific plate.) The process of the extensional faulting taking over all of the plate motion took a long time to complete—probably from about 15 million years ago up until 4 million years ago. And during that time this little fragment was pushed along with motion on both sides.

This isn't a unique situation in the geological record. We think there are other places on the earth where similar fragmentation has happened earlier and other places where it is still happening. Farther south along the Mexican margin, for example, it looks as if other blocks may be about to break off and attach to plates other than the North America plate. So we're interested in this as an example of a common geological process. We haven't figured out all the details yet; we're just scratching the surface of the geological information that's available. But we and our Mexican colleagues hope to keep working in Baja California until we can put the whole picture together. □

Since 1992 Joann Stock has been associate professor of geology and geophysics at Caltech, an institution fortunately more convenient for frequent camping in Baja California than was her previous employer, Harvard. She received her BS and MS in geophysics (1981) and her PhD in geology (1988) from MIT. From 1982 to 1984 she worked at the U.S. Geological Survey in Menlo Park, California, and taught at Harvard from 1988 to 1992, the latter two years as associate professor. She holds a Presidential Young Investigator award for 1990–95.

Of Symmetries and Factories, Matter and Antimatter

CP violation may lie at the root of why there's more matter than antimatter in the universe.

by Alan J. Weinstein

Nestled in the lush countryside near Palo Alto, the Stanford Linear Accelerator Center, or SLAC, has been a rich source of data for high-energy physicists. The large building in the foreground houses the linear collider's particle detector, while the smaller building to its right will accommodate the proposed B factory's detector. The I-280 crosses the linear accelerator, which slingshots electrons and positrons to more than 99.99999 percent of the speed of light.

In 1991, the Department of Energy and the National Science Foundation commissioned a panel to identify the most important goals in high-energy physics and to recommend funding priorities. The committee concluded that one of the few top priorities for the next decade is the "comprehensive study of CP violation in B meson decays at... a B factory." What is CP and what is its violation? What are B mesons? What is a B factory, and why is it so important to particle physics? The observation of CP violation in B meson decay has become a focal point for high-energy physics in general. Even more significantly, CP violation may lie at the root of why there's more matter than antimatter in the universe.

The physics of elementary particles is a vast field whose ambitious goal is a fundamental description of the nature of matter and energy. The field's language and body of theory is the most accurate known to modern science. That language is called quantum field theory, a forced marriage between field theory and quantum mechanics. Field theory was developed in the mid-1800s by Faraday, Maxwell, and others to describe electricity and magnetism, and is now used to describe the distribution of all matter and energy in space and time. Quantum mechanics is a product of the early 20th century—the distilled wisdom of the great physicists of the era—and describes the laws that hold sway at atomic distances, where the classical physics of Newton and his successors breaks down and traditional notions of objective reality are challenged.

The marriage is forced in that both quantum mechanics and field theory stand alone quite happily until we consider high energies, where we're compelled to use both theories. Furthermore, the mathematics seems forced—it's difficult, it's devoid of the beautiful simplicity of theories such as general relativity, and it's plagued with unphysical results called infinities that must be eliminated through an ugly prescription called renormalization. Mind you, quantum field theory and renormalization are profound and important ideas; nonetheless, the marriage that produced them seems forced. What is important here is *inevitability*—physicists are happiest when their theories couldn't possibly turn out any other way. Quantum field theory is inevitable in this sense, but I wouldn't be surprised if, one day, someone writes down a much more satisfying, simple, and elegant mathematical formulation of it.

Quantum field theory also makes use of the theory of special relativity—Einstein's discovery in 1905 of the relationships between space and time, and between matter and energy. And, finally, the symmetry principles around which much of the rest of this article revolves are derived from group theory. The branch of mathematics dealing with the relationships of objects to one another, group theory was founded by the brilliant French mathematician Évariste Galois, who led a colorful life before being killed in a duel in 1832 at age 20.

Quantum field theory is the language of the so-called Standard Model. The Standard Model attempts to provide a full description of the behavior of all the particles (which the model describes as fields, in order to provide the mathematical tools needed to create and destroy particles via $E = mc^2$) and forces (also known as interactions) in the universe. The Standard Model doesn't quite do all that, but it does describe, in detail, three of the four known fundamental forces in terms of the particles (or fields) that carry them. The most familiar of these forces is the electromagnetic one, which pervades our daily existence in the form of light waves, TV signals, and so forth, and which is carried by the photon. Less well known is the strong nuclear force, which holds quarks together to form protons and neutrons (and protons and neutrons together to form atomic nuclei), and which is carried by gluons. Even more obscure is the weak nuclear force, which is responsible for certain forms of radioactivity and for the decay of heavy quarks into lighter ones, and which is carried by the W^+, W^-, and Z^0 bosons. Gravity, carried by the hypothetical graviton, is excluded, because it's difficult to quantize. The force and particle content of the Standard Model is summarized in the tables at left.

The Standard Model has been tremendously successful at describing atomic structure, semiconductor behavior, solar physics, radioactive decay, and virtually every other phenomenon to which it has been applied. In some cases, agreement between experiment and theory has been demonstrated to one part in a trillion. In the last 30 years, this theory has even been applied to the Big Bang—the birth of the universe itself. In the early universe, the relationship between matter-energy and space-time was particularly intimate, as predicted by Einstein's general theory of relativity. Cosmologists use the Standard Model to understand the creation and behavior of matter and energy in that earliest epoch. The very existence of matter may depend on CP—charge-parity—violation (see box opposite).

The Standard Model is extremely successful, but it is incomplete. Nagging questions remain about its mathematical consistency, and about the many parameters whose values cannot be derived from the theory but must be taken as they are found in the real world. For example, the theory does not predict what the mass of the electron ought to be, nor the amount of the charge on it. Some fundamental questions remain as well. What is the nature of mass? (We believe it has something to do with a particle called the Higgs boson, the discovery of which was the goal of the Superconducting Supercollider, or SSC, an ambitious project that Congress killed this past summer.) What lies beyond the Standard Model? Those nagging inconsistencies

LEPTONS				QUARKS			
PARTICLE NAME	SYMBOL	REST MASS (MeV)	CHARGE	PARTICLE NAME	SYMBOL	REST MASS (MeV)	CHARGE
Electron neutrino	ν_e	~ 0	0	Up	u	~300	$+^2/_3$
Electron	e^-	0.511	−1	Down	d	~300	$-^1/_3$
Muon neutrino	ν_μ	~ 0	0	Charm	c	~1,500	$+^2/_3$
Muon	μ^-	106	−1	Strange	s	~500	$-^1/_3$
Tau neutrino	ν_τ	< 31	0	Top or Truth	t	> 50,000 (not yet discovered)	$+^2/_3$
Tau	τ^-	1,777	−1	Bottom or Beauty	b	~ 5,000	$-^1/_3$

FORCE	RANGE	RELATIVE STRENGTH	CARRIER	REST MASS (GeV)	CHARGE	STATUS
Gravity	Infinite	10^{-36}	Graviton	0	0	Not yet discovered
Electro-magnetism	Infinite	10^{-2}	Photon	0	0	Observed directly
Weak	< 10^{-16} cm	10^{-13}	W^+	80	+1	Observed directly
			W^-	80	−1	Observed directly
			Z^0	91	0	Observed directly
Strong	< 10^{-13} cm	1	Gluon	0	0	Confined

PARTICLE NAME	QUARK CONTENT	CHARGE	MASS (MeV)
Proton	uud	+1	938
Neutron	udd	0	940
Λ	uds	0	1116
Σ^+	uus	+1	1189
Σ^0	uds	0	1193
Σ^-	dds	−1	1197
Ξ^0	uss	0	1315
Ξ^-	dss	−1	1321
Ω^-	sss	−1	1642
Λ_c^+	udc	+1	2285
π^+, π^-	$u\bar{d}, d\bar{u}$	+1, −1	140
π^0	$(u\bar{u} - d\bar{d})/\sqrt{2}$	0	135
K^+, K^-	$u\bar{s}, s\bar{u}$	+1, −1	494
$K^0, \bar{K}^0$	$d\bar{s}, s\bar{d}$	0, 0	498
D^+, D^-	$c\bar{d}, d\bar{c}$	+1, −1	1869
$D^0, \bar{D}^0$	$c\bar{u}, u\bar{c}$	0, 0	1865
B^+, B^-	$u\bar{b}, b\bar{u}$	+1, −1	5280
$B^0, \bar{B}^0$	$d\bar{b}, b\bar{d}$	0, 0	5280
J/Ψ	$c\bar{c}$	0	3097

The standard model in a nutshell. Top: The six known leptons (particles that are not made up of quarks, and are thus "fundamental" in their own right) are mirrored by the six known or hypothesized quarks. Quarks and leptons come in three pairs, or "generations," based on their masses. MeV stands for million electron-volts— 1 electron-volt is 2×10^{-33} grams. Middle: The four fundamental forces of the universe and the particles that carry them. GeV stands for billion electron-volts. Bottom: A bestiary of popular particles.

The names of the quarks, and the term flavor, are arbitrary; they reflect the fact that most physicists don't know Latin.

hint at some more complete theory. Studying the origin and nature of CP violation will help complete the model.

So what does the Standard Model say? First off, it contains a classification scheme for particles. Just as the hundred-odd elements of the periodic table reduce to aggregates composed of only three building blocks (the protons and neutrons in the atomic nucleus, orbited by electrons) the hundred-odd denizens of the particle zoo derive from combinations of a handful of quarks. There are two important exceptions to this rule, however—the electron and its heavier brethren, the muon and the tau, are indivisible, quarkless particles, as are the three kinds of neutrinos associated with them. Quarks come in six known "flavors," called down, up, strange, charm, bottom, and top in order of increasing mass. The "bottom" and "top" quarks are also known as "beauty" and "truth," respectively. The names of the quarks, and the term flavor, are arbitrary; they reflect the fact that most physicists don't know Latin. However, no one knows why there are six different quarks (if in fact that's all there are), and no one knows why they have the masses they do.

But the key to the Standard Model is the mathematics of symmetries, which wrestle the model's welter of complex details into a semblance of order. Thus, for example, the strong nuclear interaction, which binds quarks together into particles, is flavor-symmetric. In other words, the strong interaction doesn't care what flavor the quark happens to be—it treats all six flavors alike.

