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In this issue

Meet Bob, a ’96 Chevy Tahoe 4x4 modified by a Caltech team, primarily undergrads, to compete in a driverless off-road race from Los Angeles to Las Vegas—no remote-control joysticking allowed—on March 13. The first team to complete the course in under 10 hours would win a cool million. Instead of a map, two hours before the race the entrants were given a CD-ROM with 2,500 sets of GPS waypoints for the vehicles to follow down a corridor that varied in width from 10 meters to 10 kilometers. To find out how Bob fared, see the story on page 5; then, to see the videos, watch faculty advisor Richard Murray’s Watson Lecture on http://today.caltech.edu/theater/.

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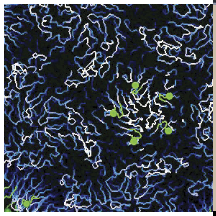

On the cover: This allosaurus skeleton, folded from 16 sheets of paper, shows that getting lots of flaps—the teeth, for example—where you want them is pretty straightforward using a software package based on tree theory. For more on computational origami design and tree theory (which has nothing to do with where the paper comes from), see the story beginning on page 8.

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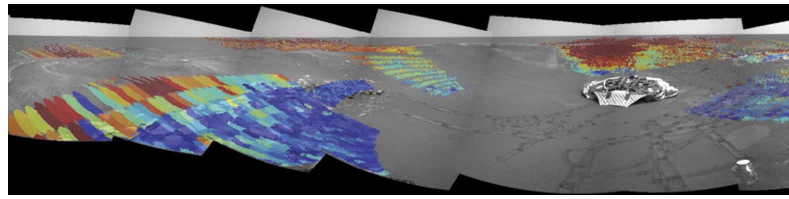


Opportunity by the Sea

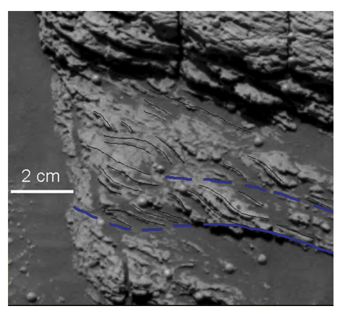
As *E&S* was going to press, it was announced that Opportunity, one of JPL's twin Mars rovers, had found conclusive evidence of gently flowing saltwater at its landing site on Meridiani Planum. The layers in a rock called Last Chance "were shaped into ripples by water at least five centimeters deep, possibly much deeper, and flowing at a speed of 10 to 50 centimeters per second," said MIT's John Grotzinger, a member of the science team. "Ripples that formed in wind look different than ripples formed in water."

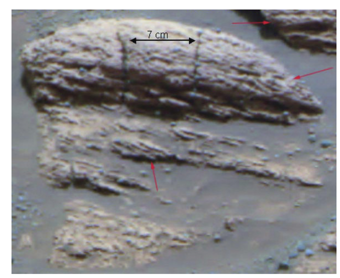
This cross-bedding, as it's called, is a characteristic of sedimentary rock and corroborates other physical and chemical evidence that hinted of minerals precipitating out of salty water as it evaporated.

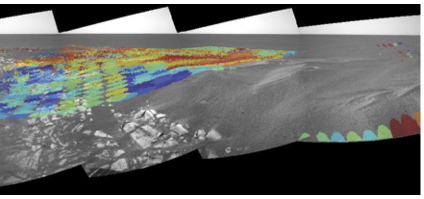
It's still unknown how long the water lasted, how extensive it was, or how long ago it was there, but it clearly shows that Mars was more hospitable to life in the past. And life's traces may remain—such rocks "offer excellent capability for preserving evidence of any biochemical or biological material" for future missions, said Cornell University's Steve Squyres, the principal investigator for the rovers' science payload.

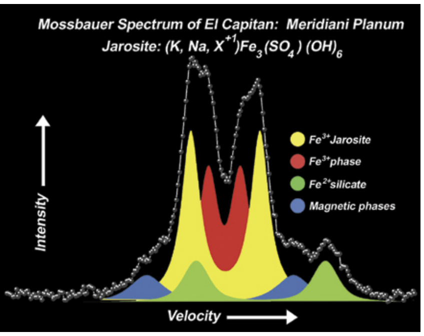
On the opposite side of the planet, the other rover, Spirit, has picked its way through the ejecta field to the rim of Bonneville crater (below), sampling rocks en route. Alas, the interior proved devoid of interesting outcrops, and Spirit is now setting out for the Columbia Hills to the far right, a couple of kilometers and perhaps several months away. □—*DS*

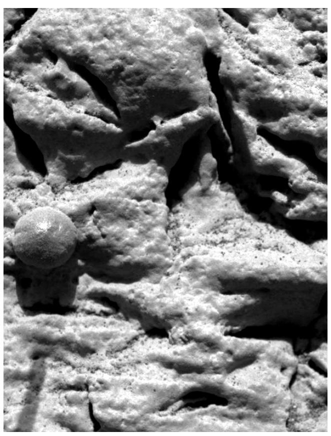
The case for a seashore, clockwise from above: 1) Opportunity scored a hole-in-one, landing in a shallow crater some 22 meters wide, and then hit the jackpot when the crater proved to have exposed bedrock—the flat, whitish stones. The rover verified high levels of gray hematite (seen in red in the overlay), which usually forms in water. 2) The outcrop contains jarosite, a mineral that incorporates water in the form of OH groups. 3) BB-sized "blueberries" of hematite are eroding out of the rock, littering the area. The embedded blueberries, like the one near the image's left edge, continue the rock's fine layering, most notably as the groove around the blueberry's middle. This shows that they formed in situ through precipitation. And the thin, flat voids, called "vugs," were created where salt crystals grew and later dissolved away; high levels of bromine and chlorine still remain. 4) The blueberries can also be seen on and around Last Chance, where the arrows point to cross-bedded areas. 5) A close-up of Last Chance's central region has black lines added to highlight the smile-shaped ripples, or "festoons." The blue dashes mark where the ripples changed direction with the shifting currents.











Meanwhile, at the Edge of the Solar System. . .

A Caltech-led team has discovered the most distant member of the solar system so far. The new planetoid, more than 13 billion kilometers from Earth, or over three times the distance to Pluto, is well beyond the recently discovered Kuiper belt and is likely the first detection of the long-hypothesized Oort cloud. This cloud, predicted 54 years ago by Dutch astronomer Jan Oort to explain the existence of certain comets, extends halfway to the nearest star and is the repository of small icy bodies that occasionally get pulled in toward the sun. The object was found on November 14, using the 48-inch Samuel Oschin Telescope at Caltech's Palomar Observatory.

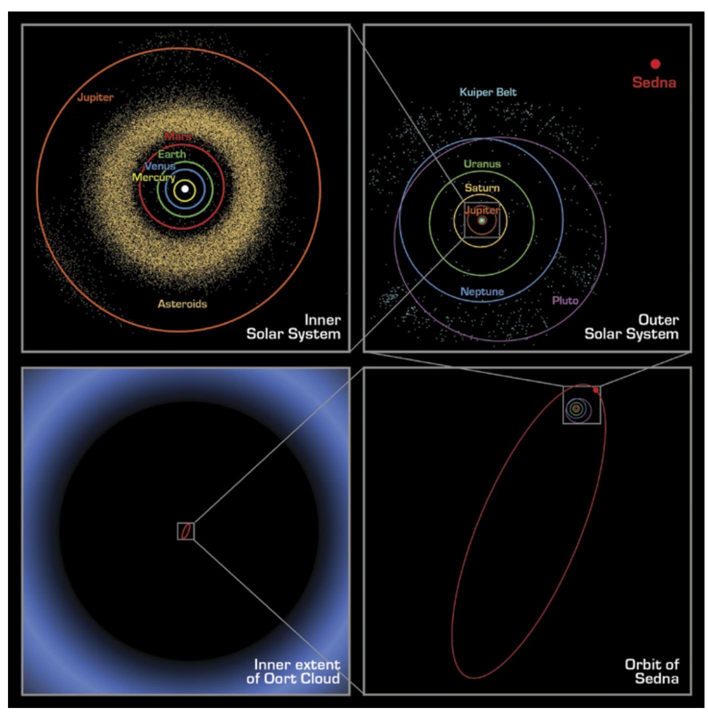
The sun is so far from this planetoid, says team leader Mike Brown, associate professor of planetary astronomy, "that you could completely block it out with the head of a pin." And the object gets this close only briefly during its 10,500-year orbit. At its most distant, it is 130 billion kilometers, or 900 times Earth's distance, from the sun, and its temperature plummets to just 20 degrees above absolute zero.

Thus Brown and his colleagues Chad Trujillo of the Gemini Observatory and David Rabinowitz of Yale University propose that the frigid planetoid be named "Sedna," after the Inuit goddess who created the sea creatures of the Arctic. She lives in an icy cave at the bottom of the ocean—an appropriate spot for the namesake of the coldest known body in the solar system.

Distant as it is, Sedna is much closer than expected, as the Oort cloud had been predicted to begin 10 times farther away. Brown believes that the "inner Oort cloud" where Sedna resides was formed by the gravitational pull of a rogue star that came close to the sun early in the history of the solar system. Such a star, says Brown, "would have been brighter than the full moon and visible in the daytime sky for 20,000 years." Worse, it would have dislodged comets further out in the Oort cloud, leading to an intense comet shower that would have wiped out any life on Earth that existed at the time.

Images from the Spitzer Space Telescope, which Caltech and JPL run for NASA, indicate that Sedna is no more than 1,700 kilometers in diameter, making it smaller than Pluto.

Right: Sedna's highly elliptical orbit, inclined from the plane of the solar system by 11.9 degrees, travels from well outside Pluto's orbit to the boondocks between us and the Oort cloud.



Brown estimates that it is probably about three-quarters Pluto's size. Rabinowitz says that indirect evidence suggests that Sedna has a moon—a possibility best checked with the Hubble Space Telescope—and he notes that Sedna is redder than anything known in the solar system with the exception of Mars, but no one can say why.

Trujillo admits, "We still don't understand what is on the surface of this body. It is nothing like what we would have predicted." But the astronomers aren't worried. They have plenty of time to figure things out—Sedna will get closer and brighter for the next 72 years before fading away again. □—*RT*

Below: Swords into plowshares—Art Center College of Design, the Caltech of the art world, has turned the onetime Southern California Cooperative Wind Tunnel on South Raymond Avenue into its new South Campus. The wind tunnel was built by Caltech during World War II for Consolidated Vultee, Douglas, Lockheed, and North American, and was upgraded in the mid-'50s to become one of the first large supersonic wind tunnels in the world. Under the directorship of Professor of Aeronautics Clark Millikan (PhD '28), it remained enormously productive through the Cold War until 1960, when operations ceased. (One of the last things tested in it was a 1/5-scale model of the Polaris missile.) This photo, taken during the upgrade, shows the tunnel's airlock, which contained the 12-foot-diameter test section. In its new life, the 17,000-square-foot tunnel hall in the background will become an exhibit and performace space. The rest of the 100,000-square-foot complex will house studios, offices, and a letterpress. The public is invited to an open house on Sunday, May 16.

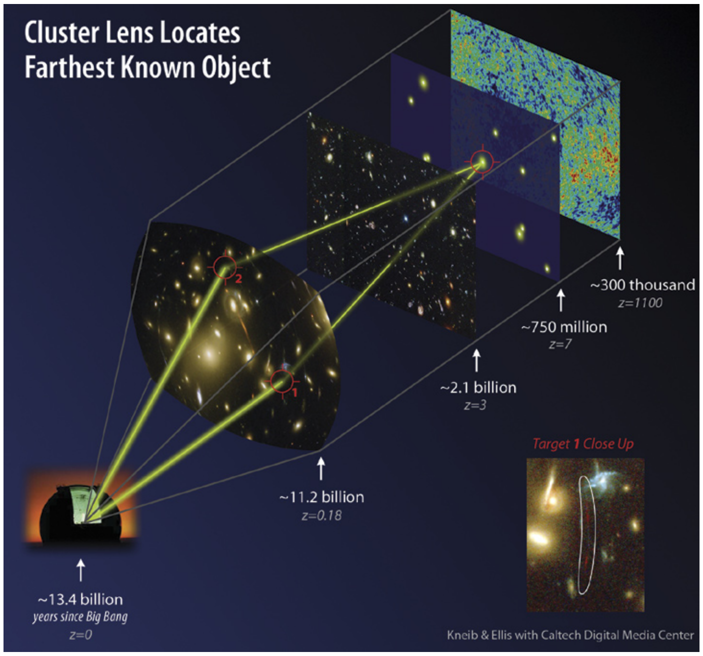
And at the Far End of the Universe. . .

Caltech astronomers may have discovered the farthest known object in the universe—a galaxy so distant that its light would have left for Earth when the universe was perhaps just 750 million years old. Visiting Associate Jean-Paul Kneib, the lead author of a paper in an upcoming issue of the *Astrophysical Journal*, says the galaxy has a redshift of 7.05, so great that its ultraviolet light is now seen at infrared wavelengths. Redshift is a measure of the factor by which light's wavelength is stretched as it passes through the expanding universe. The greater the shift, the more distant the object and the earlier it is being seen in cosmic history.

The galaxy, which was found with the Hubble Space Telescope and later studied at the Keck Observatory, is relatively small—perhaps only 2,000 light-years across, compared to our own Milky Way's 100,000 light-year diameter—but forming stars at an extremely high rate. Oddly, it seems to lack the typically bright hydrogen emission seen in many distant objects. And its intense ultraviolet signal is much stronger than that seen in later star-forming galaxies, suggesting that it may be composed primarily of massive stars. "These unusual properties, if verified, could represent those to be expected for the young stellar systems that ended the dark ages," said coauthor Richard Ellis, the Steele Family Professor of Astronomy.

The term "Dark Ages" was coined by the British astronomer Sir Martin Rees to signify the period in cosmic history when hydrogen atoms had formed, but stars had not yet had the opportunity to condense and ignite. Nobody is quite clear how long this phase lasted, and the detailed study of its end is a major goal of modern cosmology.

The team consists of Kneib; Ellis; Mike Santos, now a postdoctoral researcher at the Institute of Astronomy in Cambridge, England; and Johan Richard. Kneib and Richard are also affiliated with the Observatoire Midi-Pyrénées of Toulouse, France. □—*RT*



Above: The galaxy lies behind a relatively nearby cluster of galaxies called Abell 2218, which is at a redshift of 0.18 and whose light left for us when the universe was about 11.2 billion years old. As Einstein predicted, Abell 2218's mass bends the path of light in its vicinity, acting as an enormous lens that happens to focus the newfound galaxy's light on Earth. In this case, the galaxy is not only magnified by a factor of 25, making it visible to us, but three weirdly distorted images of it are produced, two of which are circled and one of which is shown in the inset. Also shown are some intermediate-aged galaxies at a redshift of 3, and the cosmic microwave background, which dates back to about 300,000 years after the Big Bang.

Bob Gets His Learner's Permit

Like most neophyte drivers, Bob tended to ride his brakes. As he crept around the vast, deserted parking lot at the Santa Anita racetrack in Arcadia, the '96 Chevy Tahoe bucked and lurched every 10 feet or so, brake lights flashing. His instructors, a cluster of undergrads pounding on laptops under a marquee tent a hundred yards away, conferred with their advisor, Richard Murray (BS '85), professor of mechanical engineering and chair of the Division of Engineering and Applied Science. "It's some bug in the software." "No, the gain is set wrong." No problem—the big race was still two weeks off.

Since spring 2003, when more than 50 undergrads did the preliminary studies for course credit, Caltech has been an entrant in the Defense Advanced Research Projects Agency's Grand Challenge Race. Looking for fresh approaches to tough problems, DARPA has offered a million bucks cash to the first vehicle to drive itself off-road from L.A. to Las Vegas in under 10 hours without human intervention. To prevent folks from tailoring their software to the course, the exact route was kept secret until two hours before the 6:30 a.m. race time on March 13. In fact, the course actually ran from Barstow to Primm, on the California-Nevada border, a distance of 142 miles as the dune buggy jounces. (By contrast, JPL's autonomous Mars rovers might go 80 meters on a good day.)

The challenge drew robotics enthusiasts, programming wizards, and homegrown mechanical geniuses of all sorts. They modified SUVs, ATVs, sand rails, and even a motorcycle—an idea with some seductive advantages, and some really obvious drawbacks. And there were scratch-built creations like the six-wheeler with three articulated body segments that looked like a toddler's pull toy. But Carnegie Mellon University's Sandstorm, a modified Humvee—military surplus, not the H2 marketed to yuppies—was widely seen as the 'bot to beat. CMU had spent over

QID finalists came in all shapes and sizes. TerraMax (left) is a 16-ton Army truck whose paint job screams, "Get the @#%*! out of my way!" The U. of Louisiana at Lafayette's ATV (below) weighs a few hundred pounds.

$3.5 million, and had been profiled in *Scientific American*.

At Caltech, 23 undergrads spent their summer modifying Bob and writing his software. Sixteen have continued this academic year as the "working team," with assorted faculty members and folks at JPL, Northrop Grumman, the University of Delaware, and Ford providing advice. Bob's rear seats were torn out to make room for the electronics. "The computers are mounted on foam and strapped down with bungee cords," says Project Manager David van Gogh, a Caltech staff member. "They survive the bouncing pretty well." It takes a lot of juice to run all of Bob's systems, the steering gear, and the air conditioning that keeps the computers happy, so a six-kilowatt gasoline-powered generator rides shotgun.

In case you don't remember the adrenaline rush from your first time behind the wheel in oncoming traffic, driving is hard. It takes Bob eight PCs. One operates the inertial measurement unit (IMU), which does "dead reckoning" based on data from three accelerometers and three gyroscopes. Another handles the roof- and bumper-mounted LADARs, scanning laser "radars" that look for obstacles. Computer number three takes data from the long-range stereo cameras, and number four from the short-range cameras, all of which are mounted on the roof. The fifth PC runs road-following software—"it looks for parallel line segments in each video frame, and computes where they go," says van Gogh. "We have 30 gigs of color data that are going to make a really cool movie of Bob following the road." The sixth brain does "state estimation," taking data from the onboard GPS unit, a magnetometer (a fancy compass), and the IMU, and calculating Bob's location, heading, and slope. Number seven does vehicle management, using Bob's own diagnostic package—the same one your mechanic taps into when you take your car into the shop.

The eighth computer runs a software package called the "arbiter." The arbiter presents Bob's possible next moves to the other computers, which rate them on a scale of zero to 100. "So if they all say go right," explains Murray, "Bob will turn right." If opinions diverge, the arbiter makes the call. A single "nay" can veto a plan, if cast strenuously enough. "In one early test, we were supposed to make a U-turn to the left," says Murray. "But it was late in the day, and the sun was low

enough to be in our field of view, and one computer kept saying, 'Omigod, there's this huge obstacle—DON'T TURN! DON'T TURN!!' So we kept going straight until a pole blocked the sun for a moment, and then it let us turn. But by then we were way off course, because we'd gone too far forward."

Out of hundreds of submissions, DARPA picked 25 for the Qualification, Inspection, and Demonstration (QID) at the California Speedway in Fontana. In this five-day event leading up to Saturday's race, the 'bots were to complete a 1.35-mile dogbone course with such obstacles as a cattle crossing, a sand pit, and an overpass with pillars to squeeze between. Freeway-sized concrete K-rails protected the spectators from errant entrants.

Each 'bot got a detailed safety inspection, and then had a half-hour turn to show its stuff. (Bob sports an amber light and beeper, like those found on construction equipment, to warn bystanders that it's driving itself.) Bob was the third 'bot up. It was not an auspicious beginning—the first two had sat in the starting chute for their full half hour, not advancing so much as a single wheel turn. Bob didn't begin much better—for the first 15 mintues or so, he, too, was lost in thought. Then the generator revved, and, beeping and flashing, Bob rolled onto the course to cheers from the crowd—followed immediately by a collective groan when he ground to a halt after about 20 feet, well before the first obstacle. (It turned out later that this was a prescribed live test of his remote-control kill switch.)

Five minutes of dead silence ensued, and it looked like Bob's day was going to

Some of Bob's support team. Front row, from left: Sue Ann Hong (with white visor), Raquel "Rocky" Velez, Meghan Crowley, Jacki Wilbur (with sunglasses), Tully Foote, and Mike Thielman. Back row: Ike Gremmer, Lars Cremean, Scott Fleming, Thyago Consort (holding water bottle), Jeremy Gillula's arms, and Meaghan Paceley.