CP Violation in the Early Universe

It's difficult, without the aid of quantum mechanics, to describe how K^0-$\bar{K}^0$ decays violate CP symmetry, but the consequences are nonetheless dramatic. For if the combination of charge, parity, and time is conserved in all interactions, and if some kind of interaction causes the combined symmetry with respect to charge and parity to be violated, then there must be an equal but opposite violation of time symmetry. Now, just as in the macroscopic world, the film no longer looks the same when run backward. This goes beyond the *statistical* time asymmetry implied by the second law of thermodynamics; it is a *fundamental* property of particle interactions at the microscopic level. Reactions that violate CP symmetry introduce a fundamental arrow of time into quantum physical systems.

Nowhere is this more important than in the early universe. If all the matter and energy in the universe was indeed created out of the gravitational potential energy of the Big Bang, then symmetry with respect to charge conjugation would have ensured that equal amounts of matter and antimatter would have been produced. Clearly, this is no longer the case—the universe we observe is composed virtually entirely of matter. It turns out that such an asymmetry cannot be produced by charge-conjugation symmetry violation alone; one needs CP, or equivalently, time symmetry violation, to evolve such an asymmetry out of an initially symmetric cosmos.

Andrey Sakharov established in 1967 that three ingredients are required in order for the universe to evolve a net surplus of protons versus antiprotons: CP violation; a stage in the evolution of the universe that was far from equilibrium; and proton decay. Experiments on neutral kaons have, in fact, established that at some small level, CP is indeed violated. The rapid expansion of the universe in its first moments postulated by current cosmological theories kept it far from equilibrium. And modern grand unified theories all predict that protons do indeed decay—diamonds are not forever! In fact, proton decay has not yet been observed, and sensitive experiments put the proton's lifetime in excess of 10^{32} years. (By contrast, the universe is roughly 10^{10} years old.) But even longer lifetimes, if finite, suffice to produce the matter-antimatter asymmetry observed in the universe. Cosmology suggests that this asymmetry was established some 10^{-35} seconds after the Big Bang.

As any lefty knows, the human world is far from being parity-symmetric; a parity-inverted pair of scissors is a welcome possession.

Likewise, symmetries inform the Standard Model's description of the fundamental forces. For example, electrically charged particles participate in the electromagnetic interaction. Without going into detail, electromagnetic charge can be thought of as a pointer arrow buried within each particle. No matter how an interaction rotates, or transforms, the pointer, the symmetry laws ensure that the particles' behavior remains unchanged as far as the outside world is concerned. This symmetry constraint is sufficient to derive all the properties of the electromagnetic force, including Maxwell's equations. The two other forces described by the Standard Model, the strong and weak nuclear forces, can be similarly described. It may even be possible to unite all three forces into a single grand unified theory at energies corresponding to 10^{20} K, where higher symmetries (again, with respect to abstract "pointers" within these subatomic particles) would become manifest, and the three forces would become indistinguishable from one another. Nothing in the universe has been that hot since 10^{-34} seconds after the Big Bang, when the observable universe was about a meter in diameter.

These symmetries are continuous because the physical quantities they describe vary smoothly—in shades of gray, as it were. For example, the strength of an electromagnetic field can be plotted as a smooth, continuous curve. And for every continuous symmetry, there is a conserved quantity—one whose net value doesn't change, although its distribution among the particles within the system may vary. Thus, the symmetry that gives rise to electromagnetism is associated with conservation of electric charge. The strong nuclear force also has a conserved "charge"—three of them, actually—known fancifully as color. And the weak nuclear force conserves something called hypercharge. A particle carrying a charge associated with one of these forces interacts with other such particles via that force.

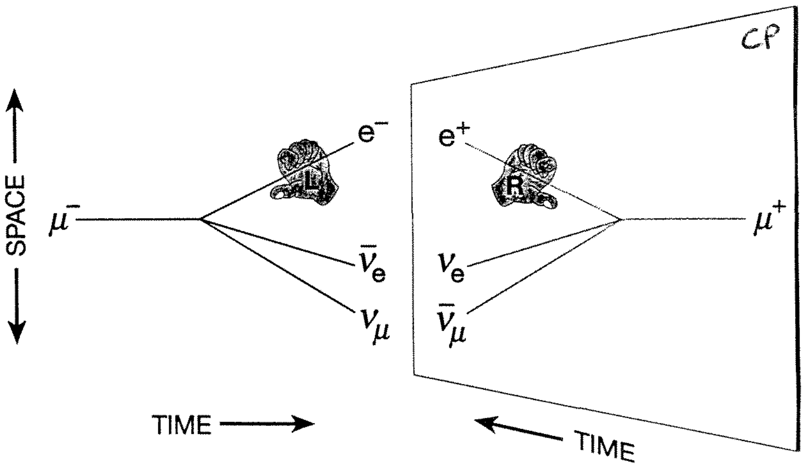
There are other, equally important discrete symmetries that describe discontinuous, black-or-white quantities—an electric charge is either positive or negative, for example. Chief among the discrete symmetries are the following three: Parity inversion is the inversion of all three spatial dimensions through some arbitrary point as if by a mirror, making right-handed systems appear left-handed and vice versa. Time reversal is the inversion of the temporal dimension, as when one runs a film backward. And charge conjugation is a change in the sign of the charges of all the particles in the system so that each particle becomes its antiparticle—for example, electrons become anti-electrons, called positrons, and vice versa.

These symmetries are respected at the subatomic level. Biological systems aside, the rates of chemical reactions rarely depend on whether a molecule is left-handed or right-handed. (Almost all of the molecules essential to life are left-handed. This is an example of spontaneous symmetry breaking—once one form of matter gains an advantage over another, even if by accident or happenchance, that dominance is maintained thereafter.) And a movie of two atoms colliding to form a molecule, run backward, is indistinguishable from a movie of that same molecule splitting up into the two atoms. Furthermore, when subatomic collisions convert energy to matter (via Einstein's $E = mc^2$), they produce exactly as many positrons as electrons.

However, these symmetries aren't perfect. The different quark flavors have different masses and electric charges, and thus they behave differently—in the real world, the flavor symmetry is broken. The electromagnetic, strong, and weak interactions are vastly dissimilar in our experience. Furthermore, as any lefty knows, the human world is far from being parity-symmetric; a parity-inverted pair of scissors is a welcome possession. And as anyone who has ever spilled milk knows, the world looks funny when the film runs backward, so time-reversal symmetry is broken. It's equally obvious that charge conjugation is a poor symmetry in nature, or positrons would be as abundant as electrons, anticarbon as common as carbon.

The lack of symmetry we see with respect to parity, time, and charge is the result of spontaneous symmetry breaking and the second law of thermodynamics. But at the fundamental level, these symmetries are conserved. In fact, in any universe in which one simultaneously performs the charge, parity, and time transformations, the laws of physics should be unchanged. This is known as the CPT theorem, and it is built into the mathematics of quantum field theory. It is difficult to even conceive of a universe in which the combination of charge, parity, and time transformations would yield different physical laws.

However, it *is* possible to imagine a universe in which one or more of these three symmetries is violated, as long as an equal but opposite violation occurs in one or both of the other two. Indeed, this is the case in our own universe. It was discovered in 1957 that the weak nuclear interaction, in which the ghostly particle known as the neutrino plays a crucial role, holds commerce only with left-handed neutrinos and right-handed antineutrinos. (The neutrino comes in both left-

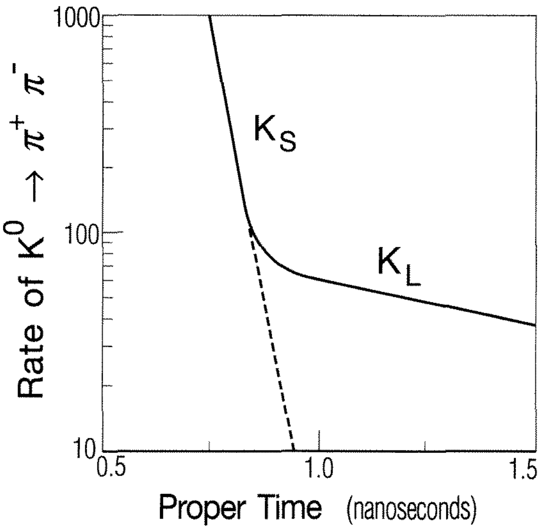


In this example of charge-parity conservation, a negatively charged muon (μ^-) decays into a left-handed electron (e^-), an electron antineutrino ($\bar{\nu}_e$), and a muon neutrino (ν_μ). The reaction looks just the same in the CP mirror, except that the particles' signs are reversed, and the positron (e^+), or antielectron, is now right-handed. An electron's handedness can be measured by bouncing it off a target of known spin polarization, and observing the scattering angle. (It's hard to measure the handedness of neutrinos, as they don't interact much with matter.)

and right-handed, as well as particle and antiparticle, incarnations.) It appears that the weak interaction, unique among the known fundamental forces, violates parity conservation and charge conservation; but it was believed that, at least, the *product* of parity and charge was conserved. Thus, reactions would proceed in an identical manner to their mirror reflections, if all the reacting particles were replaced by their antiparticles. This is illustrated in the drawing (above) of muon decay, in which the handedness of the electron so produced is measured.

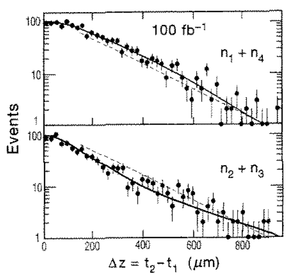
A universe in which both parity and charge have opposite senses with respect to ours would be indistinguishable from ours. Or would it? The weak interaction violates charge and parity individually, while conserving the combination—called CP for short—to a very high degree. But in 1964, while Christensen, Cronin, Fitch, and Turlay were studying the decays of the K meson, they observed that CP was violated in one decay in 500. If CP were strictly conserved, the decay rate for kaons, as K mesons are also called, as a function of time would be exactly equal to that for antikaons. In fact, there was a slight asymmetry in the decay rates. Not only was this very subtle phenomenon difficult to observe experimentally, it was also difficult to interpret theoretically. The explanation that eventually emerged runs as follows. The particles studied by Christensen et al. were neutral kaons—the K^0, which is composed of a down quark and a strange antiquark; and the K^0's antiparticle, the $\bar{K}^0$, which is composed of a down antiquark and a strange quark. But, says the theory, the particles coursing through the experiment's beam pipes and detectors were somehow neither and both: they were quantum-mechanical superpositions of K^0 and $\bar{K}^0$ mesons. This is a classic example of mixing, a bizarre phenomenon unique to quantum mechanics. As a final complication, the experiments revealed that the superposition itself exists in two states, called K_S and K_L because the former's lifetime is about 100 times shorter than the latter. Relatively speaking, of course—K_L lives to a ripe old age of about 50 billionths of a second.