Left: Bob takes a hill on the QID. The LADARs are the gray things that look like coffee makers. Note the good-luck toy flamingo next to the IMU, below the stereo cameras. Below: Alan Somers and Jason Raycroft cheer Bob on.

Above: In the starting chutes at the Slash X Café near Barstow are, from left, Sandstorm, SciAutonics II, and Bob.

be over almost before it began. Then—doot, doot, doot—he came to life. He took off at a brisk five miles per hour, with a cheering crowd of Techers, media, and other onlookers in hot pursuit. Bob aced the first half of the course, pausing at times for bouts of intense cogitation, and headed for the overpass. He shot the gap, but lost his GPS signal under the bridge. The IMU wasn't working, so Bob drifted to the right. As soon as he cleared the K-rails protecting the bridge, he made a hard right and took off toward a second set of K-rails some 30 yards from the course. He stopped about 10 feet short, and considered his options. "The sensors are telling him there's an obstacle ahead," explained undergrad Scott Fleming. "And he knows that he's too close to the wall to just cut his wheels and go forward. So what he should do is back up, straighten out, and get back on the course. But we've been having trouble with the transmission controller, and I don't know if we *have* reverse. He's been stuck in first gear all day."

After what seemed like an eternity, but was probably only two or three minutes, Bob very slowly and deliberately drove into the wall. Caltech's track time was over for that round, but the buzz of being the first live contender was tremendous, and Team Caltech's triumph was all over CNN by the time Bob got back to the garage.

What the QID mainly demonstrated was the programmer's version of Murphy's Law: There are three things one should never expect to do tricks on command—your children, your pets, and your software. Everyone suffered from glitches at one point or another. Virgina Tech managed to get crosswise in the starting chute. Sandstorm shifted into gear of its own accord and rammed a closed gate. And Digital Auto Drive nearly crashed into a minivan parked on the course as an obstacle, and was shut down by remote control. (After some discussion, DAD's handlers were allowed to come out and reposition it to clear the van, like a kid picking up an errant slot car and putting it back on the track.)

By Thursday afternoon, Bob had successfully run the course twice, as had Sandstorm, which, 24 hours after Bob's big start, became the first entrant to actually finish a lap. Five other teams, including DAD, completed one lap. In toto, 15 vehicles were given the nod to try their luck in Barstow.

The desert's secret weapon proved not to be rocks, brush, or ditches, but barbed wire. Hard for even humans to see, at least four vehicles wound up wearing it. Bob ran afoul of it at mile 1.3. Says Lecturer in Engineering Antony Fender, who returned at the same hour the next morning and followed Bob's tracks, "The contrast between the dirt road and the shadows across it was extremely high. It appears that Bob tried to drive around a large shadow. He turned left through the wire fence at a shallow angle, maneuvering neatly to avoid the posts, and drove parallel to the road for a couple of hundred yards, weaving among the bushes. Then he made a right-angle turn to go back on the road, absolutely dead center between two posts, and got stuck."

Sandstorm did the best, and even it only got to mile 7.4. It ran off a mountain switchback, and was saved from a career-ending plunge by getting its undercarriage stuck on the berm. With its left wheels dangling in space, the right rear tire dug in, snapping the half-shaft, and the front one spun until it caught fire. DARPA's chase crew hit the kill switch and extinguished the blaze before it spread.

Caltech is already planning for the rematch, for which DARPA has upped the prize to $2 million. The date has not been announced, but, says van Gogh, "It would be nice if it were in 18 months instead of 12." ☐—*DS*

Bob's front bumper and its LADAR unit left a perfect impression in the barbed wire.

Origami: Complexity in Creases (Again)

by Robert J. Lang

In this origami composition, "Hummingbird and Trumpet Vine," Lang folded the bird, each blossom, and each leaflet from a single, uncut square of paper.

Over a decade ago, I wrote an article for *Engineering & Science* magazine about origami, the Japanese art of paper folding, and its appeal to scientists and mathematicians. Toward the end of the article, in a fit of wild speculation, I asked: "Could a computer someday design a model deemed superior to that designed by man?"

Little did this would-be futurist know what the following decade would bring. The past 10 years have seen an astonishing cross-fertilization of ideas between origami, math, and computer science. We have origami solutions to ancient problems, such as how to double a cube or trisect an angle, and origami solutions to new ones, including how to fold airbags to fit into steering columns, or telescope mirrors to fit into spacecraft. And certain origami crease patterns have been found to encode some of the hardest problems known to computer science. But most remarkably, yes, there is indeed a computer program that can, in 30 seconds or so, design origami models more complex than anything conceived over the previous thousand years. When I wrote that *E&S* article in 1989, the field of origami mathematics was almost nonexistent, but over the past 10 years, researchers from many fields have developed the principles that led to that program and to the application of origami to real-world engineering problems.

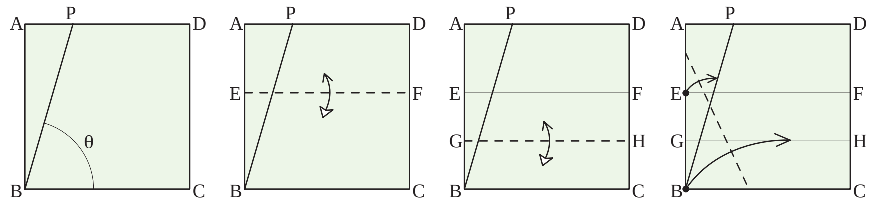
Paper folding did not start out as an engineering discipline; it started as a craft. Origami is the art of folding uncut sheets of paper, usually squares, into decorative shapes. The name is Japanese and the Japanese form of the art is the most well known, although other countries (notably Spain) have their own independent tradition of paper folding as entertainment. There are two kinds of origami in Japan: abstract, ceremonial shapes, such as the good-luck pattern known as *noshi*, and representational origami—origami that looks like something. Historically, the usual subjects for representational origami were birds, fish, flowers, and the like. It was a woman's art: simple figures passed down from mother to daughter, valuable primarily for teaching or entertaining the young. The ceremonial figures were imbued with great symbolism, but for the most part, representational origami was viewed with the same respect that we give cootie catchers and paper airplanes—which is to say, not very much.

That began to change in the early part of the twentieth century, when a Japanese factory worker named Akira Yoshizawa began creating artistic new designs. He also promoted origami in books and exhibitions, initially in Japan, and eventually around the world. Origami as an art form caught on in the West in the 1950s and 1960s. Some people seem to have a peculiar susceptibility to the charms of origami—the simplicity of folding a pedestrian sheet of paper into unexpected and beautiful shapes. Through the 1960s and 1970s, the number of people infected by this particular bug grew at an exponential rate.

Somewhere along the way, the ranks of the infected were joined by mathematicians and scientists, who began asking questions like: What is possible in origami? How can I fold any given object? Can one quantify the difficulty of an origami design? Of course, scientists don't just ask questions—they set out to answer them.

One of the first areas to be explored was the problem of geometric constructions. You probably recall from high-school geometry that you can draw an equilateral triangle or bisect a given angle using nothing but a compass and a straightedge. But some constructions, the most famous being the trisection of an angle, are impossible with just those tools. It comes as a surprise to many people that it is possible to trisect any angle using origami—it came as a surprise to the editors of the *American Mathematical Monthly*, which printed an article in 1996 "proving" the impossibility of origami angle trisection, and then printed a correction six months later noting that an origami solution for angle trisection was over 20 years old.

Tsune Abe's trisection method works for any angle less than 90°. There are other methods that work for larger angles.

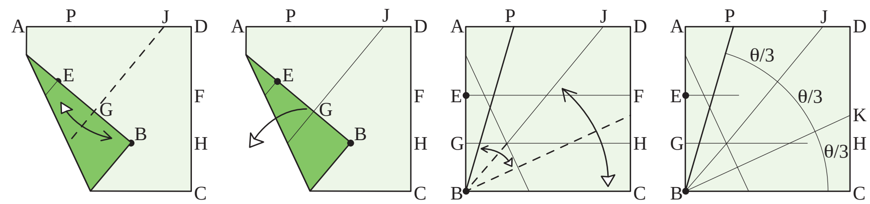


1. Draw the desired angle, PBC, so that point B is in the corner of a square of paper as shown.

2. Make a horizontal fold anywhere across the square, defining line EF.

3. Fold line BC up to line EF and unfold, creating line GH.

4. Fold the bottom left corner up so that point E touches line BP and point B touches line GH.



5. With the corner still up, fold both layers to continue the crease that ends at point G all the way to J, then unfold.

6. Unfold corner B.

7. Fold along the crease that runs to point J, extending it to point B. Fold the bottom edge BC up to line BJ and unfold.

8. The two creases BJ and BK divide the original angle PBC into thirds.

There are always a few adventurous high-schoolers who, when told of the impossibility of angle trisection, seek to find a method on their own. However, it's been mathematically proven that a compass and unmarked straightedge don't allow angle trisection—at least, not without cheating. The way this was proven was to show that all the different operations you could make with compass and straightedge—striking arcs, drawing straight lines through points, and so on—were only enough to solve quadratic equations, while trisecting an arbitrary angle requires the solution of a cubic equation. One of the compass-and-straightedge cheats involves holding your compass against the ruler and manipulating the two as a single object, thus effectively letting you do things with a *marked* straightedge. This simple change adds another new operation to compass-and-straightedge that allows the solution of cubic equations, and thus, angle trisections. In the origami angle trisection, the action in step four—

It came as a surprise to the editors of the *American Mathematical Monthly*, which printed an article in 1996 "proving" the impossibility of origami angle trisection, and then printed a correction six months later noting that an origami solution for angle trisection was over 20 years old.

folding two different points to lie on two different lines—fills the role of the marked straightedge. This maneuver, or one like it, is at the heart of several origami solutions to problems that bested Euclid. One of the most elegant is "doubling the cube," that is, constructing two line segments in the ratio of 1: $\sqrt[3]{2}$. An approach devised by Peter Messer is shown on page 12.

Origami geometric constructions are part of a family of pure mathematical problems in which the object is to fold an arbitrary geometric shape or a pure number represented as a distance proportional to the edge of the paper. While the origami construction of a 13-gon has a certain allure, for many folders (myself included), origami's appeal has always been that you folded a specific subject: a bird, fish, or cuckoo clock. My own interest has been more practical: given the subject, how can I use mathematics to figure out how to fold it? This has been dubbed mathematical origami design.

This field owes a great debt to computational geometry, itself only about 30 years old. One of the first formal results was proven in 1994, when Marshall Bern and Barry Hayes, computer scientists at Xerox PARC in Palo Alto, California, showed that the problem of origami crease assignment—given a pattern of creases on a square, how to decide whether each crease should be a mountain fold (making a peak) or valley fold (making a trough)—could be computationally intractable for relatively small problems.

In lay terms, Bern and Hayes proved that "origami is hard"—a point most people don't need to be convinced of. But in fact, they proved its difficulty in a significant way. They showed that crease assignment was one of a broad class of problems known as "*NP*-complete" that contains some of the most challenging problems known to computer science (see sidebar). These problems share two characteristics: if you find a quick way to solve one of them, you can use the same approach to quickly solve all the others; and no one has ever found a quick way to solve any of

NP-Completeness and Origami

NP-complete problems are defined by their computational complexity, which measures how the work involved in solving a problem relates to the size of the problem itself. For example, when you add two n-digit numbers, you start at the right and add each pair of digits (plus any carries), record the result, and go on to the next pair. You do this n times and thus the problem's complexity is said to be of order n, abbreviated as $O(n)$.

For simple addition, complexity increases linearly, but often it grows much faster. For example, you "convolve" two lists of numbers by multiplying every number in one list by every number in the other list and then adding them up in groups. (Convolution is what Adobe Photoshop does when it blurs or sharpens an image.) For two lists of n numbers, there are n^2 multiplications and n^2 additions, so the problem is said to be $O(n^2)$. Now, if you double the problem's size, you quadruple the program's running time.

Sometimes there are faster approaches. While multiply-and-add is $O(n^2)$, the Fast Fourier Transform allows you to do a convolution in $O(n \log n)$, meaning that the number of steps is proportional to the product of n and its natural logarithm. Of course, $n \log n$ still grows, but much more slowly than n^2. A fast algorithm can make the difference between minutes and days of computing.

Addition and convolution are called class *P* problems, where *P* stands for "polynomial time," because the time needed to solve them is bounded by some finite polynomial in n (meaning n raised to a finite power; thus, $n \log n$ is bounded by n^2).

But a host of nasty problems appear to scale as an exponential of their size and quickly become intractable as n increases. Running an exponential-time algorithm might easily take longer than the age of the universe even for fairly small values of n.

One famous example is the traveling salesman problem: given the locations of n cities, what is the shortest route that visits each city? A related form of the problem asks if there is a route shorter than a specified distance. Although people have figured out relatively fast ways of finding pretty good answers—routes that are among the shortest—the only known way to guarantee you've really found the shortest one is to compare all possible routes, or at least a fairly large subset of them. The traveling salesman is in a class of problems, called *NP* for "nondeterministic polynomial time," which may or may not be solvable in polynomial time, but whose solutions, once found, can be *checked* in polynomial time. For example, it's easy to see whether a route is under 100 miles long.

The traveling salesman problem and several others are in a special corner of *NP*, called *NP*-complete, which means that they are hard in a particular way. As in the case of convolution, problems can sometimes be converted, or "reduced," to other problems. *NP*-complete problems have the property that *every* problem in *NP* can be converted into *any* *NP*-complete problem, which means that if you could knock off one of these incorrigibles in polynomial time, you could use the same approach to solve all *NP* problems and make millions of dollars along the way. The frustrating thing is that although almost everyone believes that there are no polynomial-time algorithms for *NP*-complete problems, no one has been able to prove it.

Which brings us to an origami problem: given a pattern of creases, how can you assign valley and mountain folds to the creases so that the result can be folded flat? It's pretty easy to analyze a single vertex where creases intersect. For example, if four creases come together, they will only fold flat if there are three mountain folds and one valley fold or vice versa, *and* the sums of opposite angles are equal. (To see this, fold a square in half and then in half again to make a new square one-fourth the original size.)

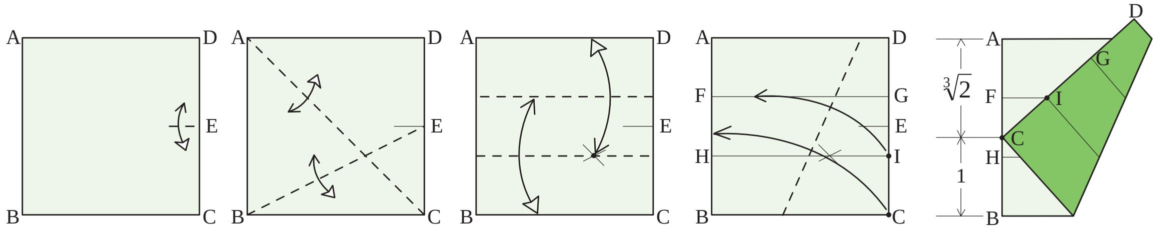
The complexity arises when edges and layers start to collide in a large pattern. You can't pass the paper through itself, and a crease that runs all the way across the paper can make widely separated regions interfere with one another. Such long-range interconnectedness is a hallmark of the traveling salesman problem and its ilk.

Bern and Hayes showed that assigning mountain and valley folds is equivalent to the so-called "not-all-equal three-variable satisfiability" problem, which is known to be *NP*-complete: given a collection of clauses, each containing exactly three true-false logic variables, determine whether you can make each clause have either one or two, but not zero or three, "trues." A simple example is shown in the margin. Bern and Hayes converted the clauses into small crease patterns connected by long, skinny pleats. A noninterfering set of mountains and valleys corresponded to a valid set of trues and falses. So a pleat that went mountain-valley might mean "Pat is the husband, Kim is the wife," whereas valley-mountain would mean "Pat is the wife, Kim is the husband." Thankfully, only one particular class of crease-assignment problems is *NP*-complete, or this article would not have been written.

As noted earlier, if you could solve one *NP*-complete problem efficiently, you've solved them all, but proving that a problem is *NP*-complete does not prove that no efficient algorithm for solving it exists. It just means that while I can't find one, neither can all the famous folk.

This brainteaser uses genders instead of "true" and "false." Four couples attend a party: Pat and Kim, Renay and Leslie, Lynn and Lee, and Sydney and Chris. Each couple consists of a husband and wife, though not necessarily in that order. Each of the following trios includes two members of one sex and one of the other:
1. Leslie, Lynn, and Sydney;
2. Pat, Leslie, and Chris;
3. Kim, Renay, and Lynn;
4. Kim, Leslie, and Lee.
If all the husbands get together in one room and all the wives in another, who is in the room with Renay? **For the answer, see page 44.**

Peter Messer's construction of the cube root of 2.



1. Make a small fold halfway up the right side of the paper.

2. Make a crease connecting points A and C and another connecting B and E. Only make them sharp where they cross each other.

3. Fold the top edge down horizontally to touch the crease intersection and unfold. Then fold the bottom edge up to touch this new crease and unfold.

4. Fold corner C to lie on line AB while point I lies on line FG.

5. Point C divides edge AB into two segments whose proportions are 1 and the cube root of 2.

them. Absent that magic bullet, cracking such problems basically boils down to trying out an appreciable fraction of all the possible solutions and seeing which one works. Bern and Hayes showed that some origami crease patterns can be used to encode *NP*-complete logic problems; solving the crease pattern would be equivalent to solving the logic problem.

The difficulty of assigning mountain and valley folds to an existing crease pattern grows quickly with the number of creases; therefore it is possible to construct patterns for which mountain-fold and valley-fold assignments would stump even the most powerful computer. Small problems are amenable to trial and error—just try every possible combination of mountain and valley folds—but this quickly becomes impractical as the size of the pattern grows.

Not all crease problems are intractable; in fact, some of them are at just the right level of difficulty to make good puzzles. On the opposite page is a crease pattern designed by Hayes, who called it "Get Off the Moon!" In honor of JPL's current successes on the red planet, I've created a modified version titled "Get Off of Mars!" Cut out the black square and fold it, making creases only on the dotted lines, to conceal all six rovers—three on each side of the paper.