If one applies the CP transformation to the K_S and K_L states—changing the quarks to antiquarks and vice versa (charge) and swapping the two quarks' positions within the particle, so that, as it were, the quark on the left is now on the right (parity)—something strange happens. The mathematical representation of the K_S, which is CP-even, retains its original sign—while the K_L, which is CP-odd, changes its sign. But things get stranger still. Experiments have revealed that the mixing pattern is only approximate. At some small level, the K_L has a CP-even piece, and the K_S has an equal but opposite CP-odd piece. One way in which this shows up is that the K_S, being primarily CP-even, decays into an even number of particles—in this case, a positively charged pion and a negatively charged antipion. The CP-odd K_L decays into an odd number of particles, with the third one being an uncharged pion, which is its own antiparticle. In the absence of CP violation, a plot of pion-antipion pairs produced versus time should go to zero very quickly as the short-lived K_S's decay. Seeing a K_L



Right: A plot of K^0s decaying to $\pi^+\pi^-$ pairs over time. If all the $\pi^+\pi^-$ pairs were produced by K_S decays, the rate would quickly fall to zero, as indicated by the dashed line. But instead, a small percentage of K_L mesons decay the "wrong" way, contributing a trickle of $\pi^+\pi^-$ pairs even after the K_S mesons are all gone. ("Proper time" is time corrected for the velocity at which the particles are traveling. At the near-lightspeed clip these guys are going, time slows down significantly.)

Below: How the data would actually appear in a particle detector. If there were no CP violation, the number of detection events versus difference in decay lengths (Δz) in both plots would be identical, as shown by the dashed lines. Instead, there is a slight excess of one decay, matching a slight deficit in the other.



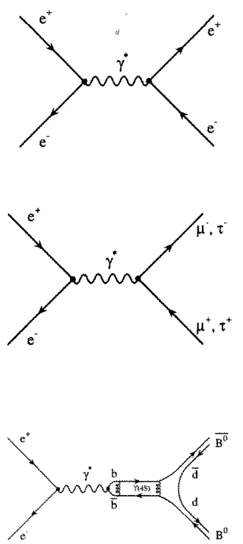
go into only two pions indicates that it has a CP-even piece to it. Instead of dropping all the way to zero, a trickle of pion-antipion pairs remains, produced by K_L's that violate CP symmetry and decay the wrong way. This is what Christensen and his colleagues observed. Which brings us back to the question of a CP-inverted universe...

Suppose there existed, in some remote part of the universe, a realm peopled with intelligent beings made of antimatter—high-energy antiphysicists. If we could communicate with such beings, how could we determine whether they were indeed composed of antistuff? Touching them would suffice; if our matter and their antimatter annihilated ourselves and them, we could be sure that they were of a different breed. Short of that, we could imagine communicating via the exchange of light signals, i.e., photons. But photons are their own antiparticle, and would behave the same in an antiworld as they do in ours. And how could we agree, unambiguously, on what "left-handed" and "right-handed" mean? We could tell them that the electrons emitted from the radioactive decay of, say, cobalt-60 were left-handed; but this would be insufficient information unless we could also uniquely define which is "matter" and which is "antimatter" or, equivalently, a "negative" or "positive" charge. CP violation provides an unambiguous answer. Antiphysicists could perform experiments with K_L and K_S mesons. A negative charge is then defined as that of the electron associated with the slightly less abundant decay mode of the K_L. The spin of those electrons is defined as left-handed, and matter is composed of nuclei with a positive charge, while antimatter has negatively charged nuclei. Which are you?

If matter-antimatter symmetry were respected in the universe, sooner or later the matter and antimatter would find and annihilate each other. Stable chunks such as stars, planets, and people would not be around for long. In some sense, then, we have CP violation to thank for our enduring presence, and it behooves us to ask where it comes from. Except for the weak nuclear force, the fundamental forces of nature appear to respect CP symmetry. Is there something inherent in the weak interaction that permits such violations?

There does exist a mechanism in the Standard Model that can produce CP violations; it was proposed by Kobayashi and Maskawa in 1973. At the time, only three quarks (up, down, and strange) were known. Kobayashi and Maskawa anticipated the discovery of three more quarks, grouped by their masses into three pairs, or generations. The up and down quarks form the first generation; the then-undiscovered charm quark pairs with the strange quark in the second generation; and the still-undiscovered top quark rounds off the third generation, currently occupied only by the bottom quark. The quarks in the second and third generations have proved to be unstable. The second and third generation's heavier quarks (charm and top) decay primarily to the lighter particle in that same generation, via the emission of a W^+ boson (W^- for antiquarks). The subsequent decay of the lighter quark to a lower-generation particle occurs because the down-type quarks (down, strange, and bottom) quantum-mechanically mix with one another. This happens at a much slower rate than the decay from the heavy quark to the light quark within a generation, which is an unmixed reaction. There is a wave function that describes the mixed reaction, and another one that describes the unmixed reaction, and it is the complex phase difference between the two wave functions that produces the interference pattern characteristic of CP violation. Kobayashi and Maskawa knew that the down and strange quarks mixed, and boldly suggested that a third generation of quarks—and thus a third down-type quark that could mix with the down and the strange quark—existed, three years before there was any experimental evidence for that third family. (The mathematics of the Standard Model won't produce CP violation with only two generations of quarks—it takes three.)

To really test this idea, we have to perform experiments on the third generation of quarks. And it is the bottom quark, being the one that quantum-mechanically mixes in order to decay, that is the key to the puzzle. This is fortunate, since the top quark is so very massive that it hasn't yet been discovered! ($E = mc^2$; and the biggest particle-accelerator yet built—the Tevatron, at Fermilab near Chicago—is just at the threshold of generating enough E to make the top quark's m.) But a bottom quark can't be studied in isolation, because the strong nuclear force, which binds quarks into particles, is *so* strong that only combinations of quarks having no net color can be isolated. So we have to study B mesons, which are the commonest colorless combinations containing bottom quarks, instead. A bottom quark combined with an up antiquark makes a B^- meson. Other possibilities include its antiparticle, the B^+, formed from a bottom antiquark and an up quark. And a bottom antiquark and a down quark form a B^0. Its antiparticle is the $\overline{B}^0$, formed from a bottom quark and a down antiquark. B mesons can be produced in a high-energy collision, but they're rare because they are so massive. (Like car crashes, particle collisions tend to produce a very few massive chunks and a lot of small, lightweight debris.) The B mesons' large mass also makes it possible for them to decay to lighter particles in many different ways, and with a very short lifetime—about one trillionth of a second. The experimental study of B decays is no easy matter.



Feynman diagrams of three things that can happen when an electron (e^-) and a positron (e^+) collide. Top: They annihilate each other, forming a virtual photon (γ^*) that relapses into an electron-positron pair. Middle: The photon transmutes into either a muon-antimuon ($\mu^{\pm}$) or tau-antitau ($\tau^{\pm}$) pair. Bottom: The photon becomes a bottom quark (b)-bottom antiquark ($\overline{b}$) pair, bound together into "bottomonium" by the exchange of gluons—rendered here by coiled squiggles resembling telephone cords. The bottomonium acquires a paired down quark (d) and antiquark ($\overline{d}$) from the vacuum, forming a pair of B mesons (B^0 and $\overline{B}^0$).

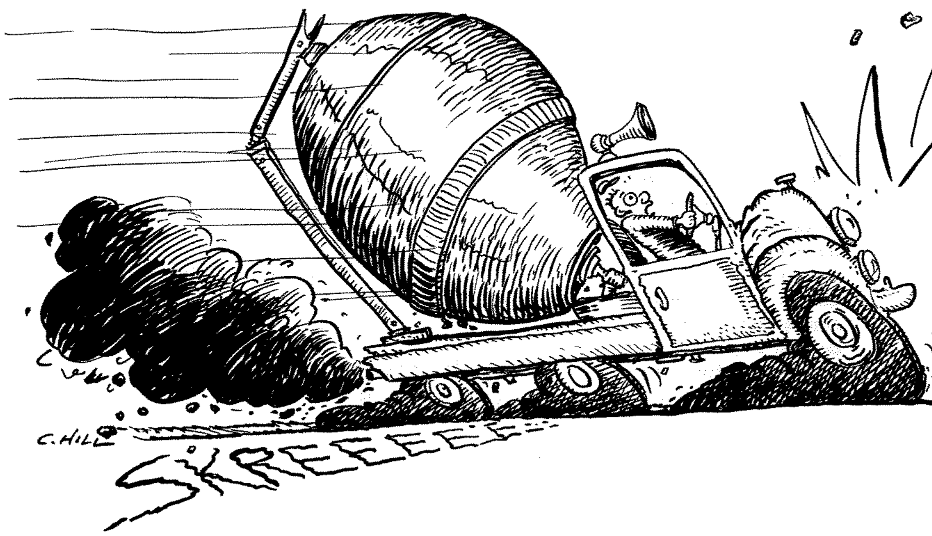
Most of what we know about B mesons comes from electron-positron colliders. The Cornell Electron Storage Ring (CESR) at Cornell University in New York, and the DORIS ring at the DESY Laboratory in Hamburg, Germany, are circular rings of magnets that store counter-rotating beams of electrons and positrons moving at 99.99999953 percent of the speed of light, and bring them into collision in the center of large and complex particle detectors. Each beam runs at about 5 billion electron volts, or 5 GeV, of energy. (An electron volt is the amount of energy it takes to move an electron across a one-volt electrical potential. One electron volt is not an awful lot of juice—by comparison, it takes 13.6 eV to ionize a hydrogen atom.)

Lots of different things can happen when electrons and positrons collide. Most often, they just bounce off each other. Less frequently, the electron and positron can annihilate into a virtual photon (the carrier of the electromagnetic force), or a Z^0 (the electrically neutral carrier of the weak nuclear force). (A virtual particle is one that fleetingly materializes from the quantum-mechanical vacuum of space. Virtual particles live on energy "borrowed" from the vacuum, not unlike the junk-bond kings of the 1980s, who lived on borrowed money from paper profits that weren't really there either.) Almost immediately thereafter, the photon or Z^0 will transmute into a particle-antiparticle pair. Any charged particle-antiparticle pair can be produced through a virtual photon, as long as the beam energies are sufficient to produce the mass of the two particles. And any particle-antiparticle pair that participates in the weak nuclear force—and all known particles do—can be produced through a Z^0, even the electrically neutral neutrinos. The Feynman diagrams associated with some of these reactions are shown at left. The cross section, or probability, for annihilation into quarks depends on the center-of-mass energy, which, in a symmetric collider, is twice the beam energy.

Virtual particles live on energy "borrowed" from the vacuum, not unlike the junk-bond kings of the 1980s, who lived on borrowed money from paper profits that weren't really there either.

If the energies of each beam are tuned to precisely 5.29 GeV, then the production of bottom quark–bottom antiquark pairs can just barely proceed, with almost no energy left over to kick the members of the pair thus produced in opposite directions. At this beam energy, the pair binds together into "bottomonium." This state decays, again almost immediately, into a pair of B mesons: B^+-B^- or B^0-$\overline{B}^0$. The B mesons lumber off slowly, at around 6 percent of the speed of light. They don't last long enough to make it to the detector themselves, but they decay into characteristic showers of less massive particles that do. By tracing the trajectories of these secondary particles back to their sources, the identities and flight paths of the original B mesons can be deduced. These lighter particles that actually register in the detector include photons, as well as electrons, muons, pions, kaons, protons, neutrons, and their antiparticles.

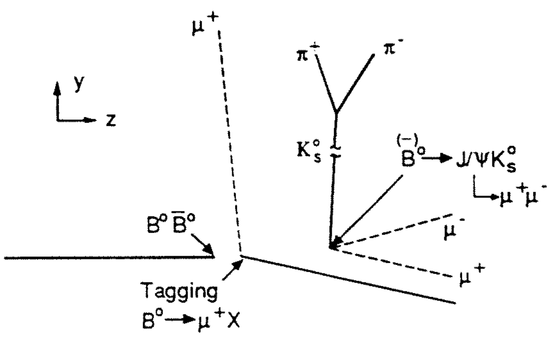
The J/Ψ particle has a double name because it was simultaneously discovered by two groups, neither of which was willing to relinquish the right to christen it.



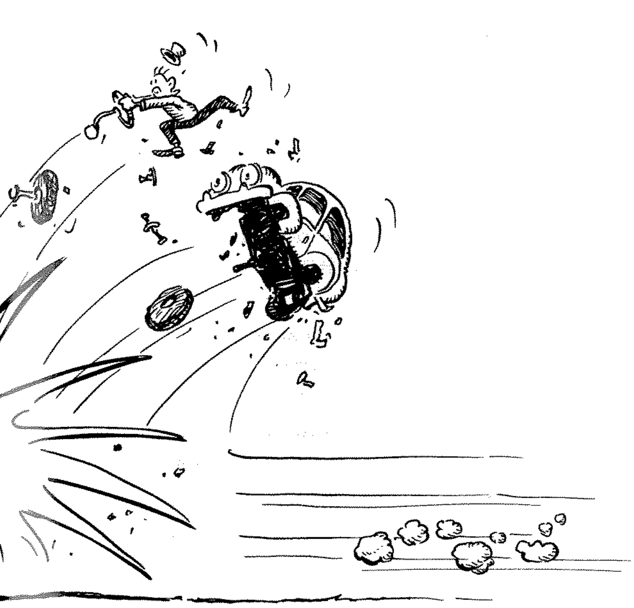
Neutrinos and antineutrinos typically sail through the detector unseen.

What makes the observation of CP violation possible here is the fact that B^0's and $\bar{B}^0$'s mix, just as K^0's and $\bar{K}^0$'s do. (This phenomenon was first observed by the ARGUS experiment at DORIS.) As the B mesons fly apart from each other, each one oscillates between its B^0 and $\bar{B}^0$ identities. A given B meson has a certain probability of mixing before it decays and a certain probability of decaying within a finite time. Specifically, a B meson has a mean life of 1.5 trillionths of a second, or 1.5 picoseconds. In that time, 63 percent of all B mesons will decay. If a B meson decays in exactly 1.5 picoseconds, it has a roughly 70 percent chance of having mixed first. In other words, if you have a sample of 100 B mesons, all of which decayed in exactly 1.5 picoseconds, about 70 of them will have mixed first. As in the kaon system, the interference between the two wave functions describing these two outcomes produces the observable CP-violating effect.

But the effect is very small. To look for such a small effect, one can try to measure a tiny asymmetry in common decays. However, a better approach is to look for a large asymmetry in certain very rare decays. Most promising are decays into systems of particles that are CP-eigenstates, that is, in which the CP product is conserved—either the particles formed by the decay are their own antiparticles, or the decay forms particle-antiparticle pairs. Either way, the final state is accessible to both B^0 and $\bar{B}^0$. One particularly promising decay is the formation of



How to tag a B^0: The bottomonium cruises along the solid line at lower left, decaying to a B^0-$\bar{B}^0$ pair at the arrowed end of the line. Shortly thereafter, the B^0 (the tag) shows up in the detector as a muon (dashed line labeled μ^+) and some other particles, shown here as a solid line. The $\bar{B}^0$ flies a bit farther before decaying into a K_S, which reaches the detector as a pion-antipion pair (π^+ and π^-), and a J/Ψ, which is detected as a muon-antimuon pair (μ^-, μ^+, dashed lines).



If a cement truck and a Volkswagen go head-to-head, the mangled metal will fly in the direction the cement truck was going.

a J/Ψ-K_S pair. (The J/Ψ particle has a double name because it was simultaneously discovered by two groups, neither of which was willing to relinquish the right to christen it.) The J/Ψ is a charm-anticharm bound state, and thus its own antiparticle; it shows up in the detector through its decay to an electron-positron or muon-antimuon pair. The K_S is not its own antiparticle, but it is a CP eigenstate; it is detected in its decay to a pion-antipion pair. Another promising decay, that of a B^0 or a $\bar{B}^0$ to a pion-antipion pair, can be observed directly. Under certain conditions, the CP asymmetry in these decays can be as large as many tens of percent. Unfortunately, only about one in 10,000 B mesons decays in the J/Ψ-K_S or pion-antipion mode.

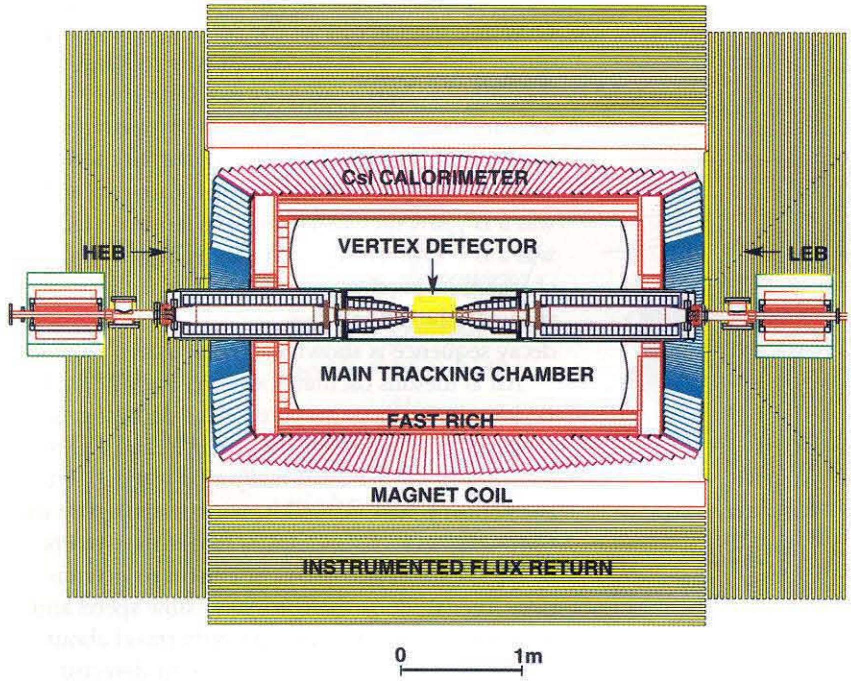
Therefore, one needs to produce many, many pairs of B mesons to see these decays. The highest luminosity—a measure of collision frequency—electron-positron collider in the world is the CESR machine at Cornell. On its best days, it produces one pair of Bs every five seconds. Taking into account the fact that not every pair produced is observed, the CLEO detector at CESR has still recorded nearly one million pairs over the last two years. But even with this unprecedentedly large amount of data, 10 to 100 times more data would be required to perform statistical analyses on these rare decays. Therefore, a B *factory* is needed.

Granted sufficient luminosity, observing CP violation remains a tricky matter. The simplest method is to observe the ratio of, say, B^0 to J/Ψ-K_S decays and $\bar{B}^0$ to J/Ψ-K_S decays. The first step in this process is to determine whether the *other* member of the B meson pair is a B^0 or a $\bar{B}^0$, thus revealing the identity of the particle that decayed into a J/Ψ-K_S. And the easiest way to identify that other B is to use events in which it decays into an electron or muon (plus other, perhaps unobserved, particles). This electron or muon, called a tag, is positively charged if its parent B was a B^0, in which case the B we're interested in was a $\bar{B}^0$. Conversely, if the tag is negatively charged, its parent was a $\bar{B}^0$ and the B that spawned the J/Ψ-K_S pair was a B^0. Such a decay sequence is shown on the opposite page.

All B mesons oscillate between their B^0 and $\bar{B}^0$ identity at the same rate before decaying, so in order to tell whether the particle that we are seeing decay as a B^0 was *really* a B^0 when it left the collision that formed it, we must measure its flight distance. (This applies to both members of the B meson pair.) But at existing electron-positron colliders, the B mesons' slow speed and short lifetime mean that they only travel about 25 microns before decaying. Present detector technology is simply not precise enough to measure such short decay lengths. And running the collider at higher beam energies, so that the outgoing B's are moving faster, is impractical because the production rate falls rapidly. Measuring both decay lengths is essential, however, so a new idea was clearly needed.