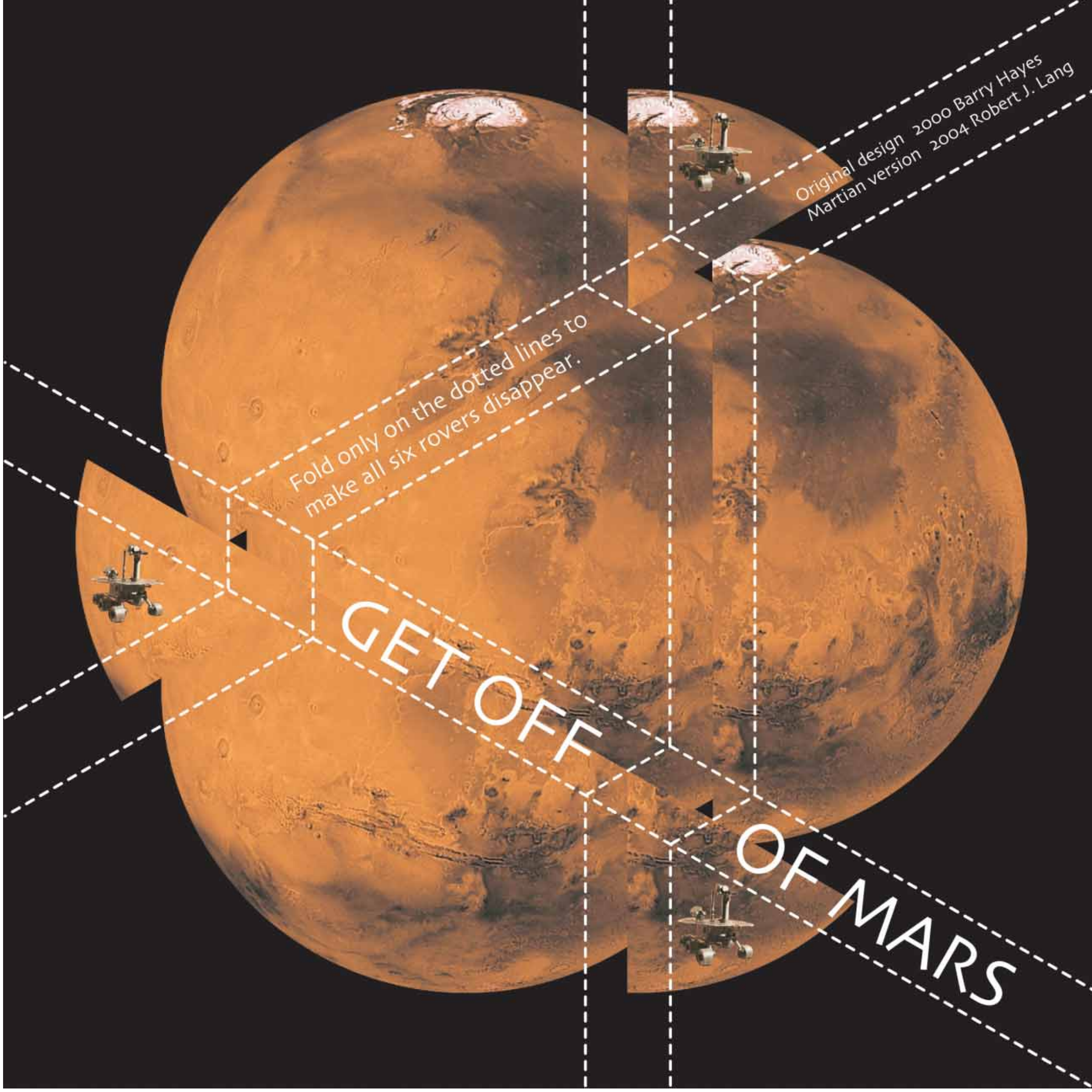
Bern and Hayes's proof would seem to rule out developing a computer algorithm for origami design; after all, how can you hope to design an unknown crease pattern if you can't even assign mountain-valley status to a known crease pattern? Fortunately, their result only applies to patterns that *may* encode *NP*-complete logic problems. If you can lay out the creases to avoid such logical challenges, then the problem might be quite tractable.

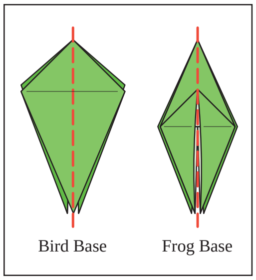
During the 1990s, Japanese biochemist Toshiyuki Meguro and I independently developed a set of techniques for expressing the structure of a large class of folded shapes in a way that could be transformed into creases on a sheet. Just as importantly, the mountain-valley status of most of the creases was predetermined by the shape itself, and the remaining creases could easily be assigned using simple, polynomial-time rules.

Creating a rigorous definition of a "flap" was fundamental to our solution. A not-so-rigorous definition is "a loose bit of paper that gets turned into an appendage." Flaps become wings, legs, arms, feet, ears, horns—basically, anything that sticks out from the rest of the model. In origami, a shape with a bunch of flaps is called a "base." In general, a base resembles the subject to be folded by having the same number and length of flaps as the subject has appendages. For example, a base for a bird might have four flaps, corresponding to a head, tail, and two wings. A slightly more complicated subject such as a lizard would require a base with six flaps for the head, four legs, and a tail. And an extremely complicated subject such as a flying horned beetle might have six legs, four wings, three horns, two antennae, and an abdomen, requiring a base with 16 flaps.

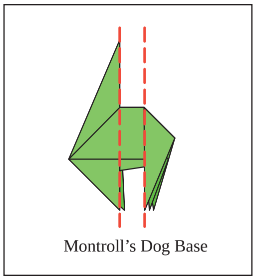
The number of flaps required depends on the level of anatomical accuracy desired by the paper folder. Historically, much origami design was performed by trial and error—manipulating a piece of paper until it began to resemble something recognizable. For a complex subject, this is rather inefficient, since one is unlikely to stumble upon a 16-pointed base with flaps of the right size in the right places purely by luck. A more directed approach was clearly needed.

Creating a rigorous definition of a "flap" was fundamental to our solution. A not-so-rigorous definition is "a loose bit of paper that gets turned into an appendage."



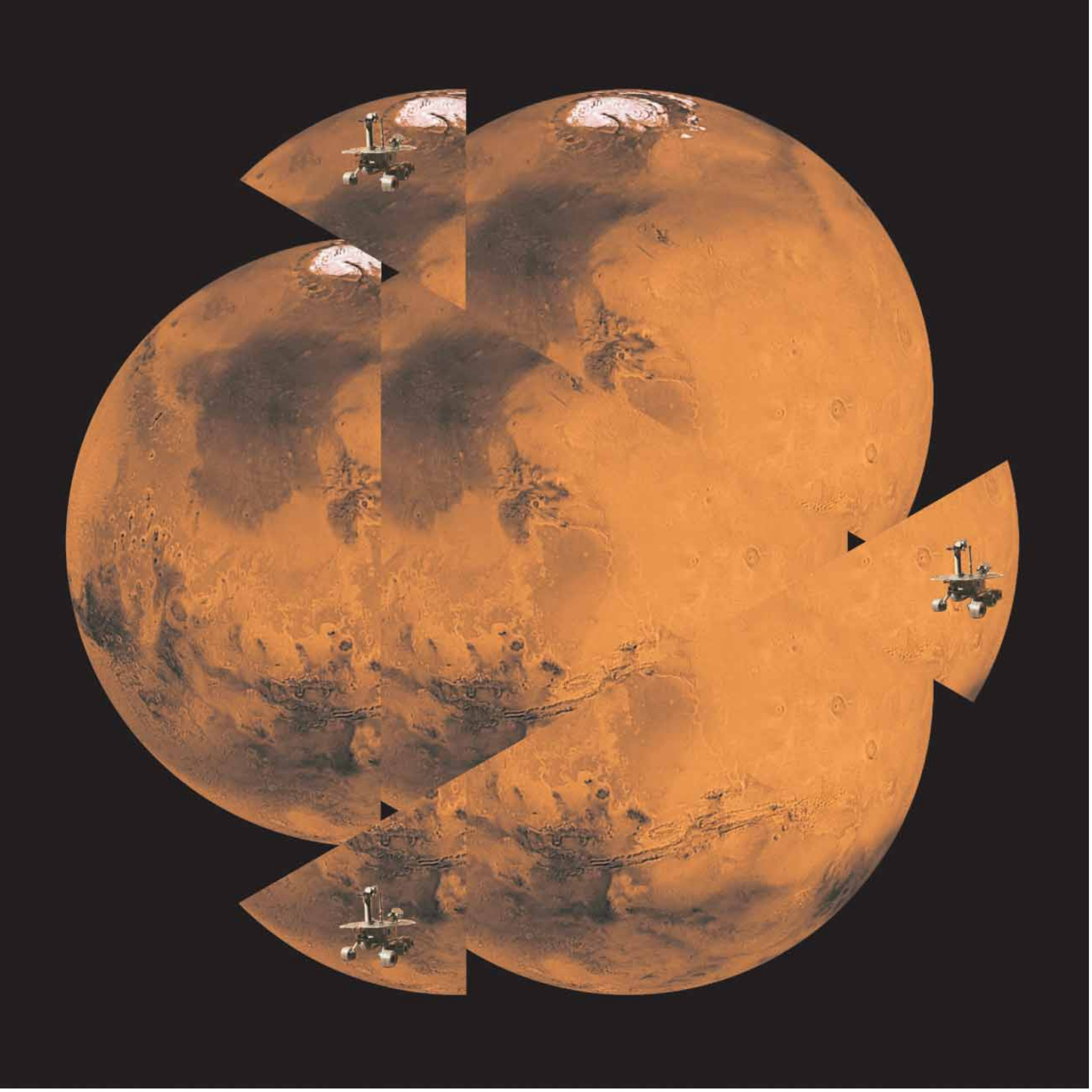


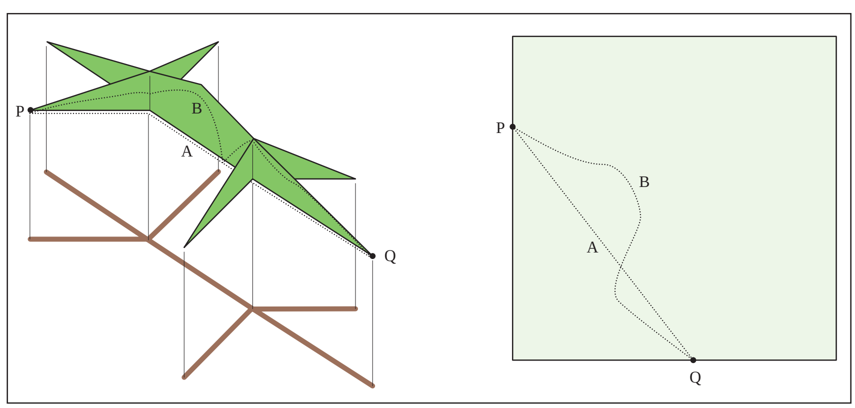
Left: The traditional Bird Base and Frog Base are uniaxial bases. Right: John Montroll's famous Dog Base is not, having two distinct axes.



I focused my attention on a class of bases that can be oriented so that all of the layers run up and down and all of the flaps have their tips and at least one edge in a horizontal plane. If you take either base shown at left and rotate it 90 degrees around the red axis, you'll see what I mean. This class, which I named the "uniaxial" base, takes in all of the traditional origami bases, including the Kite, Fish, Bird, and Frog [see *E&S*, Winter 1989] and many (though not all) modern bases as well.

If you illuminate a uniaxial base from directly above, its shadow will consist solely of lines, as you can see on the next page. It turns out that the most important properties of a uniaxial base—indeed, much of its structure—can be determined solely from the properties of its shadow. In mathematical terms, this shadow forms a "tree graph," which is a fancy term for a "stick figure." The tree graph consists of "edges," or line segments, and "nodes," which are points where edges either come together or terminate. The flaps have a one-to-one correspondence with the graph's edges; similarly,





A folded uniaxial base (right) casts a tree-graph shadow. We can take many paths between leaf vertices P and Q, the shortest of which (path A) is the same length as the shadow. When the paper is unfolded (far right), this path becomes the crease connecting P and Q.

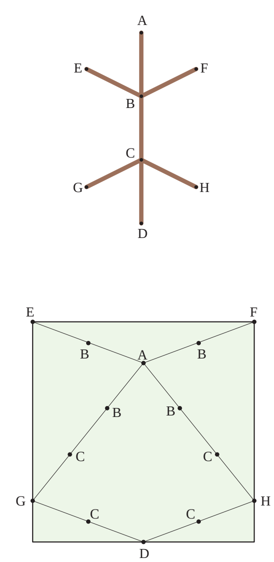
Origami subjects with relatively large, rounded bodies are not so well suited to tree theory. This figure, "Night Hunter," uses a mixture of tree theory and intuition in its design.

the flaps' tips match up with the "leaf nodes," which are the nodes that have exactly one edge connected to them. While graph theory generally doesn't care about the lengths of the graph's line segments, we do; we assign the length to each edge that we desire in the corresponding flap of the base. With this, we are ready to start figuring out the creases.

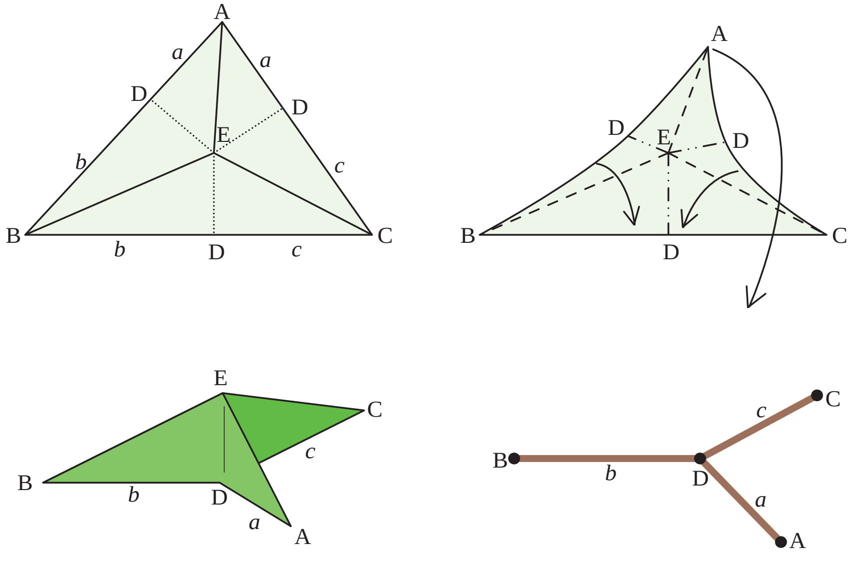
Let's consider the hypothetical base at left, and the relationship between paths on the unfolded paper, the same paths in the folded base, and the shadow. Suppose you drew a line, not necessarily straight, on the paper. What would that line look like in the folded base, and how long would its shadow be?

A point on the paper whose shadow is a leaf node is called a "leaf vertex." Each vertex corresponds to the tip of a flap, so that any path between two leaf vertices will, in the folded base, run from the tip of one flap to the tip of another—say between points P and Q. This path might travel in a horizontal plane in the base, as path A does, or it might go uphill and downhill within the folds of paper, like path B. How does the length of the path compare to the length of its shadow? If the path is purely horizontal, like path A, then the two lengths are equal. Any other path, including path B, is longer than its shadow. Thus the distance between any two leaf vertices on the unfolded crease pattern must be greater than or equal to the distances between the corresponding leaf nodes on the tree graph. I named this mathematical expression the "path condition" for the two vertices, and there is a path condition for every possible pair of leaf nodes.

This seems pretty obvious, but in the early 1990s I was able to show something not so obvious: that the inequalities embodied in the path conditions were not only *necessary* for a valid crease pattern, but they were *sufficient*, as well—a much more useful result. In other words, if you found a set of points on a piece of paper that satisfied all possible path conditions, then those points were the leaf vertices of a pattern that would fold into a base whose shadow was the graph. Furthermore, whenever the length of a path between two vertices exactly equaled the distance between the corresponding nodes, a fold line ran between those vertices, and that fold was almost always a valley. For example, path A is perfectly horizontal and runs along the bottom of the base. Any path that descends to this line, like path B, has to change direction in the folded base or leave the paper; consequently, there must be a crease there. Constructing all such valley folds produces the creases that serve as a framework for the base.



Top: The tree graph for a six-flap base. Bottom: The skeleton of the crease pattern that will fold into the corresponding base. Now all we have to do is construct the secondary folds that will, for example, bring together all the points labeled B.



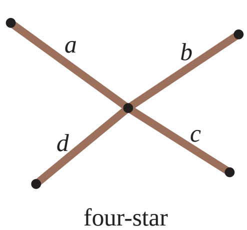
Top left: The crease pattern for the triangle molecule. Top right: The molecule is formed by folding along the angle bisectors and bringing the three points marked D together as you flip the paper over. (Dashed lines are valley folds, dot-dashed lines are mountain folds.) Bottom left: The folded molecule. If you now folded tips B and C forward to meet tip A, all of the original triangle's edges would now lie on a common line. Bottom right: The molecule's tree graph.

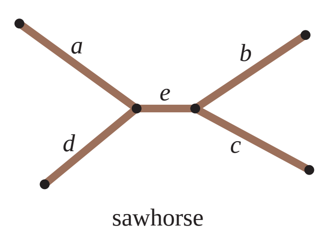
These first folds aren't the entire crease pattern, of course, but they establish its overall structure by dividing the paper into polygons that correspond to various pieces of the tree graph. Now we need to fill in these polygons with creases in such a way that each polygon folds flat with all its edges along a common line. Several crease patterns that do this—dubbed *bun-shi* (molecules) by biochemist Meguro—were found for triangles and some special quadrilaterals by Koji Husimi, Jun Maekawa, Fumiaki Kawahata, Toshikazu Kawasaki, and me during the 1980s and early 1990s. The creases that fill in a triangle are very simple to construct; they bisect the three corners.

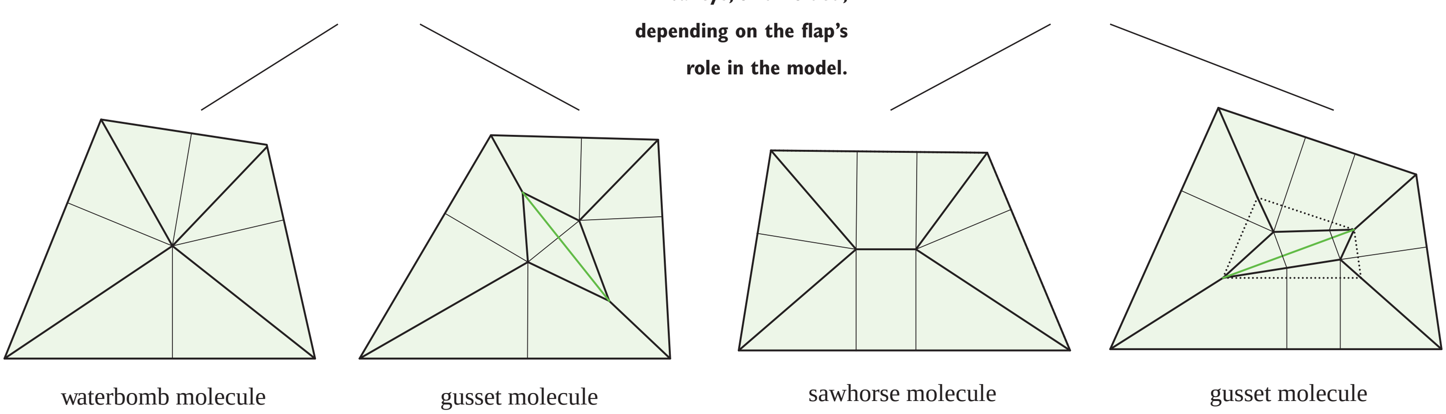
There's a close relationship between a polygon and its tree graph: the sides of the polygon, when folded, become the edges of the graph. For a triangle, it's a one-to-one relationship; there is exactly one triangle for a given three-leaf-node tree graph and vice versa. Quadrilaterals are a bit more complicated, first, because there are two possible tree graphs with four leaf nodes, and second, because there can be many different quadrilaterals for the same tree graph. The two tree graphs are called the "four-star" and the "sawhorse," and are illustrated below, along with two molecules for each. As the number of sides goes up, the number of graphs and molecules grows rapidly.

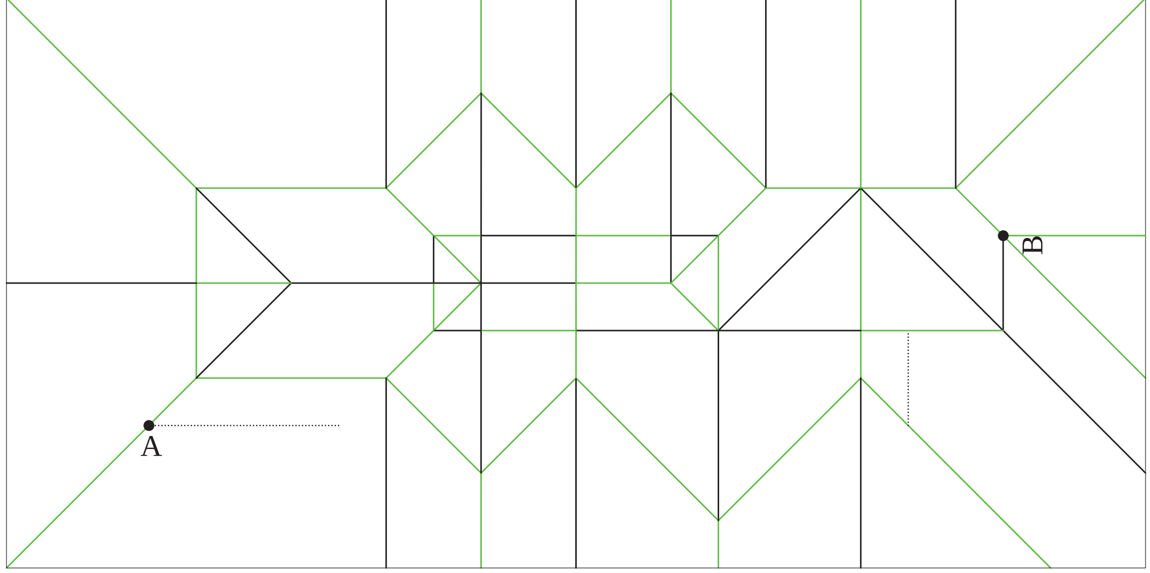
One type of molecule, called the gusset, is particularly versatile; one version of it can be folded into a four-star, and another into a sawhorse. In 1995, I discovered a generalization of it that worked for any convex polygon, no matter how many sides it had. I dubbed the algorithm that creates these solutions the "universal" molecule. Any tree graph can be decomposed into one or more polygons, each of which can be folded into a universal molecule, giving a full crease pattern for any uniaxial base.