And a new idea was born, inspired by the asymmetry that was the goal of the experiment. An electron-positron collider with beams of equal energy will produce the bound quark pair called bottomonium at rest with respect to the detector. But in 1987, Pierre Oddone of Lawrence Berkeley Laboratory proposed an *asymmetric* B factory. If two loaded cement trucks run into each other head-on, the wreckage will remain where they collided. But if a cement truck and a Volkswagen go head-to-head, the mangled metal will fly in the direction the cement truck was going. Similarly, Oddone realized that by giving one of the collider's beams more energy than the other while keeping the total collisional energy equivalent to bottomonium's mass, the collision could produce a bottomonium pair moving in the direction of the higher-energy beam. When the bottomonium decays into a B meson pair, the B's will be moving, too, and at a significant fraction of the speed of light. Thus a B flies a lot farther in its fleeting lifetime. (Its lifetime gets longer too, due to the relativistic effect of time dilation as a particle's speed approaches that of light!) Sufficiently asymmetric collisions will produce decay lengths of 200 microns or more, lengths measurable with today's detector technology.

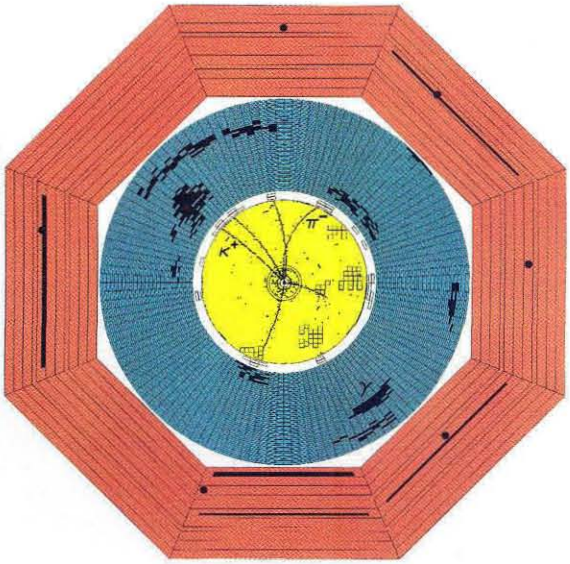
A particle detector works a bit like an eyeball.



A cross section of an asymmetric B factory's particle detector. The high-energy beam, (HEB) enters from the left; the low-energy beam (LEB) from the right. The detector is asymmetric, too—its center is to the LEB's side of the collision point, as the debris will fly in that direction. The vertex detector is the small yellow square in the center. The nozzles to either side are magnets that cause the beams to collide. Drift chambers fill the "Main Tracking Chamber." The red rectangle called "Fast RICH" is a Ring Imaging Cherenkov counter, a particle-velocity detector. The cesium iodide crystals in the calorimeter are drawn as thin red and blue slabs—the blue ones form the cylindrical detector's circular end caps. The tracking system is embedded in a superconducting magnet. The "Instrumented Flux Return" contains iron sheets (yellow) and muon-detecting drift chambers (white).

We see something by measuring the direction, color, and intensity of light from a scene, from which our brain constructs an image. Analogously, a particle detector "sees" a collision by measuring the angles, energies, and number of particles coming from it, from which a computer constructs an image. However, a particle detector is considerably more sensitive than an eyeball. The detector can sense a single particle, whereas only the best-trained eyeballs can detect a single photon. And the detector measures a great range of energy carried by particles of all sorts, not just photons of visible light. Most importantly, the detector can distinguish different kinds of particles, instead of merely registering photons. Of course all this sensitivity and precision comes at a price—a particle detector is considerably larger and more massive than an eyeball. A detector suitable for a B factory would be about the size of a two-story house, would weigh some 500 tons, and would look something like the illustration at left. The detector must be capable of recording data at a tremendous rate; it might have 100,000 channels of electronic readouts, and be sensitive to collisions occurring every few nanoseconds.

The detector is actually a concentric set of cylindrical detectors, each of which measures different things, nested around the electron-positron collision point like the bun around a hot dog. The innermost layer is the vertex detector —in this case an array of silicon-wafer diodes that register the passage of charged particles. The diodes record the point at which the charged particle passes through them with an accuracy of better than 10 microns, or 10 millionths of a meter. The diodes are placed just outside the two-centimeter-radius beam pipe at the collision point, because their job is to distinguish between the trajectories of particles resulting directly from the collision and the trajectories of secondary particles whose progenitors—including B mesons —may have traveled a quarter of a millimeter before decaying. The vertex detector is surrounded by many layers of drift chambers, which are chambers filled with inert gas and containing high-voltage wires strung in arrays parallel to the cylinder's axis. A charged particle passing through a chamber will interact with a number of gas atoms en route, and will knock an electron loose from some of them. These electrons drift to the wires, registering as a pulse of electrical charge. The time it takes the electron to drift to the wire is proportional to the distance from the wire to the point where the particle hit the atom. By measuring the drift time, that point can be located to an accuracy of 150 microns or better. By collecting many such measurements, the



Right: An end-on view of how a B^0 decay registered at the CLEO detector at Cornell. The B^0 decayed into a K^{*0} and a photon. The K^{*0} then decayed into a K^+ and a pion (π), as labeled. (The unlabeled tracks belong to the decay products of the other B^0.) The drift chamber is tinted yellow; dots along each particle's path show where a wire was triggered. The squares in the same region show calorimeter crystals in the end cap that lit up. The blue region displays the crystals in the calorimeter barrel, but here the lit crystals are black. The flat rectangles in the intervening white ring are lit up elements of the time-of-flight detector. The photon (γ) hit the large black region at five o'clock. The red rectangles are muon detectors; all the black registrations, however, are spurious.

Below: Heisenberg Fellow Gerald Eigen holds a crystal of thallium-doped cesium iodide, scintillating here under an ultraviolet light. This crystal, the size of the ones to be used in the B factory calorimeter, is about 34 centimeters long and weighs some five kilograms.

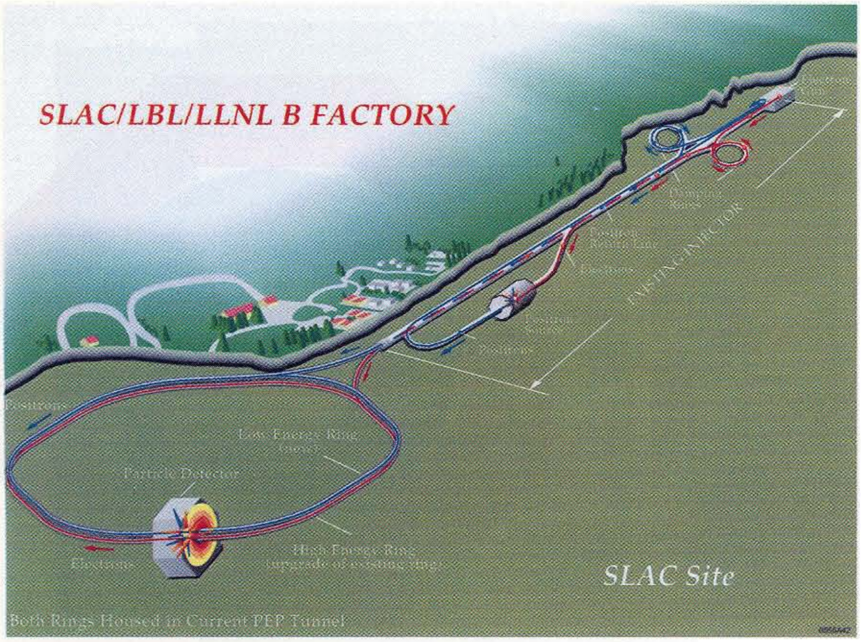
particle's trajectory can be reconstructed.

The next layer out is some kind of charged-particle identification system to distinguish pions from kaons from protons by measuring their velocities. (The tracking system has already measured their momentums; dividing a particle's momentum by its velocity gives its mass, which identifies the particle.) Then comes a precision crystal electromagnetic calorimeter to measure the energies and angles of photons and electrons. The calorimeter is an array of clear crystals, probably of cesium iodide, segmented into towers aimed at the collision point. An electron, positron, or photon entering a tower interacts with the crystal's massive atoms, creating an "electromagnetic shower" of countless electrons, positrons, and photons. The shower causes the crystal to scintillate—to absorb the energy and reemit it as light. A photodiode at the crystal's far end converts the scintillation light into an electrical pulse proportional to the energy of the incident particle. Energy measurement is like temperature measurement, so the device is called a calorimeter. These calorimeters aren't cheap; the crystals can cost as much as $20 million.

The entire apparatus is surrounded by a cylindrical magnet that generates a roughly one-tesla magnetic field. (Earth's magnetic field at the planet's surface is about 0.00005 tesla.) The field is solenoidal, which is to say that within the magnet it is everywhere parallel to the cylinder's axis. As the charged particles emanate from the collision point, the field bends their trajectories into helical arcs, and it is these arcs that the detectors see. (See drawing above.) The arcs contain a wealth of information about the particles tracing them. High-momentum particles leave nearly straight tracks, while low-momentum particle tracks curl up on themselves. Positively charged particles curve in one direction, and negatively charged ones veer in the other. Uncharged particles, of course, fly straight on through. And finally, outside the magnet, some 100 tons of iron return the magnetic flux and absorb any hadrons—particles composed of quarks—that have made it out this far. The iron allows muons, which contain no quarks, to escape into another set of drift chambers that identifies them.

Thus the key ingredients of the Asymmetric B Factory are an extremely high-luminosity electron-positron collider tuned to the production of bottomonium, asymmetric energy beams, and a high-precision detector. The B factory should produce three B^0-$\bar{B}^0$ pairs per second, or, assuming a normal operating schedule, 30 million pairs per year. Nothing like it has ever been built before, but teams of physicists around the world have spent the last five years convincing themselves that it can be done. They have now convinced the Clinton administration, too—the Department of Energy announced on October 5, 1993, that a B factory will be built at the Stanford Linear Accelerator Center (SLAC). The SLAC machine is illustrated on the next page. Similar proposals are being considered in Europe, Russia, and Japan.