Below: The two four-node graphs, and some molecules that fold into them. Heavy black lines are valley folds, heavy green lines are mountain folds, and the light black lines are "hinge creases," which may be mountains, valleys, or unfolded, depending on the flap's role in the model.









A one-cut puzzle. Cut out this rectangle and fold it only on the solid lines: mountain folds are green and valley folds are black. Then cut through all layers along a line that runs from point A to point B (from dot to dot) and carefully unfold all the pieces.

The universal molecule has an interesting property: it enables you to make any convex polygon from a folded sheet of paper with a single straight cut. The "one-cut" problem was independently solved for all polygons, including concave and multiple ones, by University of Waterloo grad student Erik Demaine, now an assistant professor at MIT, whose research revolves around folding of all kinds. Demaine's cutting algorithm bears a surprisingly close relationship to several issues in pure uncut origami design. The creases' precise locations within a universal molecule depend on the polygon's size and shape and on the lengths of the edges of the tree graph. If you freeze the polygon but shrink the graph, the universal molecule evolves toward, and eventually becomes, the solution to the one-cut problem.

In much of science and engineering, the most productive way to deal with a problem is to turn it into one that somebody else has either already solved or proven impossible. Or, put another way, the key to productivity is letting dead guys do your work for you.

I applied Demaine's algorithm for multiple concave polygons to create the one-cut puzzle above. First, fold the figure—which is, in itself, something of a challenge. Then cut along the dotted line that runs from A to B and unfold the paper. If you've done it correctly, you should obtain the initials of a well-known institution of higher learning.

Let's turn now to the concept of efficiency, around which many computational-geometry problems revolve. For example, the usual goal of the traveling-salesman problem is to find the shortest route among the salesman's cities. In origami design, the most efficient crease pattern is the one that gives the largest possible base for a given tree graph and a given-sized sheet of paper.

We measure a base's efficiency by *m*, which we call the "scale"; it quantifies how large the finished base is relative to the size of the unfolded square, whose sides we define to be 1 unit long. If *m* is very small, then all the distances specified by the tree graph are short. The leaf vertices are close together and you can always find a set of them that satisfies all possible path inequalities—in fact, there will be many possible arrangements. But these bases will be very small and, because all that paper must be tucked into them somewhere, they will also be thick, and difficult to fold. On the other hand, if *m* is made too large, no arrangement of points will work. If we have two flaps, each 1 unit long, then the separation between their leaf vertices must be at least 2 units, and you can't fit two points that far apart into a 1-unit square. Somewhere between the possible and the impossible lies the most efficient base—a crease pattern whose leaf-vertex arrangement satisfies all possible path inequalities for the largest possible value of *m*.

In much of science and engineering, the most productive way to deal with a problem is to turn it into one that somebody else has either already solved or proven impossible. Or, put another way, the key to productivity is letting dead guys do your work for you. In this case, the problem can be posed in a form known as a "nonlinear constrained optimization," namely: "find a set of variables (the scale *m*, and the coordinates of the leaf nodes in the crease pattern) that maximizes the value of *m* subject to a set of inequalities (the path conditions and inequalities that constrain all points to the square of paper)." Thankfully, nonlinear constrained optimization problems have been thoroughly studied by computer scientists. Finding the provably best possible solution is often computationally intractable, but fast, efficient algorithms for near-optimal solutions are known. "Good enough for government work" is also usually good enough for origami design.

Origami tree theory works best for subjects that can be approximated by a stick figure. It is especially suited to insects like this cicada, in which each of the legs, wings, antennae, and body can be represented by an edge of the tree graph.

Over the 1990s I developed a computer model of tree graphs, bases, and crease patterns and combined it with CFSQP, a nonlinear constrained optimization code created by Andre Tits and his research group at the University of Maryland. The resulting program, TreeMaker, does exactly what I speculated about in 1989; the user enters a tree graph and the software performs the optimization and finds the base's full crease pattern, which may then be transformed into a finished model—like the scorpion below—using common origami shaping techniques. Using TreeMaker, I've been able to design many figures whose complexity is considerably beyond what I (or others) could do by hand.

It turns out that these algorithms are good for more than just making cool animals. The theory of foldable paper also describes what's possible for other materials: cloth, metal, plastic, and so on.

One of the most direct applications has been in modeling airbags for cars. An airbag must inflate in a few milliseconds and be firm enough to stop a rapidly accelerating body, yet provide cushioning. Hitting a rigidly inflated, brick-hard airbag could do as much damage as no airbag at all, and an airbag must work for small children and large adults over a wide range of collision speeds and impact angles. So airbag design involves a lot of computer simulation—if your client is Mercedes-Benz, you don't want to crash more cars than you absolutely have to. The simulations start with the airbag folded up into a small packet and tucked into the (simulated) steering wheel or dashboard.

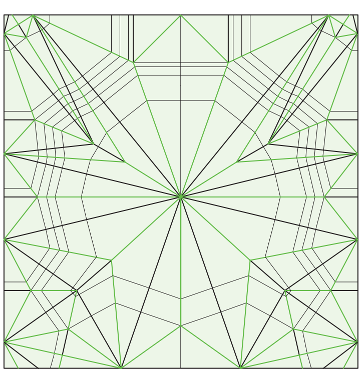
And that's where the problem arises. While flattening an airbag in real life is fairly easy—you just squash all the air out of it—simulating the process is quite a challenge. You need to treat the airbag as a rigid object, as if it were made out of cardboard; find creases that flatten it; and then fold it up into a small packet. Several years ago, I was contacted by an airbag-design firm, and the universal molecule proved to be just the solution. Thus, origami can not only make beautiful art; it can save lives.

Origami can also expand our view of the heavens. Eyeglass, a brainchild of the Lawrence Livermore National Laboratory, is a space telescope with a projected 100-meter aperture that would be able to examine Earth-like planets around nearby stars.

Eyeglass is a radical new design, but also a very old one. Most high-performance telescopes, like the Hubble Space Telescope, are "reflective." Their main optical element is a curved mirror, which lets the telescope be fairly short—just a few times the diameter of the lens. The Hubble, with its 2.4-meter-diameter mirror, is just 13 meters long. But "transmissive" telescopes, like Galileo and the pirates of the Caribbean used, are tubes with lenses at each end. Transmissive telescopes are by their nature much longer than the lens diameter, and one with a 100-meter lens would need to be thousands of meters long. This does not seem, on first consideration, like a good thing.

But there's a lot of space in space. When the nearest interfering object is 40,000 kilometers away, a kilometer or two doesn't matter much. Even better, you don't actually need to build a tube between the two lenses—simply put your main lens into one orbit, and the other lens plus the camera and associated electronics into another orbit a few kilometers away.

Calculating the crease pattern for this scorpion base required solving a complex optimization problem using CFSQP.



Lang in front of the five-meter Eyeglass prototype at Lawrence Livermore National Laboratory.

PICTURE CREDITS: 8, 10, 12-18, – Robert Lang; 19 – Rod Hyde, LLNL

Eyeglass will use a diffractive lens—a large sheet of glass or plastic with precise grooves machined into its surface, like the lens on an overhead-transparency projector. A thin plastic lens wouldn't be very stiff or strong, of course, but in orbit, this doesn't matter.

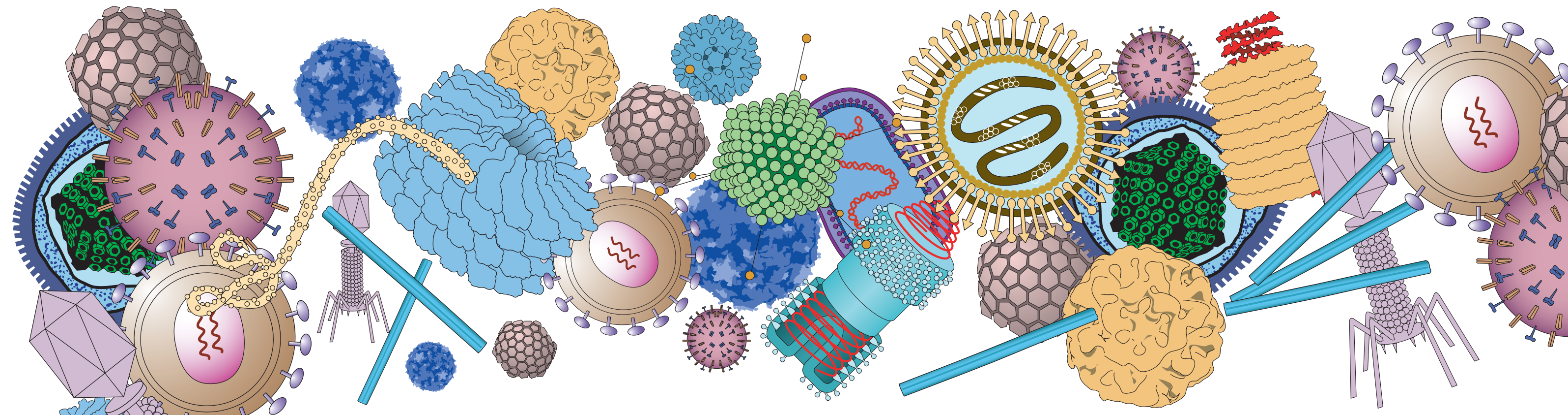
But how do you get it up there in good shape? That 100-meter sheet of plastic is going to have to get crumpled, folded, or otherwise stuffed into a tube about four meters in diameter and 10 meters long, like a sleeping bag going into a stuff sack. Although diffractive lenses have looser tolerances than mirrors, one thing they can't tolerate is being crumpled up. The only way such a surface could go into a rocket would be if it were collapsed along a precise set of creases carefully laid out so as not to degrade the optical performance.

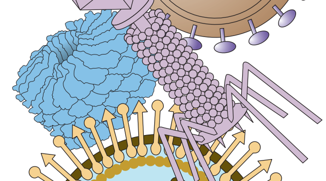
Roderick Hyde and his colleagues at Livermore's diffractive optics group discovered that a folding, origami-based solar panel designed by Koryo Miura had powered Japan's Space Flyer Unit back in 1995. Further research led Hyde to my own work, and a phone call revealed the happy coincidence that I lived just five miles from his lab. Over the next few months, I met with the Eyeglass team several times and adapted several origami structures for their consideration. They needed something that was radially symmetric, so that it could be spin-stabilized; would collapse on a finite number of creases; and would then fit into a cylinder. They chose the "Umbrella," which, when furled, looks like a collapsible umbrella. This design can easily be scaled up, has mass-producible parts, and folds from a large flat disk down to a much smaller flanged cylinder. A five-meter prototype has been built, and when unfolded and hung in a test rig, it successfully focused an expanded laser beam fired at it from 100 meters away.

As often happens, once you solve one problem, four or five or ten new ones pop up. Over the past two years, MIT's Demaine and I have collaboratively extended origami tree theory to address crease patterns with regular angles, and the construction of two-dimensional patterns and three-dimensional polyhedra, among other forms. (Regular angles means forcing all crease angles to be some multiple of an integral division of 360°, for example, multiples of 45°.) Computer-aided design solved one set of problems but introduced another: once you've computed the locations of hundreds of creases, how do you figure out how to fold them? Forcing the crease angles to be regular makes it possible to develop tractable step-by-step folding sequences.

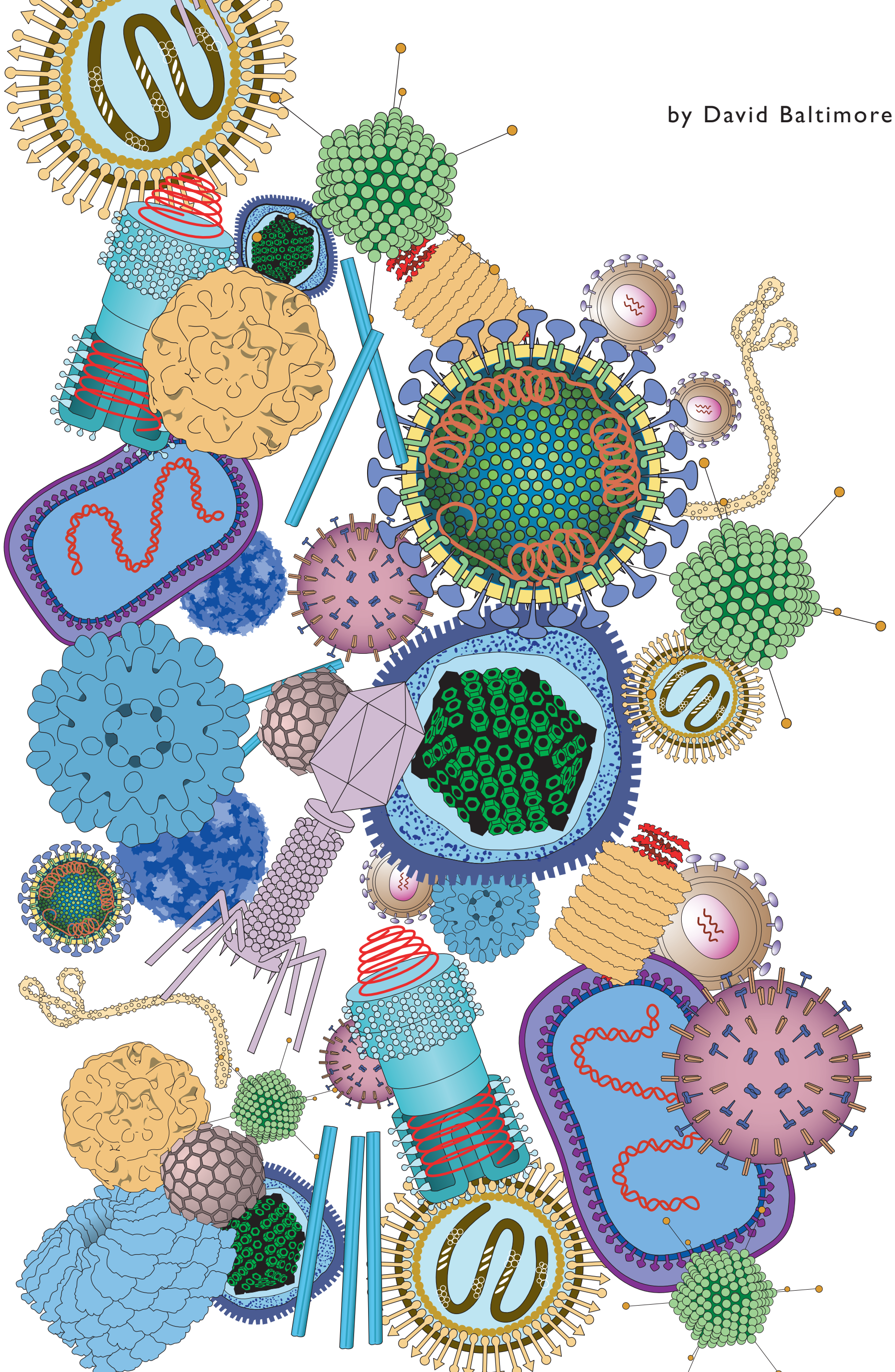
So origami has finally hit the big time, it appears—at least in the world of computational geometry. But mathematical origami is also affecting the ancient Japanese craft. There has been a dramatic shift in the art of origami as geometric techniques—what one might call "algorithmic" origami design—have become more widespread. For years, we concentrated on getting the right number and lengths of appendages, to the near-exclusion of considerations such as line, form, and character. With algorithmic origami design, point count comes automatically. Origami art and origami science have sometimes been at odds in the past, but now the origami designer can focus on the art of folding, secure in the knowledge that the science will take care of itself. □

Robert J. Lang (BS '82, PhD '86) was a Member of the Technical Staff at JPL when he wrote "Complexity Increasing" in the Winter 1989 issue of Engineering & Science*. He is now a full-time origami artist, the author of eight books, and a consultant specializing in the application of origami to engineering problems. His most recent book,* Origami Design Secrets *(2003, A K Peters, Ltd.), describes the theory of origami design.*





Viruses, Viruses, Viruses



by David Baltimore

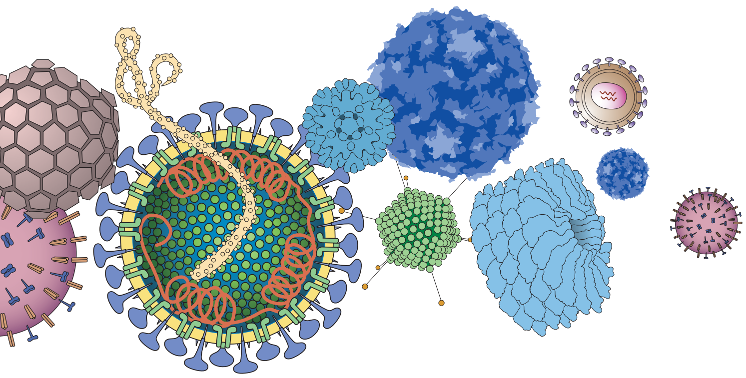
Almost every day some virus or other makes news—HIV, SARS, smallpox as a bioweapon, last fall's new flu, and, most recently, the avian flu in Southeast Asia. But it's my impression that most people don't know what a virus *is*. So, since viruses have played a critical role in my professional career, I felt that I was in a good position to be useful and explain a bit about them.

Viruses exist in uncountable variety, since every animal, plant, and bacterial species has its own set of them. It's not sufficiently interesting for anyone to bother to find out how many different viruses exist on every obscure species, so I think we'll never really know the extent of these tiny devils. But scientists have already isolated tens of thousands of them. You can observe them in an electron microscope, get an idea what their shape is, do a little molecular biology, put them in their place relative to other viruses, and thus classify them. We now recognize more than 1,500 species of viruses, each one of which can be broken down into subspecies and further.

The notion of a virus goes back only to 1892, when Ivanovski in Russia showed that a filter that would hold back bacteria would pass the agent that caused mosaic disease in tobacco. That agent, he realized, is much smaller than a bacterium. Bacteria were at the limit of a light microscope's resolution, so no one could see these objects then; all they knew was that they were very small.

In 1911 Peyton Rous discovered that one agent that passed through bacterial filters could cause cancer. This was one of the seminal experiments in cancer research, but because such tiny agents were difficult to conceive of, the work wasn't immediately appreciated. Rous finally won the Nobel Prize in 1966, 55 years later; it took that long to realize how critical his discovery was to unraveling the problem of cancer.

When the electron microscope was invented around World War II, the first pictures could be taken of viruses. Then scientists could see that the



We now recognize more than 1,500 species of viruses, each of which can be broken down into subspecies and further.

particles were indeed very small, in the range of 25 to 100 nanometers (10^{-9} meters; by comparison, the wavelengths of visible light are 380–780 nanometers). From chemical analysis, we learned pretty quickly that viruses consisted mostly of protein and that they contained either RNA or DNA. Of course, by the 1950s, it was clear that DNA was the hereditary material of higher organisms, bacteria, and many viruses, so it was a bit of an anomaly that some viruses didn't have DNA. But it was demonstrated in 1957 that the RNA isolated from a plant virus was infectious, showing that RNA could be hereditary material just like DNA.

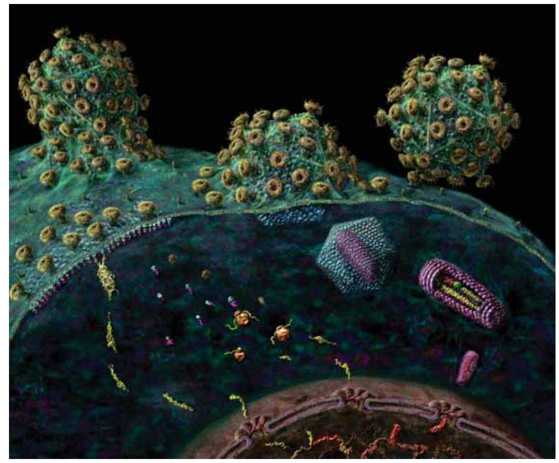
Hermann Muller, a great drosophila geneticist, wrote a paper in 1927 saying that because viruses are so small, there's just no space in there for anything other than the hereditary material of life. That insight, which took many years, and the advent of molecular biology, to prove, was actually the key to understanding viruses. Viruses are, in fact, protein shells packed full of genetic information. They have no cellular machinery (or at most, very little) of their own.

Viruses can grow only inside of cells. They can't multiply in the environment and are to some extent dead objects there. There's a running debate about whether viruses are alive or dead because, when you crystallize them and they behave like crystalline proteins, they're like dead chemical objects. (Bacteria, on the other hand, are definitely living organisms.) And yet, when allowed into a cell, they can hijack the total metabolism of the cell (in minutes in a bacterium, hours in a mammalian cell) and completely reprogram that cell so that the only thing it can do effectively anymore is make more viruses.

To that extent I think they're about as alive as anything. In a cell they can multiply extremely rapidly, a thousandfold in six hours. But to stay alive, since they have to grow inside cells (and cells exist only as parts of living beings), they have to spread from host to host. That's a tough way to earn a living, especially when the host has an immune system, as we do, and can fight off the virus. Usually, when we get a virus infection, our immune system is activated and within days is making antibodies and T-lymphocytes that can attack viruses and virus-infected cells and clear the virus from the body within a week. That, for instance, is the course of the common cold.

So, the virus has to pass to another host before the immune system revs up and inactivates it. If it doesn't pass to at least one other individual before the immune system clears it, it dies out. If at each instance of infection it is able to infect one more person, it effectively lives forever. Measles virus, for instance, passed continually from person to person, used to spread very widely before we had a vaccine. Young children usually got it, and when they got over it, they were immune thereafter; the immune system has a wonderful memory of what it has seen before. But when some isolated populations who had never seen measles were exposed, it was devastating to them because they had to fight it off as adults. For one reason or another, young people usually fight off viruses much better than older people do.

When viruses pass from one organism to another, they adapt to that host; viruses of humans adapt to the specific ways that humans interact. We shake hands; that's one of the best ways to pass viruses. I think the Japanese learned to bow because they realized they stayed healthier if they bowed to one another rather than shaking hands. When I feel as if I have a virus disease, I just don't shake hands with people. (I have to explain so they don't get insulted.) Sneezing and coughing, obviously, are good ways, but mostly just in the immediate local area, because a sneeze dries up very rapidly in dry air. And then there are other wonderful things we do, such as kissing and sex, which provide the opportunity to pass viruses as well as sentiments.



To escape a cell and venture out to find new hosts, the human immunodeficiency virus sends out its viral proteins (the yellow squiggles at left) and implants them in the cell's outer membrane. When the virus buds off the cell, it carries with it a piece of the cell membrane, now studded with proteins that can recognize and infect new cells. (Copyright Russell Kightley Media, rkm.com.au)

Over many, many years, viruses have adapted to our way of life. If you put one of our viruses in a mouse, it won't survive because mice don't kiss or shake hands, and they don't raise their kids in communal kindergartens. The fact that viruses have become attuned to our lifestyle is wonderful in one way: it means that if you eradicate a particular human virus, it will never come back, because it can exist only in humans. That is, in fact, what happened when a worldwide vaccination campaign got rid of smallpox. Lots of other species have related pox viruses, but they're not adapted to us.

Stopping the spread of smallpox faced the world with a difficult decision: whether or not to get rid of all the smallpox stocks that exist in the world's laboratories. An edict came down from the World Health Organization: yes, we should make smallpox extinct, but an exception was made for two laboratories, one in the United States and one in the Soviet Union.

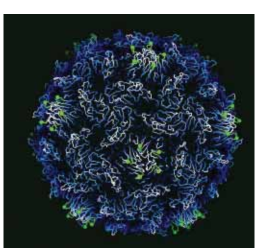
Why do we keep it at all? I am one of those who believe that we should totally get rid of it. It only continues to exist because some people got sentimental over smallpox. Environmentalists, in particular, feel that we should never eradicate a living species. Of course it happens all the time, but this would have been conscious, and some people felt bad about it. To be fair, the environmentalists were joined by a large number of virologists who did not want to see an object of their potential inquiry taken from them.

The question also arose as to whether some countries lied. We're still worried that there are caches of smallpox held by rogue governments or terrorists that could be developed as bioweapons. Since vaccination ended when the virus was eradicated, we are defenseless against it now.

Polio is another virus that has been virtually eliminated by vaccination and very conscious activity on the part of the World Health Organization. A few places in the developing world (India, in particular) still have outbreaks of polio, but there hasn't been any polio virus in the Western hemisphere for a couple of decades.

Because viruses multiply inside cells, they are faced with the problem of exiting from the cell. They have found two solutions: they can either break the cell open, or they can bud off the cell's surface, carrying the outer membrane of the cell with them. In the second mode, the virus modifies the cell's outer membrane by insertion of one or more viral proteins. This protein is picked up by the budding virus and endows the virus with the ability to recognize new host cells and infect them. Both of these ways of escaping the cell are pretty efficient, but the budding process is the most insidious because it doesn't kill the cell and can continue for the life of the cell.

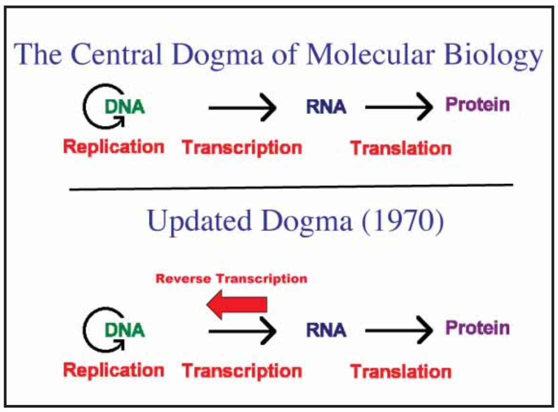
Top: Electron micrograph of the smallpox virus. (Courtesy of F. A. Murphy, School of Veterinary Medicine, UC Davis.) Bottom: Computer model of the polio virus. (Courtesy of James Hogle, Harvard Medical School.)



Molecular biology of viruses

We know an enormous amount about many viruses today, but it was only when molecular biology was born that they began to make sense. So let me give you a very brief course in molecular biology. The nucleus of a cell has chromosomes in it; the number varies from species to species. If you unravel those chromosomes far enough, you see that they contain supercoiled molecules of DNA. When you uncoil the DNA, you see that it's a double helix, held together by cross bridges of complementary chemical bases, which are paired up. That's almost all the molecular biology you really need to know. When Watson and Crick published their famous paper in 1953 describing this structure, it became obvious what was going on at the basic level: the DNA was encoding the structure of proteins. And it also became clear (although it took some time to prove it) that the way to duplicate this molecule took advantage of the fact that the two strands are redundant; they carry the same information, because a pairing rule determines their structure. The duplication of DNA, therefore, involved unwinding the duplex

Ever since DNA's double-helical structure was discovered in 1953 and its role in encoding proteins became clear, it was assumed that DNA copies itself, that RNA is made from it, and that RNA directs the making of proteins. In 1970, the discovery of reverse transcriptase proved that the process can work backwards—that RNA can transcribe itself back into DNA. It was work with viruses that led to this discovery and to the Nobel Prize.



Below: Max Delbrück (left) and Salvador Luria, shown here at Cold Spring Harbor in 1953, worked with the bacteriophage virus in making many of the early discoveries in molecular biology.

and duplicating each strand individually.

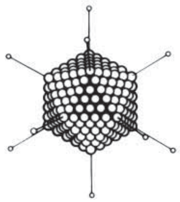
The one other thing you need to know about molecular biology is that it has a central dogma. That dogma says that DNA duplicates itself (replication); that RNA is made from it (transcription); and that RNA is the key material that directs which proteins are in the cell (translation). The proteins do the work of the cell; they're the muscles in the structure of the cell itself. That *was* the central dogma until 1970, when Howard Temin (PhD '60) and I did an experiment that showed that you can also reverse-transcribe RNA back into DNA. At the time, that looked like a particular characteristic just of viruses, but we now know that it happens a lot in the life of cells, especially over evolutionary time. In fact, about 50 percent of the genetic material that we carry around in each of our cells arose by reverse transcription.

Many of the discoveries in molecular biology depended on working with viruses, particularly bacteriophage, a virus adapted to bacteria. The great gods of bacteriophage research were Max Delbrück, here at Caltech, and Salvador Luria, first at Indiana University and then at MIT, where he was my mentor. It was with bacteriophage that A. D. Hershey and Martha Chase at Cold Spring Harbor demonstrated that DNA was the hereditary material, and that Seymour Benzer (now the Boswell Professor of Neuroscience, Emeritus, at Caltech) showed that genes had a fine structure that corresponds to the individual nucleotides in the DNA. It was also at Caltech that experiments using bacterial viruses showed that RNA carried the information from DNA to protein.

Mammalian viruses also played their role. Our discovery of reverse transcriptase came from mammalian viruses, as did splicing, a process by which the transcript RNA is cut up and certain sections are removed. And plant viruses showed us that RNA is able to act as a genetic material. We thought this was an oddity at the time; it doesn't happen in any other class of organisms. But it was the first clue to what was probably a very important stage in evolution, when there was an RNA world in which DNA had not yet evolved. Life back then depended on the genetic abilities of RNA, as well as on its protein-like catalytic capability.

Equilibrium and nonequilibrium viruses

Let's get back to how viruses are adapted to individual species—to us, in particular. These I call equilibrium viruses, because they live in equilibrium with us. They know how to keep passing from person to person, but they're not terribly lethal. They may kill a few people (smallpox killed more than a few), but, in general, the equilibrium viruses that occasionally give us colds are not a very big danger to us. Many people, including me, think that part of a virus's



Viruses come in all shapes and sizes. From top: the tiny picornavirus, the larger adenovirus, the reverse-transcribing retrovirus, an orthomyxovirus, a coronavirus (the cause of SARS), the bullet-shaped rhabdovirus (rabies), and a poxvirus, showing exterior and interior. (Courtesy of F. A. Murphy, UC Davis.)

evolution is that it adapts to its host species in ways that keep its host alive so that it can continue to infect the host's children.

But when an equilibrium virus in one species jumps into another species, it becomes a nonequilibrium virus. Such a virus will rarely spread well in a population because it's not well adapted to the new species' lifestyle. A few people may get it from an infected monkey or rodent; it can be highly lethal, but it's not likely to cause an epidemic in the overall population. It *could* become an equilibrium virus in the new species, but only over a long time.

We guess that HIV first jumped into the human population in the 1930s and certainly no later than the 1950s. Yet it's clearly not an equilibrium virus. It is highly lethal, but only over a long time; it is spread among people, but not efficiently, requiring either injection or sexual contact. It and flu, which are the two nonequilibrium viruses that most bother us, do not follow the rule of poor spreading as a guest in the population, because they are able to pass well enough from person to person that they can be a serious problem.

Equilibrium viruses include polio, smallpox, measles, mumps, herpes, most of the common cold viruses, and lots of others. Among the nonequilibrium viruses are the influenza, HIV, SARS, Ebola, and Hantaan viruses. Flu is the oddest, because it clearly passes around among us as if it were an equilibrium virus. But one of the reasons it can be so devastating is that it is constantly regenerating from a reservoir in wild birds. We believe the birds infect domesticated ducks, they in turn infect pigs, and the pigs infect people. This all generally happens in China—until it finally breaks out of China by finding a ship or an airplane or some other conveyance, and becomes a part of our circulating pool of viruses. It's the only virus I know of that can jump out of another species and adapt itself rapidly enough to the human species that we pass it around as if it were one of our own.

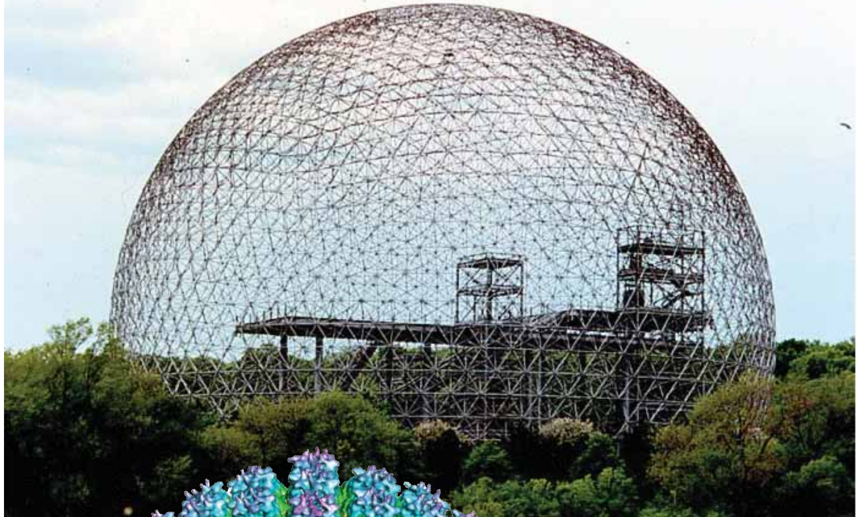
SARS came from an as yet unknown animal, maybe a civet cat. It originated in China and was carried out of that country by people traveling to Canada and other places, where local epidemics then began. The virus never started a serious epidemic in the general population. Most cases occurred in hospitals or in medical personnel; a couple of cases spread in an apartment house. But there was never a real epidemic.

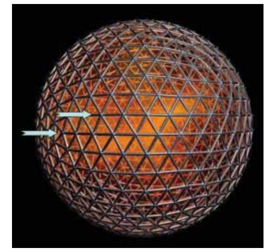
The amazing variety of viruses

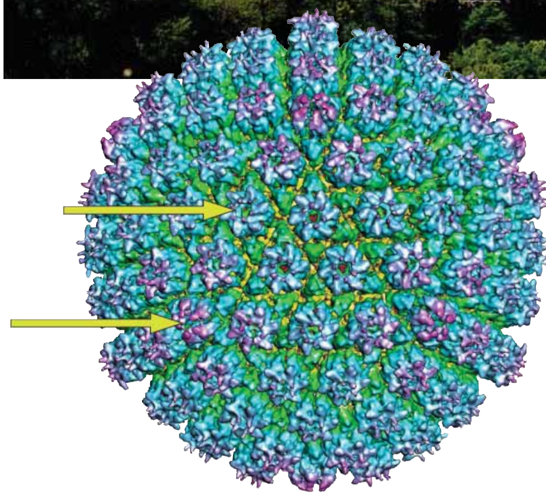
Viruses come in an astonishing assortment of shapes and sizes and have evolved some quite remarkable features. What I'd like to do now is examine some individual viruses and look closely at what's interesting about each of them. Some, like parvoviruses and picornaviruses, are extremely small, only about 25 nanometers across, just big enough to package an RNA or DNA molecule inside. The bigger adenovirus can accommodate a much larger piece of DNA. Particularly large RNA viruses include retroviruses like HIV and coronaviruses, of which SARS is an example. All these are spherical in shape, but then we have things like the bullet-shaped rhabdoviruses and the complicated poxviruses. A poxvirus makes more than a hundred different proteins and is much closer to being an actual organism than most of the others.

Herpes simplex is a large, spherical virus, which I'd like to discuss from the point of view of its structure. Herpes, related to the viruses that cause chicken pox, infectious mononucleosis, and shingles, is the virus of cold sores. (A close relative, herpes simplex type II, causes genital herpes.) It has a way of passing from person to person that most other viruses don't have. Its size enables it to encode some special mechanisms, one of which is the ability to sneak into nerve cells to hide and emerge later. The herpes virus hides in the nerve cells in the brain and comes back out later to cause cold sores on our lips, which can then pass the virus on to a new host. Other kinds of herpes viruses hide in other parts of the nervous system, emerging occasionally to cause problems such as shingles.

The computer model of the inner core of the herpes virus on the next page illustrates the







The icosahedral symmetry of the herpes virus (right) is the key to encoding the proteins that repeat to form its coat. It's a symmetry made up of fives and sixes. Most of the blue and purple subunits (proteins) are surrounded by six others (top arrow), but some (bottom arrow) have five neighbors. (Courtesy of Z. Hong Zhou, U. of Texas Medical School, Houston.) The same symmetry is the basis for Buckminster Fuller's geodesic dome structure (top), which can be seen more clearly in the Fuller globe next to it. The top arrow points to a hexagon, the bottom arrow to a pentagon.

answer to a very important question, raised years ago by Watson and Crick in another, not-so-famous, paper: Where does all the information come from to make the viral protein that coats the DNA or RNA with a complex protein shell? The answer lies in the virus's symmetry, which allows one protein to be used over and over again. This is the nature of viruses: they encode one or a small number of coat proteins that know how to aggregate themselves into beautiful shapes that enclose space—and the DNA or RNA is in that space.

The nature of this symmetry is quite interesting. Most of the proteins in the model are surrounded by six other proteins (top arrow). But you can see some (bottom arrow) that have five neighbors. So this is a funny kind of symmetry; it's not exactly the same over the whole surface. Actually called quasi symmetry, it's made of fives and sixes.

Buckminster Fuller didn't know anything about viruses when he developed these principles himself. He realized that he could enclose space with an elegant structure, one that is light and simple because it uses the same parts over and over again. It's hard to see on the actual geodesic dome above, but it's easier on the adjacent model of the complete Fuller sphere. The top arrow indicates six units around a point, and the bottom arrow points to one with five. (Most of them are sixes; other fives are hard to find.)

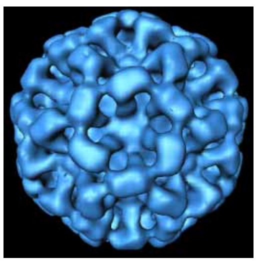
Fuller's design is basically that of an icosahedron. Icosahedra have 20 triangular faces, either fives or sixes at the vertices. If you place hexagons (sixfold symmetric objects) next to one another, they form a flat surface, like old-fashioned bathroom tiles. But if you try to do that with pentagons, it won't work. You have to tilt the pentagons around to make the edges meet, and when you do, you get a classic solid, the dodecahedron. So five is something that leads to curvature, while six is flat. That's what is going on in the Fuller dome: the curvature of the dome, which leads ultimately to a spherical form, comes from the fivefold axes, while the sixfold axes just tile a flat or slightly curved surface. Another well-known example is the buckyball (named for Fuller), a natural chemical form of carbon.

I'm very taken with this quote from Buckminster Fuller:

When I am working on a problem,
I never think about beauty.
I think only of how to solve the problem.
But when I have finished,
If the solution is not beautiful,
I know it is wrong.

That's not exactly a scientific proof, but when Watson and Crick published their structure of DNA, what convinced so many people it was right was its beauty.

Viruses enclose space with this same elegant geometric symmetry. Poliovirus, much smaller than herpes, also encloses its space on the principle of icosahedral symmetry, as does Norwalk agent. But I'd like to discuss Norwalk agent from the point of view of how it's spread. Most viruses are unstable in the environment. If you sneeze out a stream of droplets containing virus particles, and the droplets have a chance to dry, the forces of drying are so great that the virus is ripped apart and is no longer infectious. But this isn't true of Norwalk, which is quite resistant in the environment. That's why it has become known as the cruise-ship virus. It created a number of mysterious illness outbreaks and headlines last fall, some of them (62 people in a Canadian mounted-police academy, 74 at a wedding) on land, but it's the cruise ships that give us the really impressive statistics, where hundreds can be infected on a single cruise. Norwalk infections are estimated at 23 million cases per year in the United States, and most of these are actually on land. Most of them are probably mistaken for something else, because the illness looks very much like food poisoning. I'm not a physician or an epidemiologist, but I think that a large fraction of people who get what they think is food poisoning have actually come in contact with Norwalk agent. Food poisoning comes from a bacterium, which causes a fever along with the other disagreeable symptoms. Norwalk doesn't cause a fever, and you get over it quickly. So, most of the cases of overnight distress that you blame on the restaurant you just visited may have had nothing to do with food but rather came from some other infected individual you interacted with over the previous few days.