A Caltech group led by Barry Barish, Linde Professor of Physics, and me has been exploring the physics of B mesons with Cornell's CLEO



A cutaway view of the B factory. A new ring for low-energy positrons will be added to the existing electron ring, which will be souped up. The electron beam comes from an electron gun—basically a bigger version of the cathode-ray gun in your TV set—at the drawing's upper right. A damping ring then squeezes the beam until it is thinner than a pencil lead, making it easier to inject. Next, the beam rockets down the linear accelerator to reach injection speed. Most of the beam gets injected clockwise into the high-energy electron storage ring. However, some electrons get shunted into a side tunnel, where they slam into a tungsten plate. The tungsten atoms emit positrons, which get piped back to the beginning of the linear accelerator. There they hang a tight U-turn, come back through a damping ring of their own, and shoot down the accelerator toward a counterclockwise injection in the low-energy ring.

detector since 1990. And Professor of Physics David Hitlin and Associate Professor of Physics Frank Porter have led the effort to build an asymmetric B factory at SLAC. Hitlin heads the detector-design team, and Porter is helping design the accelerator itself and the computing systems needed to analyze the large volume of data.

(It may also be possible to study CP violation at proton-proton colliders such as the Tevatron. There, B mesons are produced far more copiously, but it's considerably more difficult to reconstruct them from their decay products, because proton-proton colliders produce more of everything else, too. It's easy for the B decay products to literally get lost in the background.)

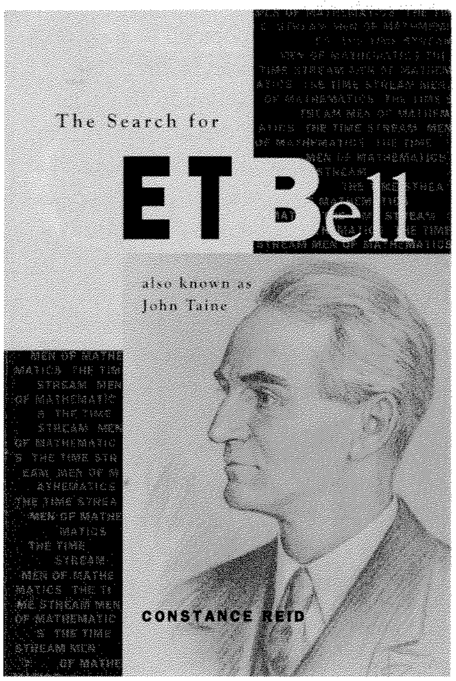
At the B factory, physicists would measure the B meson's decay rates into various CP eigenstates as a function of the decay length. If, indeed, Kobayashi and Maskawa's suggested mechanism is responsible for CP violation in the K and B systems, and if there are exactly three generations of quarks, then the measured asymmetries will satisfy certain mathematical relations. If all the factory's data fall in the expected range, then we will have performed a crucial test of the self-consistency of the Standard Model. If they do not, this would represent the first failure of the Standard Model, and we will have a "smoking gun" for physics beyond it. The observed deviations from the Standard Model's predictions will provide valuable clues as to the nature of the new physics. This would be even more noteworthy than observing CP violation itself.

If one ignores or fails to measure the decay flight distances, as in the case of a collider with beams of equal energy, the CP-violating asymmetry vanishes—you don't know which particle you started with, and therefore which set of decay products to expect. This is why you need an asymmetric collider to study CP violations. However, the asymmetry doesn't vanish, even at a symmetric collider, if charge, parity, and time are *all* violated. As mentioned above, CPT invariance is built into quantum field theories, and it is difficult to even conceive of a theory in which CPT is violated. Nevertheless, it should be possible to detect CPT violations in B meson decays at the percent level, should they exist, at a B factory. Such a discovery would revolutionize particle physics!

The B factory is ambitious and costly, but doable. It may be the best, perhaps even the only chance we have of observing CP violation at the fundamental level, outside of the kaon system. Either it will confirm Kobayashi and Maskawa's mechanism for producing CP violation—which is far from answering the question of why CP violation exists—or it will provide crucial clues to physics beyond the Standard Model. Either way, it is destined to be a landmark experiment. Such a machine will also permit physicists to perform very precise studies of the decays of other heavy particles as a spin-off from the ultimate goal of observing CP violation.

CP violation in the B system is one of the high frontiers of particle physics. Exploring this far-removed-from-everyday-life phenomenon has become a focus for hundreds of particle physicists around the world, who are eager to devote a large part of their careers and research dollars to it. This obscure effect is something of a keystone in the elaborate structure of particle physics, an edifice that encompasses everything we think we know about the fundamental nature of all forms of matter and energy. B uried in this phenomenon somewhere is a profound insight into the nature of space-time and matter-energy, and into the very basis of our existence. □

Assistant Professor of Physics Alan J. Weinstein earned his AB from Harvard in 1978 and his PhD in 1983, both in physics. He then joined the Institute for Particle Physics at the University of California, Santa Cruz, and spent most of his time at SLAC, where he worked on the linear collider, among other things. Weinstein came to Caltech in 1988.



The Mathematical Association of America, 1993
372 pages
$35.00

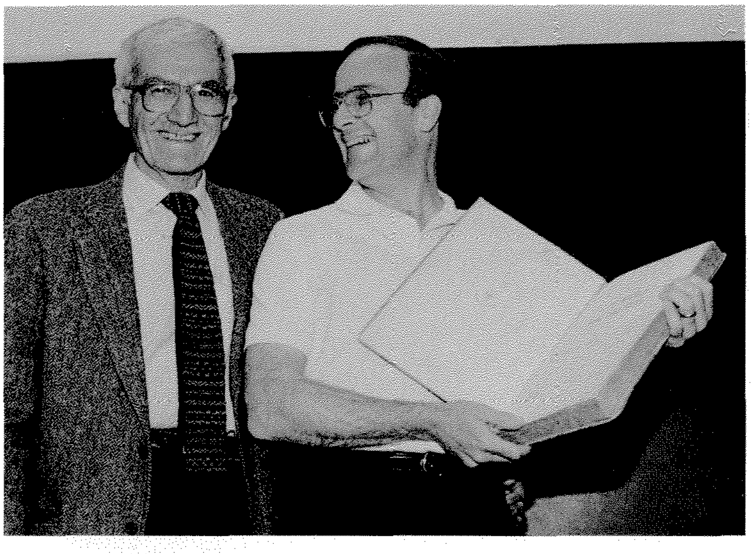
"A Cat That Can't Be Caught" is the first chapter of this quite readable story of the life of Eric Temple Bell. Constance Reid carries us along on her private-eye-like search for the truth about his early years, which he had kept secret from his friends, his family, and even from his beloved wife, and which he had even distorted (the polite word) when filling out a form for the Caltech administration in 1943. By a combination of diligence and luck the author has discovered that when Bell was about a year old his father moved the family from Scotland to San Jose, thence south to the farm country of Santa Clara County, where he began a fruit orchard. It was here that Bell spent his boyhood, and images of an idealized pastoral countryside find their way into many of his poems and stories. Why was it necessary for him to keep these years secret? Reid never finds this out.

He was a teenager when his father died, and his mother returned the family to England, where Bell entered what we would call a high school and fell in love with mathematics. But it was back in the United States that Bell did his university work—Stanford, Washington, and Columbia. After finishing his PhD, he began his teaching career and for many years seemed to want little more. Mathematical research was a minor activity. Poetry demanded more attention, and it was the time for beginning an epic work, *The Scarlet Night*, the revision of which was to occupy the last years of his life. It was also the time for his marriage, at the age of 27, to his beloved Toby.

The author said to Bell's son Taine: "The thought has passed my mind that your father might have preferred being a poet to being a mathematician," to which Taine replied, "I think he might have if he had had any success." Bell found no conflict between his dual interests, and wrote that "mathematics and poetry are simply isomorphic."

His mathematical research began to expand in original directions, which were, however, apparently not very well described in his publications. One of the reviewers contacted by Reid had two favorite instances of Bell's style: "the following complete sentence: 'Hence, etc.' and my very favorite footnote: 'A set of elements form a semi-group if they have the *group property*, etc.'" A few years later his "recreational writing" began under the name of John Taine (the basis for the name is obscure—it is not in his family history) in the genre we now call science fiction. A friend suggested that it served "as a relief from the grind of mathematics."

Although Reid comments clearly on Bell's fictional products, her descriptions of his mathematics is another matter; for



Lyle Bell (right), E. T. Bell's grandson, presents to the Caltech Archives the 1670 edition of the *Arithmeticorum* of Diophantus, given to Bell when he retired from Caltech. The volume reproduces Fermat's famous margin notes postulating his "last theorem" and is signed by all the members of the 1953 mathematics faculty. Accepting the book is Tom Apostol, professor of mathematics, emeritus, one of the signers.

example: "The paper contains the fundamental general treatment of the algebraic properties of generating functions that he used to explain the development of his theory of numerical functions, especially factorable or multiplicative functions." I have always thought of myself as one of those readers so sought after by writers in *Scientific American*—the "educated layman"— but that sentence mystifies me. Unhappily, it is not a unique example.

In the mid-1920s, R. A. Millikan persuaded Bell to come to Caltech, in spite of better financial offers from eastern universities, such as the University of Chicago. He and Toby acquired their small house on the corner of San Pasqual and Michigan, and later the lot next door where he built his small hexagonal study in the midst of a bamboo jungle. This was to be the "generating site" for his mathematical papers, the expanding list of John Taine sci-fi novels, and another type of publication that now began to get his attention: books and pamphlets intended to popularize science and mathematics. (This last seemed ironic to some of his colleagues who found his descriptions of his own work obscure.)

He established good relationships with his fellows on the Caltech math faculty—Harry Bateman, A. D. Michal, Harry Van Buskirk, Morgan Ward (who had been a graduate student of Bell's), and others—and a rather stormy one with H. P. Robertson (also a former Bell student). He enjoyed his contacts with other faculty—T. H. Morgan, Paul Epstein, and, in particular, Edwin Hubble. Bell credits Hubble's wife, Grace, with important assistance in his nonmathematical writings, for example in his famous set of biographies, *Men of Mathematics*.