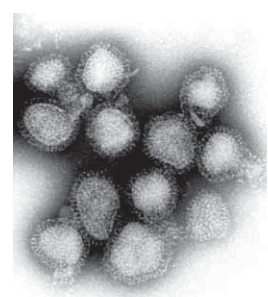


A computer model of the Norwalk virus. (Courtesy of B. V. V. Prasad, Baylor College of Medicine.)

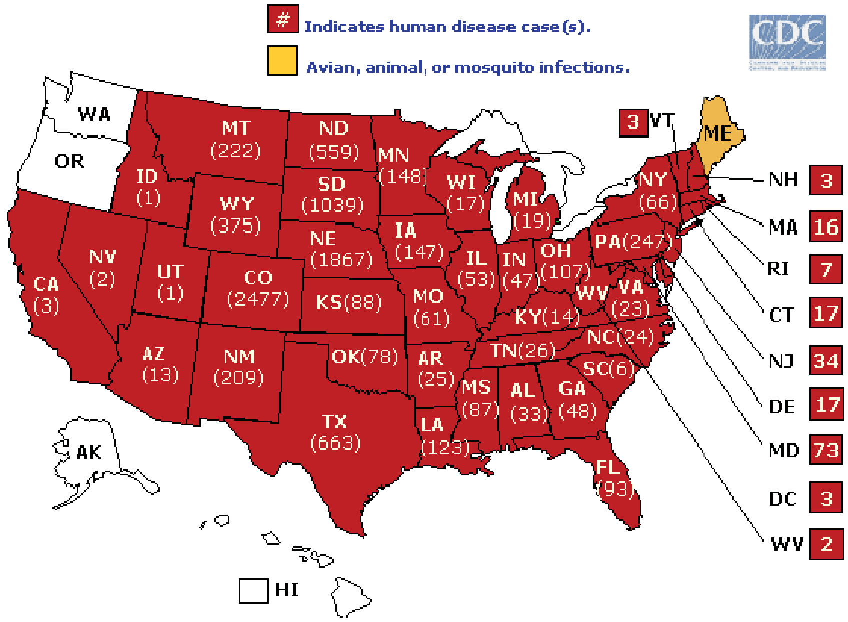
Plants also have a lot of different viruses, as many as animals do, some icosahedrally symmetric, some helically. There are, for example, more than 30 viruses of beets alone. Beet growers know all about these viruses, but the rest of us fortunately are spared having to acquire this knowledge. I don't know of any case of a plant virus infecting a human, but they have been known to infect insects. Plant viruses are, actually, responsible for one of the few *good* things viruses do; they can cause beautiful streaking in flowers. In the 17th century, this led to the first widely known financial bubble, when the Dutch became obsessed with ornamental tulips and were willing to pay enormous sums of money for them. The most expensive tulip bulbs were the virus-infected ones with streaked petals. So the tulipmania bubble, which had many of the same properties and craziness as the recent Internet bubble, was caused by a virus.

Influenza virus, which kills more people annually than any virus besides HIV, has a very particular property. Rather than having one long piece of genetic material, as most viruses do, it has eight separate pieces. This gives it the ability to recombine itself with other influenza viruses. So, human and bird influenza viruses can infect the same animal, say a pig, and reassort their RNAs in that animal. This reassortment is one of the reasons we get so many new flu viruses. Since flu varies all the time, it never really reaches a nice equilibrium, so we can't make a general vaccine that will protect us against it once and for all. But we can make a vaccine that varies from year to year by modifying just one piece of RNA. We can also take advantage of the viruses' reassortment strategy to make a vaccine by inserting a new RNA molecule that will interfere with its multiplication.

The stripes in tulip petals are caused by a virus, one of the few nice things that viruses do.



Electron micrographs of the influenza virus (above) and the Ebola virus (right). (Courtesy of F. A. Murphy, UC Davis.)



Starting in 1999, when it first hit New York, West Nile virus has spread across the country, carried by mosquitoes. Although as of February 2004, as illustrated here, it's still quite rare in the West, it's permanently established in the country and unlikely to be eradicated.

The trick to making a flu vaccine for a particular winter flu season is to be able to guess more than six months in advance the strains that will circulate. In the winter of 2002–03 the Fujian strain that circulated was a surprise, and the vaccine lacked representation of that precise strain. The best guessers in the world simply guessed wrong. The vaccine gave at best partial protection. The flu epidemic started early and promised to be quite severe, but then it suddenly diminished quite dramatically in early winter.

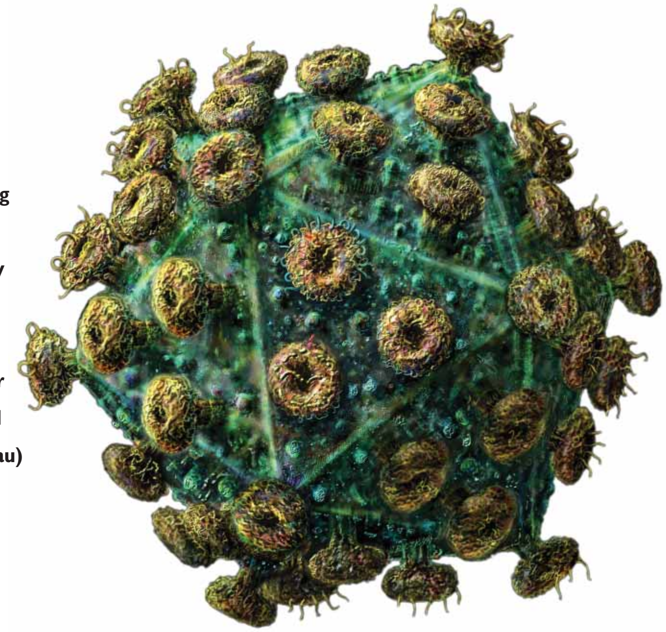
West Nile virus is interesting because, while it naturally infects birds, it's carried by mosquitoes. Mosquitoes, in turn, can infect humans (and horses). More than 99 percent of infected people are asymptomatic and never know they had it, but there's no danger of them passing it on to others, because it's a nonequilibrium virus. Some fraction of people (and we don't know what's different about them) develop a fever, and some cases even progress to infections of the brain, which can be fatal. West Nile does cause a significant number of deaths, and we don't yet know how to vaccinate against it. The only way we know how to protect ourselves is to avoid mosquito bites.

West Nile virus was discovered in 1937 in Uganda and spread widely in Africa and the Middle East over subsequent decades. It's amazing that it didn't reach the United States until 1999, when a few cases were discovered around New York. Then it began to spread. In 2003 there were 9,136 cases and 228 deaths. The year 2002 saw 284 deaths. But the frightening thing about it is that it's now permanently established here. No one believes that we can eradicate it with anything we know about today, because it winters in an animal reservoir, particularly mosquitoes. At least it's good for the mosquito-repellent industry. And even though it has spread widely, there are still very few cases west of the Rocky Mountains. I don't know if that's because the virus finds it difficult to maintain itself in the West, or if it's just a matter of time before we have as big a problem as the East and middle of the country.

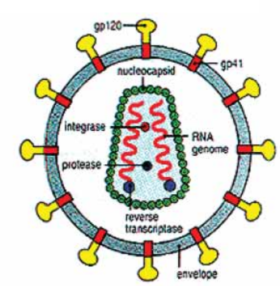
Ebola is a virus of helical symmetry, long and convoluted because it's not rigid. It looks aggressive and is aggressive. Like other viruses, Ebola is not one fixed virus but a complex family of viruses. We can get the complete RNA sequence from each outbreak and construct a tree that shows how closely related they are. For example, the Ebola viruses isolated in Gabon in 1994 and 1996, and in Zaire in 1995 and 1976, are very similar, indicating that there must be an animal reservoir in that part of Africa. No one can find it, although they've looked very hard. It's probably an equilibrium virus in some rodent living in the forest or bat living in a cave, and it may not much bother the animal species that maintains it in equilibrium. It's always the same virus coming out again and again. Other Ebola viruses, slightly different in their RNA, have broken out farther away, in the Ivory Coast and Sudan, where they must reside in other reservoirs—different but related. Then there's a very strange set of Ebola viruses that appeared in Reston, Virginia, and starred in the book and movie *The Hot Zone*. Interestingly, these viruses infected monkeys, not humans, but because of its reputation in Africa, the fear was that it would spread to humans. Still another Ebola-like virus, Marburg agent, very different from all the rest, erupted in Germany in 1980, killing a significant fraction of the people it infected before it was quickly contained.

HIV, THE WORLD'S MOST SERIOUS HEALTH CHALLENGE

HIV (human immunodeficiency virus) has a beautiful, very unusual internal structure. For unknown reasons, it's asymmetric. HIV is not known for its beauty, however, but for its relentless and lethal effects. The horrifying statistics from the end of 2003 show 40 million people infected with HIV/AIDS worldwide. This past



The little studs projecting from the surface of the human immunodeficiency virus (HIV) are the proteins that enable the virus to attack and enter a cell. (Copyright Russell Kightly Media, rkm.com.au) HIV has an unusual asymmetric internal structure (below).



year brought 5 million new cases and 3 million deaths, more deaths than tuberculosis and malaria, which were the two greatest infectious killers in the world until HIV came along. In some African countries, life expectancy has been reduced by more than 20 years. This is an epidemic on a scale that we have not seen in modern times, and we should be doing a lot more about it than we are.

What kind of response can we make? We have been very good at making drugs to combat it. The pharmaceutical industry rose to the occasion and makes a lot of money selling drugs that slow down the infection's development enormously, even if they don't cure it. Many people are living today who would have been dead 10 years ago without these drugs. It's a great success story, but not a perfect one; these drugs are very expensive, and they require a lot of attention from the patient. So they have not been transferred into the developing world with any efficiency. This may be changing now with the money coming from the Gates Foundation, the U.S. government, and elsewhere to make these drugs more available.

This is an epidemic on a scale that we have not seen in modern times, and we should be doing a lot more about it than we are.

Education has also worked. Educating people about a sexually transmitted disease is a very difficult job, but the programs in Uganda and Thailand have been very effective, reducing transmission by 60 to 80 percent. But education, also employed in the United States, requires constant vigilance. For instance, new cohorts of young men entering a gay lifestyle must continuously be taught to protect themselves.

But the right answer for protection against a virus is a vaccine. A vaccine preprograms your immune system so that the memory protects you forever, without your having to be exposed to the virus. The scientific community has been trying to make a vaccine against HIV since the day the discovery of the virus was announced. Margaret Heckler, then secretary of the Department of Health and Human Services, got up in front of the press in 1984 and said, "We've discovered the virus; we know what it is; we'll have a vaccine in a year or two." She could not have been more wrong, but I can understand why she said it. We had been so successful making vaccines against smallpox, polio, measles, mumps, and lots of other viral diseases. But, while the immune system controls all the other viruses pretty well, it can't control HIV, for a set of complex reasons. That makes a vaccine very difficult. The truth of the matter is that we're not even sure we can make a vaccine. We *can* vaccinate monkeys against a related virus, and we *can* show that in certain cases people can be protected by their immune system, but there has been no successful efficacy trial of any vaccine against HIV.

HIV, oddly enough, may give us a way of doing the only other good thing viruses can do (besides striped flowers). Viruses, as we've seen, are able to bring genes into cells. And if we can splice good genes into a virus, we can get those genes into cells in place of the damaged ones (gene therapy). In my lab and in laboratories around the world, we are trying to use genes to turn the HIV viruses on themselves and actually make them valuable. The idea is to use a stripped-down version of the virus to carry into cells genetic components that can interfere with the growth of the real virus. It works in the lab, but it will be a while before we can know if it works in people.

Last but not least of our headline-making viruses is SARS, a coronavirus, so called because the proteins, strung on a long stalk surrounding the virus, resemble a halo. Thanks to modern molecular biology, the SARS genome was sequenced within weeks after the virus was discov-

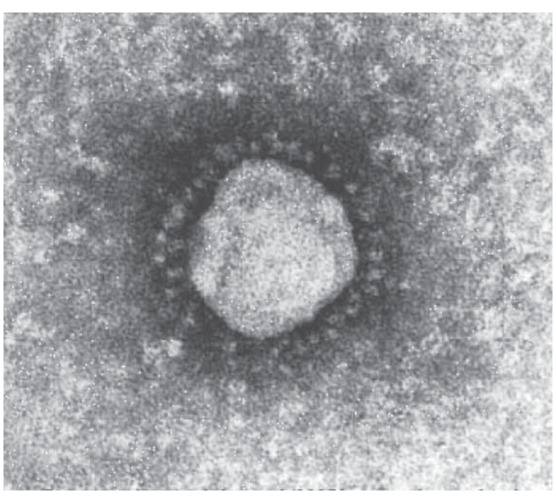
This huge reservoir is not going to just sit there and stay in its species; some of the viruses are going to jump over to our species. We should consider this at least as much of a challenge as bioterrorism.

PICTURE CREDITS: 20-21 – Doug Cummings; 23 – Caltech Archives; 26 – Free Foto

ered. Comparison to other known coronaviruses showed that it was on its own branch of the genetic tree, which told us instantly that this was a virus we had never seen before. It was something brand new. The sequence also told us about all the proteins the virus makes. Many of them turn out to be quite unusual, and it will take years to figure out what they all do.

SARS (severe acute respiratory syndrome) started in China in November 2002. The last case was found in June 2003 (with the exception of two separate cases in laboratory workers who were infected from lab samples). The number of cases topped out at 8,098, with 774 deaths, none in the United States. There is no evidence that there was a large number who were infected but not symptomatic (as, for instance, with West Nile virus). This is fortunate, because it means that the 8,000 is not really 800,000. Some experts claim there's a reservoir somewhere, probably in humans, and predicted that it would come back again in the fall of 2003. This is the standard thing viruses do—come in November and leave by June, like flu or the common cold. In October my forecast was that SARS would not reappear, that it's gone, and that the only place it exists now is in some unknown animal reservoir in China. Could it come out again? Yes, it could, but the Chinese should be ready for it next time, and it should be quickly contained. So far my prediction has held up.

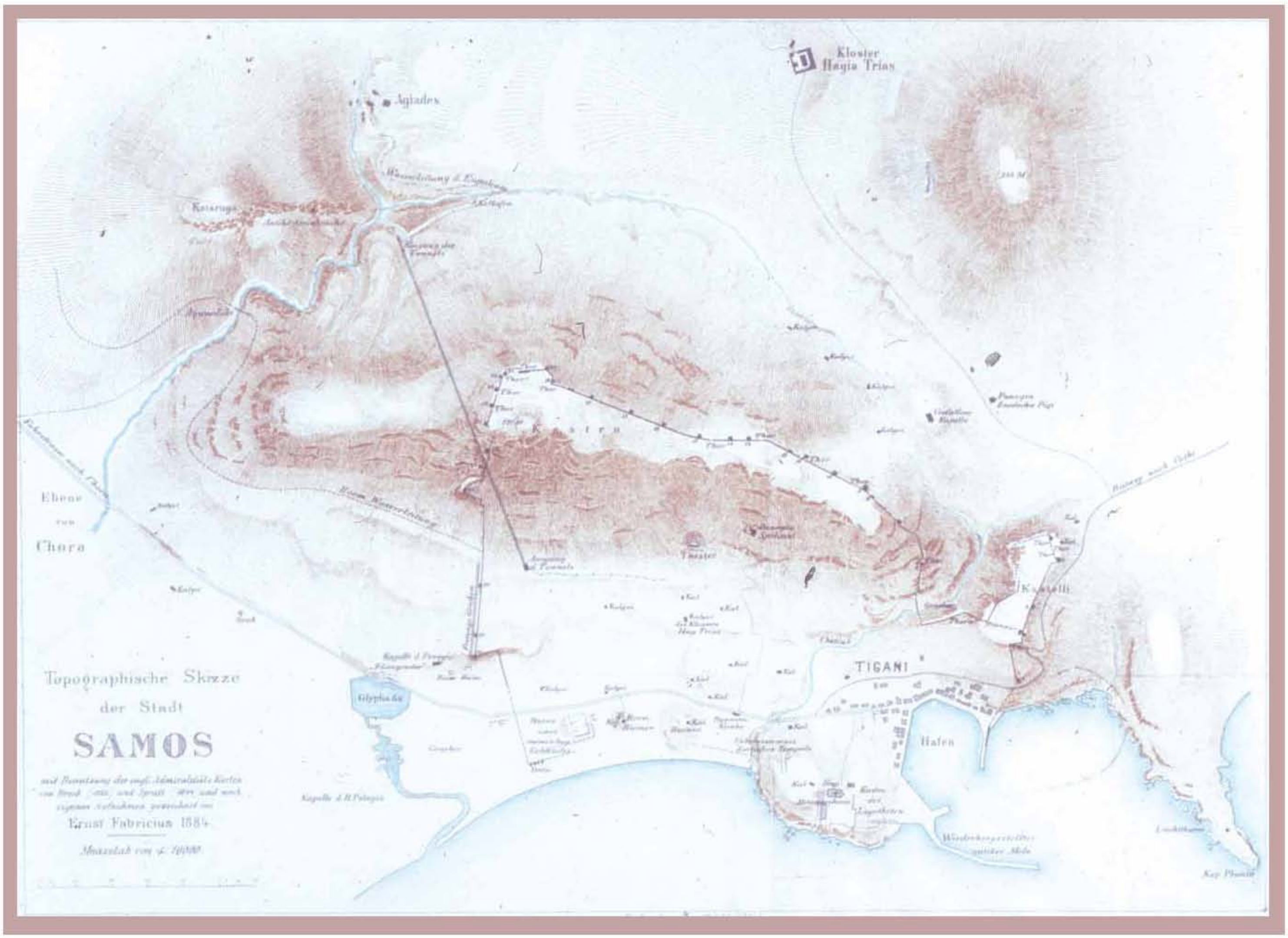
The bottom line is that it's these non-equilibrium viruses that we need to be concerned about. They emerge from a huge pool in nature to cause havoc among us. Although I don't see SARS in our future, we have to expect that more viruses will emerge. This huge reservoir is not going to just sit there and stay in its species; some of the viruses are going to jump over to our species. We should consider this at least as much of a challenge as bioterrorism. In fact, it's sort of nature's own bioterrorism and, fortunately, similar. We can employ the same public health skills that have been put on alert to deal with bioterrorism to watch out for viruses coming out of nature. SARS was a good rehearsal. □

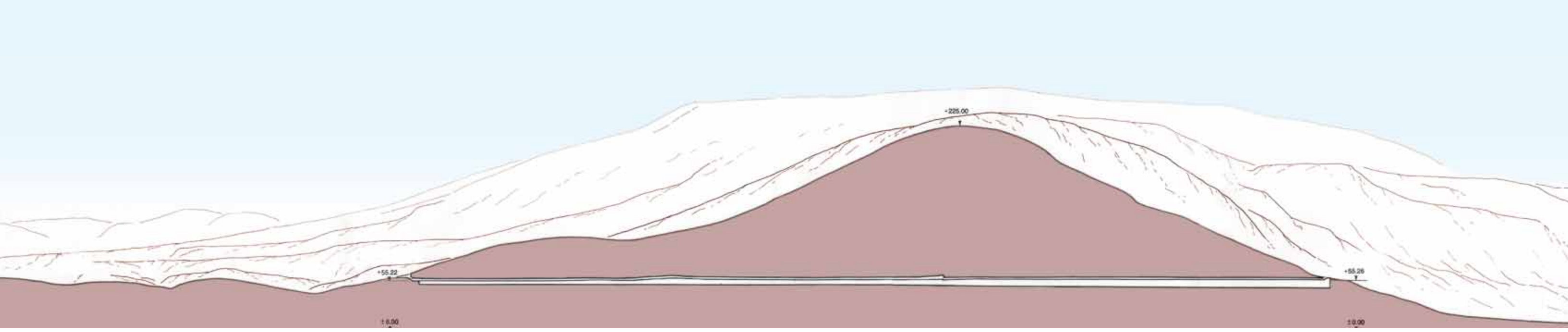


The SARS virus is a coronavirus, so called because of the garland of proteins that surrounds it. The SARS genome was sequenced only weeks after the virus was discovered.

David Baltimore, Caltech's president since 1997, has good reason to appreciate viruses; he's been studying them for a long time. He won the Nobel Prize in 1975 for his discovery of reverse transcriptase, an enzyme that allows a strand of RNA to copy itself back into DNA—work published in 1970 that came out of his research on how cancer-causing RNA viruses manage to infect a healthy cell. The discovery added significantly to scientists' understanding of retroviruses such as HIV. Baltimore earned his BA in chemistry from Swarthmore College in 1960 and his PhD in biology from Rockefeller University in 1964. He was founding director of MIT's Whitehead Institute and spent most of his professional career at MIT (except for a few years at Rockefeller University, as a professor and president) before coming to Caltech. From 1996 to 2002, he has chaired the National Institutes of Health AIDS Vaccine Research Committee. This article was adapted from Baltimore's Watson Lecture last fall.

One of the greatest engineering achievements of ancient times is a water tunnel, 1,036 meters (4,000 feet) long, excavated through a mountain on the Greek island of Samos in the sixth century B.C.

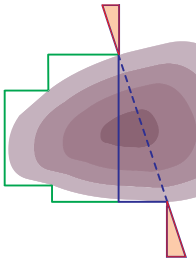




The Tunnel of Samos

by Tom M. Apostol

Facing page: This 1884 map by Ernst Fabricius shows the tunnel running obliquely through the hill marked as Kastro, now Mount Castro. The small fishing village of Tigáni has since been renamed Pythagorion. The cutaway view through Mount Castro at the top of this page comes from a detailed 1995 survey by the German Archaeological Institute in Athens. Below: Hero of Alexandria's theoretical method for working out the line of a tunnel dug simultaneously from both ends.



One of the greatest engineering achievements of ancient times is a water tunnel, 1,036 meters (4,000 feet) long, excavated through a mountain on the Greek island of Samos in the sixth century B.C. It was dug through solid limestone by two separate teams advancing in a straight line from both ends, using only picks, hammers, and chisels. This was a prodigious feat of manual labor. The intellectual feat of determining the direction of tunneling was equally impressive. How did they do this? No one knows for sure, because no written records exist. When the tunnel was dug, the Greeks had no magnetic compass, no surveying instruments, no topographic maps, nor even much written mathematics at their disposal. Euclid's *Elements*, the first major compendium of ancient mathematics, was written some 200 years later.

There are, however, some convincing explanations, the oldest of which is based on a theoretical method devised by Hero of Alexandria five centuries after the tunnel was completed. It calls for a series of right-angled traverses around the mountain beginning at one entrance of the proposed tunnel and ending at the other, maintaining a constant elevation, as suggested by the diagram below left. By measuring the net distance traveled in each of two perpendicular directions, the lengths of two legs of a right triangle are determined, and the hypotenuse of the triangle is the proposed line of the tunnel. By laying out smaller similar right triangles at each entrance, markers can be used by each crew to determine the direction for tunneling. Later in this article I will apply Hero's method to the terrain on Samos.

Hero's plan was widely accepted for nearly 2,000 years as the method used on Samos until two British historians of science visited the site in 1958, saw that the terrain would have made this method unfeasible, and suggested an alternative of their own. In 1993, I visited Samos myself to investigate the pros and cons of these two methods for a *Project MATHEMATICS!* video program, and realized that the engineering problem actually consists of two parts. First, two entry points have to be determined at the same elevation above sea level; and second, the direction for tunneling between these points must be established. I will describe possible solutions for each part; but first, some historical background.

Samos, just off the coast of Turkey in the Aegean Sea, is the eighth largest Greek island, with an area of less than 200 square miles. Separated from Asia Minor by the narrow Strait of Mycale, it is a colorful island with lush vegetation, beautiful bays and beaches, and an abundance of good spring water. Samos flourished in the sixth century B.C. during the reign of the tyrant Polycrates (570–522 B.C.), whose court attracted poets, artists, musicians, philosophers, and mathematicians from all over the Greek world. His capital city, also named Samos, was situated on the slopes of a mountain, later called Mount Castro, dominating a natural harbor and the narrow strip of sea between Samos and Asia Minor. The historian Herodotus, who lived in Samos in 457 B.C., described it as the most famous city of its time. Today, the site is partly occupied by the seaside village of Pythagorion, named in honor of Pythagoras, the mathematician and philosopher who was born on Samos around

Clockwise from left: A well-preserved portion of the massive ring of fortifications surrounding the ancient capital; the impressive breakwater of Pythagorion; the church in Agiades that now sits atop Eupalinos's colonnaded reservoir; and a view of this tiny hamlet from the south. (Agiades photos courtesy of Jean Doyen.)

572 B.C. Pythagoras spent little of his adult life in Samos, and there is no reason to believe that he played a role in designing the tunnel.

Polycrates had a stranglehold on all coastal trade passing through the Strait of Mycale, and by 525 B.C., he was master of the eastern Aegean. His city was made virtually impregnable by a ring of fortifications that rose over the top of the 900-foot Mount Castro. The massive walls had an overall length of 3.9 miles and are among the best-preserved in Greece. To protect his ships from the southeast wind, Polycrates built a huge breakwater to form an artificial harbor. To honor Hera, queen of the Olympian gods, he constructed a magnificent temple that was supported by 150 columns, each more than 20 meters tall. And to provide his city with a secure water supply, he carved a tunnel, more than one kilometer long, two meters wide, and two meters high, straight through the heart of Mount Castro.

Delivering fresh water to growing populations has been an ongoing problem since ancient times. There was a copious spring at a hamlet, now known as Agiades, in a fertile valley northwest of the city, but access to this was blocked by Mount Castro. Water could have been brought around the mountain by an aqueduct, as the Romans were to do centuries later from a different source, but, aware of the dangers of having a watercourse exposed to an enemy for even part of its length, Polycrates ordered a delivery system that was to be completely subterranean. He employed a remarkable Greek engineer, Eupalinos of Megara, who designed an ingenious system. The water was brought from its source at Agiades to the northern mouth of the tunnel by an underground conduit that followed an 850-meter sinuous course along the contours of the valley, passing under three creek beds en route. Once inside the tunnel, whose floor was level, the water flowed in a sloping rectangular channel excavated along the eastern edge of the floor. The water channel then left the tunnel a few meters north of the southern entrance and headed east in an underground conduit leading to the ancient city. As with the northern conduit, regular inspection shafts trace its path.

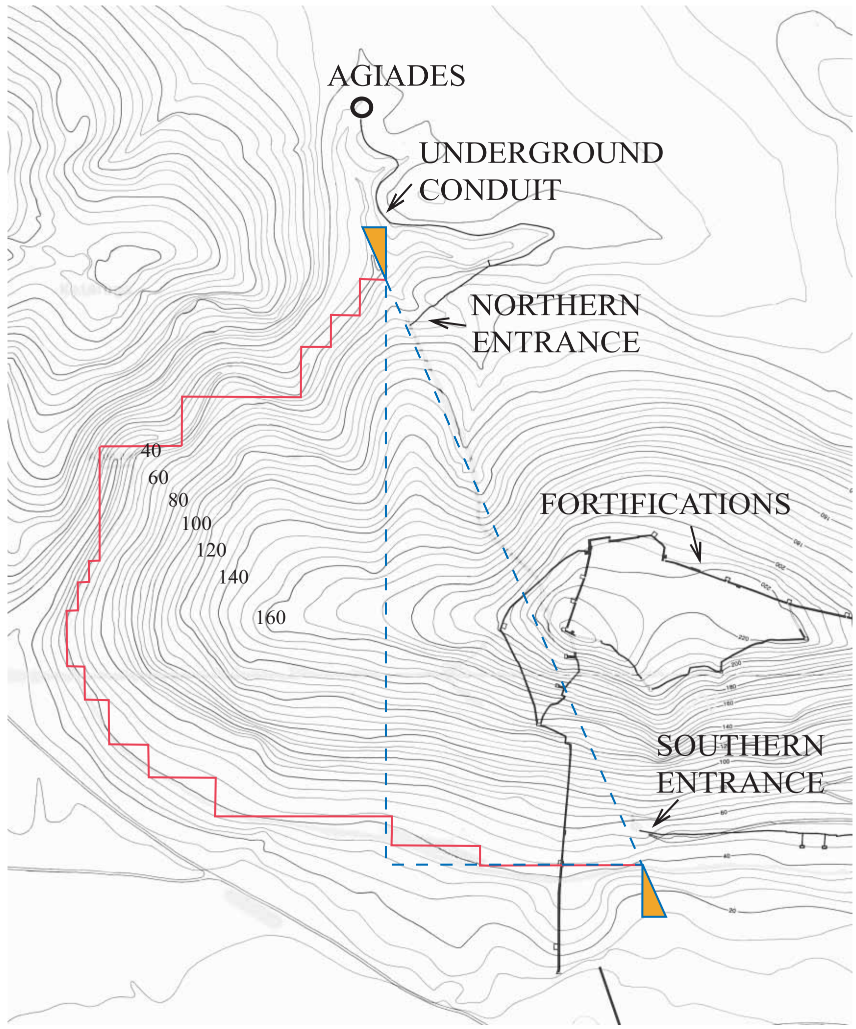
The tunnel of Samos was neither the first nor the last to be excavated from both ends. Two other famous examples are the much shorter, and very sinuous, Tunnel of Hezekiah (also known as the Siloam tunnel), excavated below Jerusalem around 700 B.C., and a much longer tunnel under the English Channel completed in 1994. The Tunnel of Hezekiah required no mathematics at all (it probably followed the route of an underground watercourse), the Tunnel of Samos used very little mathematics, while the Channel Tunnel used the full power of modern technology. There is no written record naming the engineers for Hezekiah's tunnel, just as there is none for the pyramids of Egypt, most cathedrals of Europe, or most dams and bridges of the modern world. Eupalinos was the first hydraulic engineer whose name has been preserved. Armed only with intellectual tools, he pulled off one of the finest engineering achievements of ancient times. No one knows exactly how he did it. But there are several possible explanations, and we begin with Hero's method.

Hero, who lived in Roman Alexandria in the first century A.D., founded the first organized school of engineering and produced a technical encyclopedia describing early inventions, together with clever mathematical shortcuts. One of history's most ingenious engineers and applied mathematicians, Hero devised a theoretical method for aligning a level tunnel to be drilled through a mountain from both ends. The contour map on the right shows how his method could be applied to the terrain on Samos. This map is part of a detailed, comprehensive 250-page report published in 1995 by Hermann Kienast, of the German Archaeological Institute in Athens. The sloping dashed line on the map shows the tunnel direction to be determined.

Using Hero's method, start at a convenient point near the northern entrance of the tunnel, and traverse the western face of the mountain along a piecewise rectangular path (indicated in red) at a constant elevation above sea level, until reaching another convenient point near the southern entrance. Measure the total distance moved west, then subtract it from the total distance moved east, to determine one leg of a right triangle, shown dashed on the map, whose hypotenuse is along the proposed line of the tunnel. Then add the lengths of the north-south segments to calculate the length of the other leg, also shown dashed. Once the lengths of the two legs are known, even though they are buried beneath the mountain, one can lay out smaller horizontal right triangles on the terrain to the north and to the south (shown in orange) having the same shape as the large triangle, with all three hypotenuses on the same line. Therefore, workers can always look back to markers along this line to make sure they are digging in the right direction.

This remarkably simple and straightforward method has great appeal as a theoretical exercise. But to apply it in practice, two independent tasks need to be carried out with great accuracy: (a) maintain a constant elevation while going around the mountain; and (b) determine a right

We can get an idea of working conditions in the tunnel from this Greek mining scene depicted on a tile found near Corinth.



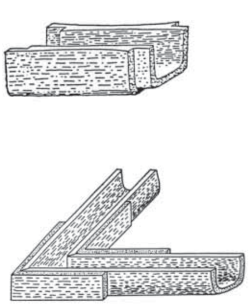
This schematic diagram shows how Hero's method can be applied to the terrain on Samos. The hypotenuse of the large right triangle is the line of the proposed tunnel. Markers can be put along the hypotenuses of the small right triangles at each entrance to help the tunnelers dig in the right direction.

angle when changing directions. Hero suggests doing both with a dioptra, a primitive instrument used for leveling and for measuring right angles. His explanation, including the use of the dioptra, was widely accepted for almost two millennia as the method used by Eupalinos. It was publicized by such distinguished science historians as B. L. van der Waerden and Giorgio de Santillana. But because there is no evidence to indicate that the dioptra existed as early as the sixth century B.C., other scholars do not believe this method was used by Eupalinos. To check the feasibility of Hero's method, we have to separate the problems of right angles and leveling.

First, consider the problem of right angles. The Samians of that era could construct right angles, as evidenced by the huge rectangular stones in the beautifully preserved walls that extended nearly four miles around the ancient capital. Dozens of right angles were also used in building the huge temple of Hera just a few miles away. We don't know exactly how they determined right angles, but possibly they constructed a portable rectangular frame with diagonals of equal length to ensure perpendicularity at the corners. A carpenter's square appears in a mural on a tomb at Thebes, dating from about 1450 B.C., so it's reasonable to assume that the Samians had tools for constructing right angles, although the accuracy of these tools is uncertain. In practice, each application of such a tool (the dioptra included) necessarily introduces an error of at least 0.1 degree in the process of physically marking the terrain. The schematic diagram on page 33 shows a level path with 28 right angles that lines up perfectly on paper, but in practice would produce a total angular error of at least two degrees. This would put the two crews at least 30 meters apart at the proposed junction. Even worse, several of these right angles would have to be supported by pillars 10 meters high to maintain constant elevation, which is unrealistic. A level path with pillars no more than one meter high would require hundreds of right angles, and would result in huge errors in alignment. Therefore, because of unavoidable errors in marking right angles, Hero's method is not accurate enough to properly align the small right triangles at the two entrances.

As for leveling, one of the architects of the temple of Hera was a Samian named Theodoros, who invented a primitive but accurate leveling instrument using water enclosed in a rectangular clay gutter. Beautifully designed round clay pipes from that era have been found in the underground conduit outside the tunnel, and open rectangular clay gutters in the water channel inside the tunnel. So the Samians had the capability to construct clay gutters for leveling, and they could have used clay L-shaped pieces for joining the gutters at right angles, as suggested in the illustration on the left. With an ample supply of limestone slabs available, and a few skilled stonemasons, Eupalinos could have marked the path with a series of layered stone pillars capped by leveling gutters that maintained a constant elevation while going around the mountain, thereby verifying constant elevation with considerable accuracy.

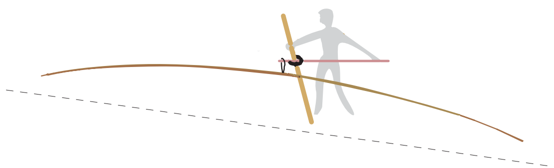
Clay gutters like these were found in the bottom of the tunnel's water channel. They could have been joined at right angles by L-shaped pieces, and used as leveling gutters around the mountain.



The southern entrance to the tunnel is somewhere within the circle, in a grove of trees. The yellow line shows the approximate route a straight path directly above the tunnel would take over the south face of Mount Castro; it's a fairly easy climb.

In 1958, and again in 1961, two British historians of science, June Goodfield and Stephen Toulmin, visited the tunnel to check the practicability of Hero's theory. They studied the layout of the surrounding countryside and concluded that it would have been extremely laborious—if not actually impossible—to carry out Hero's method along the 55-meter contour line that joins the two entrances, because of ravines and overhangs. They also noticed that the tunnel was built under the only part of the mountain that could be climbed easily from the south, even though this placed it further from the city center, and they suggested that an alternative method had been used that went over the top, as shown in the photo above.

Armed with Goodfield and Toulmin's analysis, I checked the feasibility of Hero's method. It's true that the terrain following the 55-meter contour is quite rough, especially at the western face of the mountain. But just a few meters below, near the 45-meter contour, the ground is fairly smooth, and it is easy to follow a goat trail through the brambles in a westerly direction around the mountain. Eupalinos could have cleared a suitable path along this terrain and marked it with stone pillars, keeping them at a constant elevation with clay leveling gutters, as described earlier, or with some other leveling instrument. At the western end of the south face, the terrain gradually slopes down into a stream-



Above: Mamikon Mnatsakanian holds high his invention, the leveling bow, while Tom Apostol (left) and our own Doug Smith (right) check each end. The diagram shows a handheld lever that can be used to stabilize the bow and fine-tune its elevation.

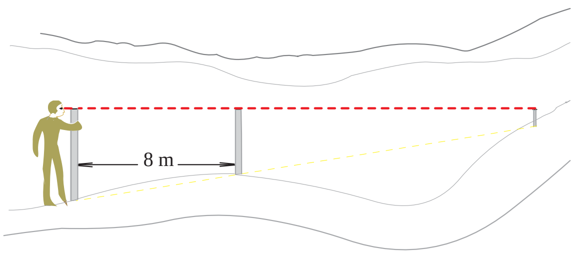
bed that is usually dry. An easy walk along this streambed leads to the northern face and a gentle slope up toward the northern entrance of the tunnel. Not only is the path around the mountain almost level near the 45-meter contour, it is also quite short—from one tunnel entrance to the other is at most only 2,200 meters.

Goodfield and Toulmin suggested that the most natural way to establish a line of constant direction would be along the top of the mountain, driving a line of posts into the ground up one face of the hill, across the top, and down the other, aligning the posts by eye. To compare elevations on the two sides of the hill, they suggested measuring the base of each post against that immediately below it, using a level. This approach presents new problems. First, it is difficult to drill holes in the rocky surface to install a large number of wooden posts. Second, aligning several hundred posts by eye on a hillside is less accurate than Hero's use of right angles. Keeping track of differences in elevation is also very difficult. There is a greater chance of error in measuring many changes in elevation along the face of a hill than there would be in sighting horizontally going around on a path of constant elevation. Because errors can accumulate when making a large number of measurements, Eupalinos must have realized that going over the top with a line of posts would not give a reliable comparison of altitude.

To ensure success, he knew it was essential for the two crews to dig along a nearly level line joining the two entrances. The completed tunnel shows that he did indeed establish such a line, with a difference of only 60 centimeters in elevation at the junction of the north and south tunnels, so he must have used a leveling method with little margin for error. Water leveling with clay gutters, as described earlier, provides one accurate method, but there are other methods that are easier to carry out in practice.

Recently, my colleague Mamikon Mnatsakanian conceived an idea for another simple leveling tool that could have been used, a long wooden bow suspended by a rope from a central balancing point so that its ends are at the same horizontal level. The bow need not have uniform thickness and could be assembled by binding together two lengthy shoots from, say, an olive tree. Such a bow, about eight meters long, would weigh about four pounds and would be easy to carry. And it has the advantage that no prior calibration is needed.

To use the bow as a leveling tool, place it on the ground and slowly lift it with the rope. If the two ends leave the ground simultaneously, they are at the same elevation. If one end leaves the ground first, place enough soil or flat rock beneath that end until the other end becomes airborne. At that instant, the bow will oscillate slightly, which can be detected visually, and the two ends will be at the same elevation. Three people are needed, one at the center and one at each end to fix the level points. To check the accuracy, turn the bow end-to-end and make sure both ends touch at the same two marks. In this way, the device permits self-checking and fine tuning. There will be an error in leveling due to a tiny gap between the endpoint of the bow and the point on which it is supposed to rest when level; this can be checked



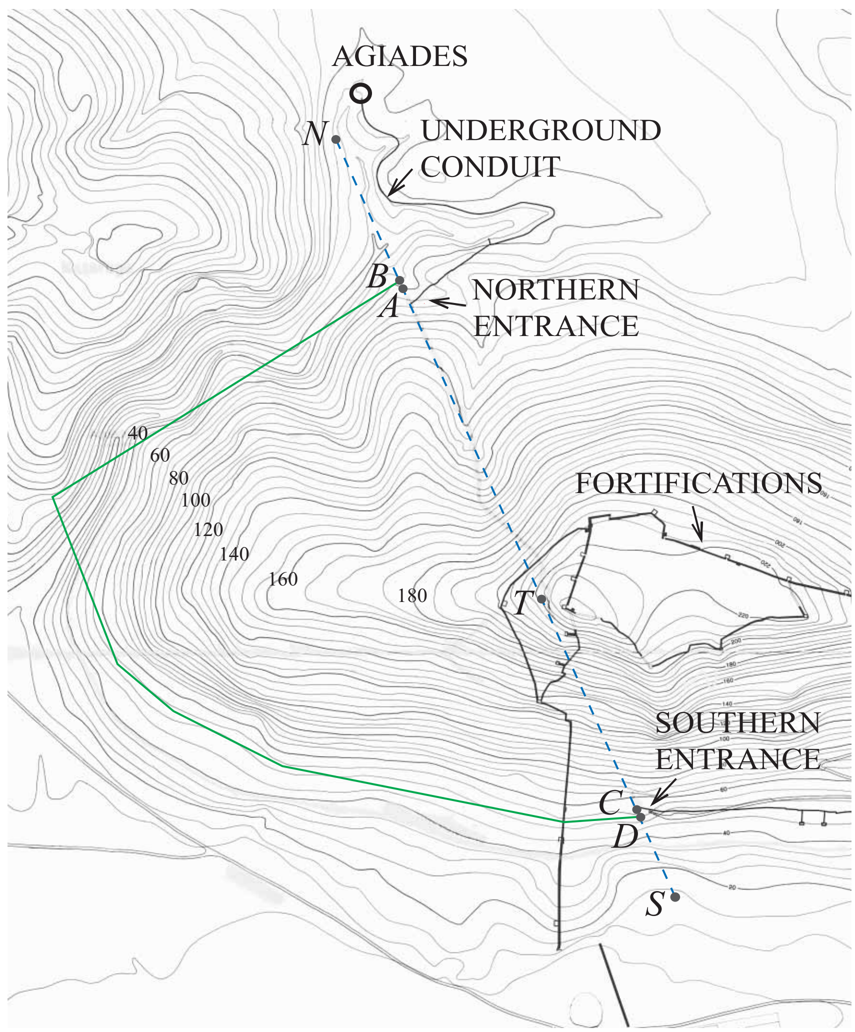
By sighting horizontally along the tops of two pillars set eight meters apart, a target point can be located up to 100 meters away; a possible error of two millimeters in the elevations of the two pillars expands to an error of 25 millimeters in the elevation of the target point.

by the human eye at close range, and would be one or two millimeters per bow length.