Toby died in 1940, and it seemed to many that Bell was never quite the same. He devoted most of his energy to the revision of his poem, *The Scarlet Night,* written decades before. He found a retreat in Redondo Beach to work on it without distraction. There, late one night, walking on the beach as was his habit, he was mugged, and was brought back to Pasadena in serious condition. Many of his friends felt that this second event, after Toby's death, caused a deep change in his personality. Nevertheless he continued to work on his poem and on another favorite project, a book about Fermat, called *The Last Problem*. But he was drinking too much and his health was steadily failing. In 1959 his son Taine took him to Taine's home in Watsonville to care for him, and it was there he died the following year.

The book is a good read (apart from a few descriptions of his mathematics). Opinions about his personality and abilities in his later years are expressed by quotes from those who knew him, and a good search of documents covers his earlier life. She enlisted some expert helpers in reviewing this material.

The most interesting discovery for me was the breadth of his activities, which I knew of but never fully appreciated—poetry, fiction, popular science, and one really out of left field: his strong hand in the organization and design of the Chicago World's Fair in the early thirties.

Albert R. Hibbs, BS '45, PhD '55
(Although a physicist, not a mathematician, Hibbs took courses from Bell and contributed one memorable quote to the book. He is now retired from his position as senior scientist at the Jet Propulsion Laboratory.)

Cambridge University Press, 1993
164 pages
$19.95

Most of us probably think we know pretty well what to expect from a book subtitled "what everyone should know about science"; in this case, we would be dead wrong. Of course, since that expectation has little to do with golems, perhaps we should not be too surprised. Collins and Pinch are among the leading practitioners of the field generally known as "sociology of scientific knowledge," or SSK. This discipline examines science from the point of view that truths are accepted, controversies resolved, and knowledge created, not by any logically rigorous "scientific method," but rather by social factors.

To support their viewpoint, Collins and Pinch present seven case studies of controversy in science, varying widely by topic as well as outcome. An excellent illustration is provided by one that might not occur to many contemporary scientists as particularly controversial: the roles of the Michelson-Morley experiment and the Eddington observations of stellar displacement during an eclipse in "proving" the theory of relativity. In the first, complications by various factors that could have caused the observed negative result—no dependence on direction of the speed of light—could not be rigorously excluded. Furthermore, another scientist subsequently obtained a *positive* result (for which he received a prize from the AAAS in 1925). Similarly, in the eclipse studies, some of the results gave deflections compatible with Einstein's prediction, while others were more consistent with classical Newtonian physics. The experiment was announced as confirming Einstein, though; the latter set of results was assumed to be of poorer quality and ignored.

From this and other studies—including episodes such as Pasteur's rejection of spontaneous generation of life, chemical transfer of memory, gravity waves, and cold fusion—Collins and Pinch conclude that there are no rigorous criteria available by which to judge the validity of an experiment and the resulting implications. Instead, such judgment is inextricably bound up with what one already believes: "relativity . . . is a truth which came into being as a result of decisions about how we should live our scientific lives . . . a truth brought about by agreement to agree about new things. It was not a truth forced on us by the inexorable logic of a set of crucial experiments."

The chapter on gravity waves introduces the key concept of the "experimenter's regress." A novel experiment gives a certain result, but is it a good experiment? A good experiment would give the correct result—but until we've carried out such an experiment, we don't know the correct result. Hence, the authors argue, it is impossible to resolve a disagreement by any rigorous experimental criteria. Thus, in their view of the cold fusion controversy, choosing to favor Pons and Fleischmann's positive results or Nate Lewis's negative ones can only be based, ultimately, on whether or not we believe in cold fusion; a dispassionate assessment of the experiments cannot be reached.

Collins and Pinch do challenge us to think about scientific research in ways that are probably rather new to most of us. Nonetheless, it is hard to see that they have even come close to justifying such sweeping conclusions, summed up as: "we have shown that scientists at the research front cannot settle their disagreements through better experimentation, more knowledge, more advanced theories, or clearer thinking." The support for the theory of relativity described above may not have been completely unambiguous, but additional results that Collins and Pinch call "mutually reinforcing" have left no doubt even in their minds about its truth. Isn't that a good example of settling a disagreement through better experimentation and all the rest?

What they do show quite clearly is that science is not Superman—it doesn't leap tall problems in a single bound, but follows an often tortuous and iterative path, affected *(but not* determined*) by the social factors upon which they lay so much stress.*

As for the experimenter's regress, again they go too far. It *is* in fact often possible to assess the validity of an experiment free from any straitjacket of belief. To take an extreme case, in evaluating the failure to observe a signal one might discover that the apparatus had not been plugged in. Some of the mistakes made by cold fusion researchers were not much less egregious. I would imagine that most readers familiar with the cold fusion story to any degree of detail will disagree strongly with the statement: "In cold fusion we find science as normal."

Should scientists read this book? It's not obvious that Collins and Pinch think so: "this view of science . . . should make very little difference to the way scientists act when they are doing their work at, metaphorically speaking, the laboratory bench." It seems to me that better sensitivity to when and where social factors enter into scientific practice could well have a positive effect on scientific progress. Collins and Pinch, on the other hand, believe that these factors are ubiquitous and inescapable, and that understanding the social view of science might even be detrimental to scientists—perhaps like the centipede who can't walk when he thinks about how he does it. It seems paradoxical but almost inevitable that, having disagreed with so many of their conclusions, I would also contest their low valuation of the potential significance of their *own* work for scientists. In any case, the book amply satisfies one key criterion for recommendation: it's fun to read.

What about the use of "golem" as title and central metaphor for science? The golem, a creature of early Jewish legend, was a clumsy monster, superhuman in physical strength but subhuman in intelligence. The implication is that science bumbles about its business, settling on answers more or less at random, and never learning from its experience how to do things better. In fact, Collins and Pinch have chosen the wrong legendary figure. What they do show clearly is that science is not Superman—it doesn't leap tall problems with a single bound, but follows an often tortuous and iterative path, *affected* (but not *determined)* by the social factors upon which they lay so much stress. For those who needed it, Collins and Pinch convincingly knock down the straw man (straw Superman?) representing a perfectly rational and straightforward scientific method. The clay man of golem science that they set in its place is far less convincing.

Jay A. Labinger
Administrator, Beckman Institute
Lecturer in Chemistry

Letters

Lilv Kay says I misinterpreted her book [*The Molecular Vision of Life;* review, Spring 1993]. What I perceived as an attempt to allege a conspiracy was rather an instance of historical determinism (a phrase not used in her book) as applied to science, which she has painstakingly revealed.

Well, I see. I, all the Caltech biologists, the Rockefeller Foundation, et al., all being "cut of the same cultural cloth," were manipulated by the genie of a historical determinism that Kay is now able to discern. The Rockefeller Foundation did not have to co-opt the Caltech biologists—they resonated to that same drummer, shaped by the same "social and political agendas," all presumably thirsting to achieve "social control" through biology .

Sorry, Ms. Kay; scientists don't think that way and science is not done that way. And to argue that it is, is demeaning to the scientists involved and false to history. The development of science does not fit your mold. Natural science has evolved in an orderly fashion, determined by the structures of nature itself and paced by the genius and inspiration of talented scientists, not by the alleged social agendas or machinations of agencies such as the Rockefeller Foundation.

The biologists and chemists at Caltech sought imaginatively to utilize the advancing knowledge in their own disciplines combined with major conceptual and technical advances in allied disciplines to achieve deeper insight into the phenomena of living organisms—into genetics and biochemistry and physiology and neuroscience, and other fields. Deeper insight could be obtained through deeper analysis of the processes underlying these phenomena. And the tools for this deeper analysis were *only then* becoming available—X-ray diffraction (and computers), electron microscopy, isotopes, ultracentrifuges, spectrophotometers, and so on.

These possibilities derived in only the most tangential sense from any "social and political agendas" of the time. They derived from the great advances in science in the 20th century. By the 1930s, '40s, and '50s, molecular approaches to biological phenomena became possible, for those with scientific vision. And the subsequent developments in molecular biology have now provided a firm base for further understanding in developmental biology, neurobiology, and others. Since the Enlightenment, the principal constraints upon science have been, with rare exceptions, the constraints of nature and the limits of available research technology, not a "political and economic framework." (Although today, admittedly, the high cost of some experiments becomes limiting).

When Kay writes: "The rise of molecular biology, then, represented the selection and promotion of a particular kind of science, one whose form and content best fitted with the wider, dominating patterns of knowing and doing. The molecular vision of life was an optimal match between technocratic visions of human engineering and representations of life grounded in technological intervention, a resonance between scientific imagination and social vision," and that "from its inception around 1930 the molecular biology program was defined and conceptualized in terms of technological capabilities and social possibilities. Representations of life within the new biology were a priori predicated on interventions that, in turn, aimed from the start at reshaping vital phenomena and social processes," she seriously misrepresents the motivations, the mindsets, of the scientists involved. By using the language of conspiracy (a conspiracy need not be secret; see Webster), whether or not every action is referred back to a postulated guiding historical determinism, she gives the whole enterprise a most undeserved and sinister cast.

Simplistic applications of historical determinism to science are not "subversive"; rather they are misguided, written by nonscientists who do not comprehend the processes of science. Progress in science does not "escape history"; it has its *own* historical logic. The past 60 years has been the feasible and natural time for the development of molecular biology. Efforts to interpret such progress in accord with an irrelevant ideology only grievously distort both the science and the scientific personalities involved.

Kay asks, "who should speak for the past?" In this instance, fortunately, the "past" is not past, for it yet resides in living memory. More generally, the past speaks for itself, but only to those who understand its language.

Robert L. Sinsheimer
Professor, Emeritus, UC Santa Barbara
(Professor of Biophysics at Caltech 1957–1977)

"The campaign has helped people think about Caltech's scientific priorities, and I consider that to be one of our significant accomplishments."

Campaign Concluded

The Campaign for Caltech: A Second Century of Discovery has reached its goal of raising $350 million in gifts and pledges by the end of 1993. A $2 million gift for scholarships put the figure over the top on October 20. The total was projected to be about $30 million over the $350 million by the end of the campaign on December 31.

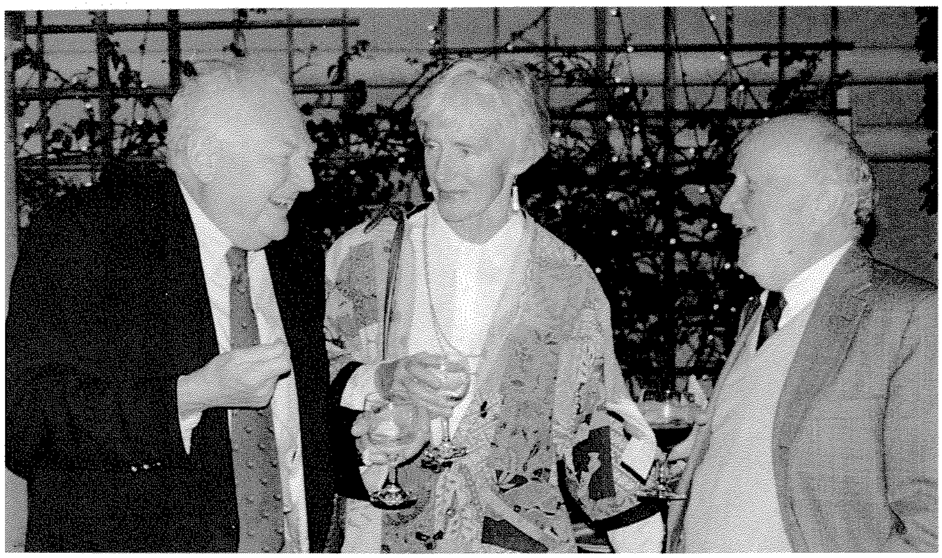
The fourth such fund-raising effort in Caltech's history, the campaign got under way in October 1989 with a "quiet phase," and entered its public phase in January 1991. The effort has been spearheaded by the Institute's board of trustees under the leadership of board chairman Ruben Mettler; William Kieschnick, vice chairman of the board and chairman of the Campaign Executive Committee; and the late James Glanville, who served as the initial campaign chairman. Caltech's Development staff, under the direction of Tom Anderson, vice president for Institute relations, and Tanya Mink, campaign director, collaborated with the trustees in the endeavor.

The campaign's overall aim has been to provide funds for a wide range of academic priorities that were first identified and outlined in a 1989 Institute-wide Aims and Needs Study. These priorities fall into three basic areas: endowment, capital funds, and programs and current operations. As of mid-December, with gifts and pledges still coming in at an increasing rate, almost all of the priorities had been funded and many of the goals exceeded. Among the major projects that will change the physical and scientific landscape of Caltech in the near future are the Moore Laboratory for Electronic Materials and Structures, funded with a $16.8 million gift from Gordon and Betty Moore; Avery House, a new student residence made possible by a $10 million gift from R. Stanton Avery (trustee chairman emeritus); the Keck II Telescope, being constructed with $74.6 million from the W. M. Keck Foundation; and the Braun Athletic Center, completed last year with a $4.7 million gift from the Carl F Braun Trust.

Monies raised for endowment, as of mid-December, will support 15 new named professorships. So far 6 postdoctoral fellowships, 18 graduate fellowships, and 49 undergraduate scholarships have been funded; although these represent only two-thirds of the goal of $40 million in that category, Anderson and Kieschnick emphasize that filling this need will remain a high priority.

Conclusion of the campaign won't signal a slowing of fund-raising initiative. Already, says Anderson, the Institute is looking ahead, knowing that in any successful campaign, the conclusion of one phase is but a steppingstone to the next. "Post-campaign, we will be studying specific campaign objectives that weren't fully funded to determine which ones need more work," he says. "The campaign has helped people think about Caltech's scientific priorities, and I consider that to be one of our significant accomplishments. We hope that Caltech alumni and friends who have learned more about the Institute's teaching and research will continue to give their support."

Right: At dinner in the Oviatt Building penthouse, Lance Davis (left) discusses what does not appear to be "the dismal science" with Nobel laureate Douglass North and his wife, Elisabeth Case.



Below: This year's Engineering Design Laboratory (ME 72) challenged students to design motorized scooters (easily stowable in a car trunk) to help senior citizens cart groceries and run other errands. Six teams showed off their inventions to a panel of judges (potential users), who rated them on safety, ease of use, comfort, durability, and aesthetic appeal. Son Chu Nguyen's team's scooter drew praise for its handy rain shelter and other special features, but didn't fare too well on the speed and handling test around campus.

Economic Historians Honor Lance Davis

When economic historian Lance Davis turned 65, some of his California colleagues decided to throw a party— and a conference—in his honor. The All University of California Group in Economic History—a group that also includes some non-UC scholars— hosted a conference at UCLA on November 13–14. The conference was organized around topics that Davis has dealt with in his work. Coincidentally, for the first time this year's Nobel Prize in Economics went to two economic historians— Robert Fogel of the University of Chicago and Douglass North of Washington University; both were on hand for Davis's birthday celebration.

Davis came to Caltech as professor of economics in 1968 and was named the Mary Stillman Harkness Professor of Social Science in 1980. He had earned his BA from the University of Washington in 1950 and his PhD from Johns Hopkins in 1956. Before coming to Caltech he taught at Purdue. At the dinner, Davis was hailed as one of the earliest and most innovative practitioners of what has become known as "cliometrics" (Clio was the Greek muse of history) or the "new economic history,"— a discipline that emphasizes the application of economic theory and massive amounts of data—from such sources as business records and government documents—to quantify hypotheses in order to reach accurate conclusions about history and longterm economic growth. It was this approach that was recognized in the most recent Nobel award. Specifically, Davis is best known for his work on the nature of capital markets, particularly in 19th-century United States and Great Britain. He has also written widely on the impact of British imperialism and on patterns of technological change.

Honors and Awards

Harold Brown, Caltech president emeritus and trustee, has received the Enrico Fermi Award from the Department of Energy "for his outstanding contribution to national security" in the areas of nuclear-weapon development and deterrence policy.

Erik Carreira, assistant professor of chemistry, has received a Beckman Young Investigator Award from the Arnold and Mabel Beckman Foundation.

Peter Dervan, the Bren Professor of

Chemistry, has been selected as the 1994 recipient of the Nichols Medal, for being "largely responsible for moving bio-organic chemistry into a new era."

Dennis Dougherty, professor of chemistry, and Edward Stone, vice president, professor of physics, and director of JPL, have been named Fellows of the American Association for the Advancement of Science.

Richard Flagan, professor of chemical engineering, was presented the 1993 David Sinclair Award of the American Association for Aerosol Research.

Douglas Flamming, assistant professor of history, has won the Philip Taft Labor History Prize for "the best book on labor history published in 1992." The book, *Creating the Modern South: Millhands and Managers in Dalton, Georgia*, was reviewed in the Winter 1993 issue of *E&S*.

Konstantinos Giapis, assistant professor of chemical engineering, has received a Camille and Henry Dreyfus New Faculty Award.

Stephen Mayo, assistant professor of biology, has been awarded a five-year Fellowship in Science and Engineering by the David and Lucile Packard Foundation, one of 20 awarded nationally to outstanding young professors.

Anatol Roshko, the von Kármán Professor of Aeronautics, has been awarded the Raman Chair by the Indian Academy of Sciences, a visiting professorship at the Indian Institute of Science.

Theodore Yao-Tsu Wu, professor of engineering science, has been awarded the Fluid Dynamics Prize, sponsored by the Office of Naval Research and presented by the American Physical Society.

Gordon Moore Elected Trustee Chairman

Gordon Moore, chairman of the board of Intel Corporation, has been elected chairman of Caltech's board of trustees, succeeding Ruben Mettler, who is retiring from the post he has held for nine years. Both men are Caltech alumni and leaders of industry.

Moore's long association with Caltech began when he entered Caltech as a graduate student in 1950, after earning his BS from UC Berkeley. Moore became one of a handful of scientists in the mid-fifties who grasped the enormous potential of seminconductor technology; shortly after receiving his PhD in chemistry from Caltech in 1954, he joined the Shockley Semiconductor Laboratory, and then in 1957 cofounded Fairchild Semiconductor Corporation with several colleagues. Here he oversaw a number of key innovations, including development of the first applications for the integrated circuit, invented by his Fairchild colleague Robert Noyce in 1959.

In 1968 Moore and Noyce founded Intel, which three years later helped launch the information revolution when it developed the silicon chip microprocessor. Intel's reported earnings last year exceeded $1 billion. Moore served as Intel's executive vice president from 1968 to 1975, as president and CEO from 1975 to 1979, and as chairman and CEO from 1979 to 1987. Currently chairman of the board, he has been a company director since 1968. In 1990 Moore won the National Medal of Technology "for leadership in the microelectronics innovations of large-scale integrated memories and microprocessors."

Moore has been an Institute trustee since 1983, and he and his wife, Betty, are life members of the Caltech Associates and members of the Presidents Circle. Their gifts to Caltech include the Gordon and Betty Moore Professorship in Engineering (held by Carver Mead) and the Gordon and Betty Moore Undergraduate Scholarship Fund. In 1991, as a major gift to the Campaign for Caltech, the Moores pledged $16.8 million to build the Moore Laboratory for Electronic Materials and Structures, scheduled to begin construction north of the Thomas Watson Lab next year.

Mettler's connection to Caltech is even longer (*E&S*, March 1986). He arrived in 1943 to participate in the Navy's V-12 program, eventually receiving his BS ('44), MS ('47), and PhD ('49) from the Institute. He then went on to play a leading role in the development of the aerospace industry, which culminated in his becoming president and CEO of TRW in 1969 and chairman and CEO in 1977, a position he held until his retirement in 1988. Named to the Caltech board of trustees in 1969, he was elected chairman in 1984, his tenure including the recently completed, successful Campaign for Caltech. As chairman emeritus, Mettler will remain on the board. The Mettlers are also Life Members of the Caltech Associates and in 1988 established the Ruben and Donna Mettler Professorship in the Division of Engineering and Applied Science.

A dinner at the Board of Trustees meeting at Smoke Tree Ranch October 30 celebrated outgoing chairman Ruben Mettler (right). Caltech officials expressed their gratitude to Mettler with several gifts, among them a pictorial "scrapbook" of the years of his chairmanship, which he peruses here with fellow trustees Ralph Landau (seond from right), Camilla Frost, and Gordon Moore, his successor as chairman.