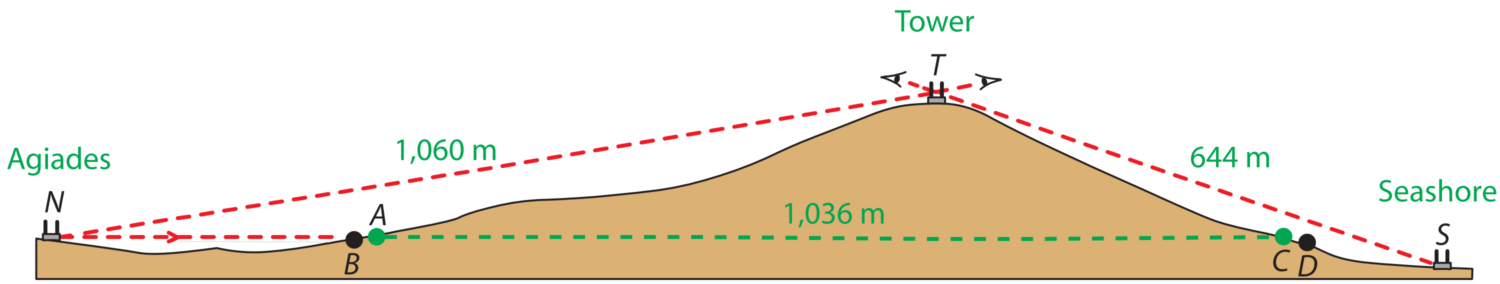
To employ the leveling bow to traverse Mount Castro at constant elevation, one can proceed as follows. Construct two stone pillars, eight meters apart, and use the leveling bow to ensure that the tops of the pillars are at the same elevation. At the top of each pillar, a horizontal straightedge can be used for visual sighting to locate other points at the same elevation and on the same line—the same principle as used for aiming along the barrel of a rifle.

Points approximately at the same elevation can be sighted visually at great distances. Choose such a target point and construct a new pillar there with its top at the same elevation, and then construct another pillar eight meters away to sight in a new direction, using the leveling bow to maintain constant elevation. Continuing in this manner will produce a polygonal path of constant elevation. The contour map on the right shows such a path in green, with only six changes in direction leading from point *B* near the northern entrance to point *D* near the southern entrance. The distance around Mount Castro along this path is less than 2,200 meters (275 bow lengths), so an error of two millimeters per bow length could give a total leveling error of about 55 centimeters. This is close to the actual 60-centimeter difference in floor elevation measured at the junction inside the tunnel. In contrast to Hero's method, no angular or linear measurements are needed for leveling with Mamikon's bow.

Without Hero's method, how could Eupalinos locate the entry points and fix the direction for tunneling? Kienast's report offers no convincing theory about this, but using information in the report, Mamikon and I propose another method that could have determined both entries, and the direction of the line between them, with considerable accuracy. Kienast's contour map (right)



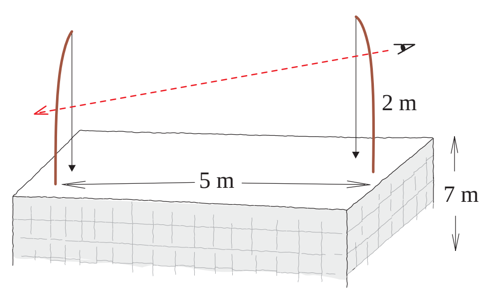
Using pillars and the leveling bow, a polygonal path, in green, can be traced around the mountain at a constant elevation above sea level to join point *B* near the northern entrance to point *D* near the southern.



From a point seven meters above the top of the profile, there is a direct line of sight to Agiades in the north and the seashore to the south. It would have been easy for Eupalinos to build a surveying tower (*T*) there. Two sighting poles such as the ones shown below could have been installed on the tower to align with markers *N* and *S* in Agiades and on the shore, respectively.

shows that the north entrance to the tunnel, point *A* on the map, lies on the 55-meter contour line, and the source at Agiades is near the same contour line. His profile map in the report, which I have adapted for the diagram above, reveals that persons standing at the crest of the mountain cannot see Agiades in the north and the seashore in the south at the same time—but they could if they were on top of a seven-meter-high tower at point *T.* The Samians could easily have constructed such a tower from wood or stone.

Mamikon has conceived a sighting tool, based on the same principle as the Roman groma, that could have been used to align *T* with two points: one (*N*) near the source in the northern valley and one (*S*) on the seashore in the south within the city walls. This sighting tool consists of a pair of two-meter-high "fishing poles" about five meters apart, with a thin string hanging vertically from the top of each pole to which a weight or plumb



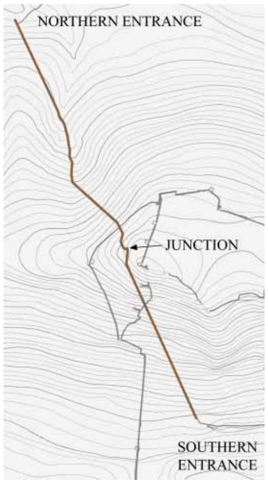
bob has been attached. Each pole would be mounted on the tower so that it could turn around a vertical axis, allowing the hanging strings to be aligned by eye while aiming toward a person or marker at point *N*. Sighting along the same device in the opposite direction locates *S*.

Using the same type of sighting instrument from point *N*, and sighting back toward *T*, the tunnel's northern entrance (point *A*) can be chosen so that *S*, *T*, *N,* and *A* are in the same vertical plane. Then the leveling bow can be used to ensure that *A* is also at the same elevation as *N*.

For the southern entrance, we need a point *C* inside the city walls at exactly the same elevation as *A*. Starting from a nearby point *B* at a lower elevation easier to traverse and in the vertical plane through *N* and *A*, a series of sighting pillars can be constructed around the western side of the mountain—using any of the leveling methods described earlier—until point *D*, at the intersection of the sighting plane through *T* and *S,* is reached. The two terminal points *B* and *D* will be at the same elevation above sea level, and the vertical plane through points *B*, *T*, and *D* fixes the line for tunneling. It is then a simple matter to sight a level line from the top of a pillar at *D* to determine the southern entrance point, *C*, that has the same elevation as *A*. Markers could be placed along a horizontal line of sight at each entrance to guide the direction of excavation.

How accurate is this method of alignment? In sighting from one fishing pole to its neighbor five meters away, there is an alignment error of one millimeter, which expands to an overall error of 22 centimeters in sighting from point *T* at the top of the mountain to point *N*, 1,060 meters away to the north, plus another error of 13 centimeters from *T* to *S*, 644 meters away to the south. So the total error in sighting from *N* to *S* by way of *T* is of the order of 35 centimeters. Adjusting this to account for the alignment error from *N* to *A* by way of *B*, and from *S* to *C* by way of *D*, gives a total error of the order of less than 50 centimeters between the two directions of tunneling. This is well within the accuracy required to dig two shafts, each two meters wide, and have them meet, and is much more accurate than the other proposed methods of alignment. Moreover, as with the alternative method of leveling, no angular or linear measurements are needed.

This picture was taken inside the tunnel looking toward the southern entrance. Although the floor is more or less level along the whole length, the roof slopes in line with the rock strata. Metal grillwork now covers the water channel on the left to prevent hapless tourists from falling in; the photo on the next page shows how treacherous it was before.



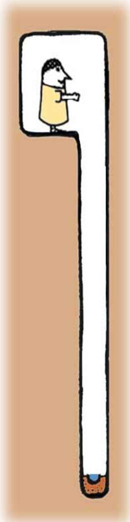
The crew digging into the northern mountainside started off perfectly in line with the southern crew, but later zigzagged off course, perhaps to bypass areas of unstable rock. They did, however, meet up almost perfectly with the southern tunnel, albeit at right angles. Right: At the southern end, the water channel is a staggering nine meters lower than the floor of the tunnel.

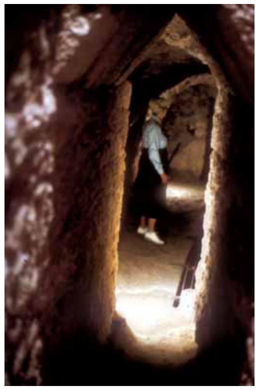
No matter how it was planned, the tunnel excavation itself was a remarkable accomplishment. Did the two crews meet as planned? Not quite. If the diggers had kept faith in geometry and continued along the straight-line paths on which they started, they would have made a nearly perfect juncture. The path from the north, however, deviates from a straight line. When the northern crew was nearly halfway to the junction point, they started to zigzag as shown in the diagram on the left, changing directions several times before finally making a sharp left turn to the junction point. Why did they change course? No one knows for sure. Perhaps to avoid the possibility of digging two parallel shafts. If one shaft zigzagged while the other continued in a straight line, intersection would be more likely. Or they may have detoured around places where water seeped in, or around pockets of soft material that would not support the ceiling. In the final stretch, when the two crews were near enough to begin hearing each other, both crews changed direction as needed and came together. The sharp turns and the difference in floor levels at the junction prove conclusively that the tunnel was excavated from both ends. At the junction itself, the floor level drops 60 centimeters from north to south, a discrepancy of less than one-eighth of a percent of the distance excavated. This represents an engineering achievement of the first magnitude.

No one knows exactly how long it took to complete the project, but estimates range from 8 to 15 years. Working conditions during excavation must have been extremely unpleasant. Dust from rubble, and smoke from oil lamps used for illumination, would have presented serious ventilation problems, especially when the workers had advanced a considerable distance from each entrance.

A visit to the tunnel today reveals its full magnificence. Except for some minor irregularities, the southern half is remarkably straight. The craftsmanship is truly impressive, both for its precision and its high quality. The tunnel's two-meter height and width allowed workers carrying rubble to pass those returning for more. The ceiling and walls are naked rock that gives the appearance of having been peeled off in layers. Water drips through the ceiling in many places and trickles down the walls, leaving a glossy, translucent coating of calcium carbonate, but some of the original chisel marks are still visible. The floor is remarkably level, which indicates that Eupalinos took great care to make sure the two entrances were at the same elevation above sea level.

Of course, a level tunnel cannot be used to deliver a useful supply of water. The water itself was carried in a sloping, rectangular channel excavated adjacent to the tunnel floor along its eastern edge. Carving this inner channel with hand labor in solid rock was another incredible achievement, considering the fact that the walls of the channel are barely wide enough for one person to stand in. Yet they are carved with great care, maintaining a constant width throughout. At the northern end, the bottom of the channel is about three meters lower than the tunnel floor, and it gradually slopes down to more than nine meters lower at the southern end. The bottom of the channel was lined with open-topped rectangular clay gutters like those in the drawing on page 34.



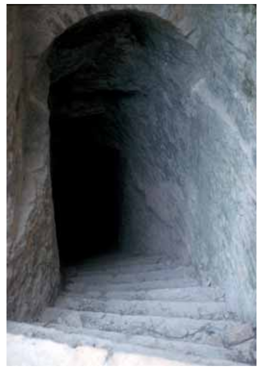


Jane Apostol descends the dauntingly narrow wooden staircase near the southern entrance, far left, which leads to a narrow walled passageway whose gabled roof is typical of ancient Greek construction, near left. Below: This old photo of the tunnel, looking north, shows the open water channel. Part of the channel above the water gutters was originally filled in with rubble, some of which is still visible.

When the tunnel was rediscovered in the latter part of the 19th century and partially restored, portions of the water channel were found to be covered with stone slabs, located two to three meters above the bottom of the channel, onto which excess rubble from the excavation had been placed up to the tunnel floor. The generous space below the slabs along the bottom of the channel provided a conduit large enough for ample water to flow through, and also permitted a person to enter for inspection or repairs. In several places the channel was completely exposed all the way up to the tunnel floor, permitting inspection without entering the channel. Today, most of the rubble has been cleared from the southern half of the channel, and metal grillwork installed to prevent visitors from falling in.

To visit the tunnel today, you first enter a small stone building erected in 1882 at the southern entrance. A narrow, rectangular opening in the floor contains a steep flight of wooden steps leading down into a walled passageway about 12 meters long, slightly curved, and barely wide enough for one person to walk through. The sides of the passageway are built of stone blocks joined without mortar, and capped by a gabled roof formed by pairs of huge, flat stones leaning against each other in a manner characteristic of ancient Greek construction. This passageway was constructed after the tunnel had been completely excavated. Excess rubble from the excavation, which must have been considerable, was used to cover the roof of this passageway, and a similar one at the north entrance, to camouflage them for protection against enemies or unwelcome intruders. Electric lights now illuminate the southern half, up to a point about 100 meters north of the junction with the northern tunnel, where there is a barrier and landfall that prohibits visitors from going further.

Modern stone walls now line the path near the northern entrance of the tunnel, left, while inside, right, a stone staircase leads down to the tunnel.



PICTURE CREDITS: 30-31, 33, 36, 38 – German Archaeological Institute; 32-34, 38-40 – Tom Apostol; 35 – Bob Paz; 39 – Hellenic TAP Service

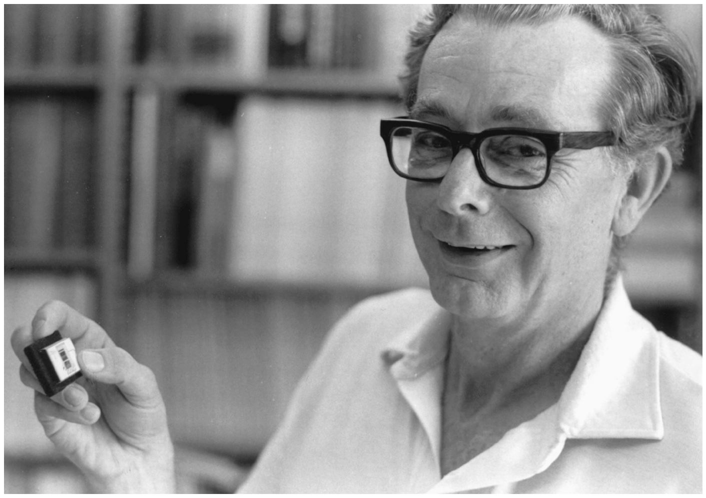
For centuries, the tunnel kept its secret. Its existence was known, but for a long time the exact whereabouts remained undiscovered. The earliest direct reference appears in the works of Herodotus, written a full century after construction was completed. Artifacts found in the tunnel indicate that the Romans had entered it, and there is a small shrine near the center from the Byzantine era (ca. A.D. 500–900). In 1853, French archaeologist Victor Guérin excavated part of the northern end of the subterranean conduit, but stopped before reaching the tunnel itself. An abbot from a nearby monastery later discovered the northern entrance and persuaded the ruler of the island to excavate it. In 1882, 50 men restored the southern half of the tunnel, the entire northern underground conduit, and a portion of the southern conduit. On the foundation of an ancient structure, they built a small stone house that today marks the southern entrance. In 1883, Ernst Fabricius of the German Archaeological Institute in Athens surveyed the tunnel and published an excellent description, including the topographic sketch shown on page 30. After that, the tunnel was again neglected for nearly a century, until the Greek government cleared the southern half, covered the water channel with protective grillwork, and installed lighting so tourists could visit it safely.

Today, the tunnel is indeed a popular tourist attraction, and a paved road from Pythagorion leads to the stone building at the southern entrance. Some visitors who enter this building go no further because they are intimidated by the steep, narrow, and unlit wooden staircase leading to the lower depths. At the north entrance, which can be reached by hiking around Mount Castro from the south, modern stone walls lead to a staircase and passageway. A portion of the northern tunnel has been cleared, but not lighted.

The tunnel, the seawall protecting the harbor, and the nearby temple of Hera—three outstanding engineering achievements—were constructed more than 2,500 years ago. Today, the tunnel and seawall survive, and although the temple lies in ruins, a single column still stands as a silent tribute to the spirit and ingenuity of the ancient Greeks. □

This lone survivor is one of 150 columns, each more than 20 meters tall, that once supported the Temple of Hera, lauded by Herodotus as one of the three greatest engineering feats of ancient times. The other two were also on Samos—the breakwater and the tunnel.

The videotape on the Tunnel of Samos has been a favorite of the educational Project MATHEMATICS! *series (www.projectmathematics.com) created, directed, and produced by Professor of Mathematics, Emeritus, Tom Apostol. He is, however, better known to students both here and abroad as the author of textbooks in calculus, analysis, and number theory, books that have had a strong influence on an entire generation of mathematicians. After taking a BS (1944) and MS (1946) at the University of Washington, he moved to UC Berkeley for his PhD (1948), then spent a year each at Berkeley and MIT before joining Caltech in 1950. Although he became emeritus in 1992, his mathematical productivity has not slowed down—he has published 40 papers since 1990, 16 of them jointly with Mamikon Mnatsakanian.*



When CCDs revolutionized optical astronomy, Bev Oke was quick to build them into his instruments.

John Beverley Oke 1928 – 2004

Bev Oke, professor of astronomy, emeritus, died of heart failure on Tuesday, March 2, at his home in Victoria, British Columbia, just 21 days short of his 76th birthday. He earned his bachelor's and master's degrees from the University of Toronto in 1949 and 1950, respectively, his doctorate from Princeton University in 1953, and was a member of the Caltech faculty from 1958 until his retirement in 1992. He was also a staff member of the Hale Observatories (Mount Wilson and Palomar) and served as associate director from 1970 to 1978.

His scientific work covered wide areas of astronomical spectroscopy, from white dwarfs to active galactic nuclei, clusters of galaxies, and supernovae. However, he is perhaps best known for devising and building unique instruments for the 200-inch Hale Telescope at Palomar, and later for the Keck. "He was one of the first really serious and really excellent astronomer-instrumentalists," says James Gunn (PhD '66), Higgins Professor of Astronomy at Princeton University Observatory, "and he and the instruments he designed and built were very largely responsible for keeping Palomar and the 200-inch telescope so far ahead of the rest of the world during the '60s, '70s, and '80s."

The first instrument Oke built after joining the Caltech faculty was a single-channel scanner for the 200-inch that could measure the spectra of stars and galaxies in successive 10-nanometer-wide segments, according to Wallace Sargent, the Bowen Professor of Astronomy, writing in the April 1 issue of *Nature*. This spectrophotometer was to play an important role in 1963, when Maarten Schmidt, the Moseley Professor of Astronomy, Emeritus, was taking photographic plates of the mysterious "radio star" 3C273 (now known to be a quasar), and realized that spectral lines indicating the presence of hydrogen, normally seen in the green and violet end of the visible spectrum, appeared to have been shifted to the red. Oke observed the star with his photometer and found a spectral line in the invisible infrared region, which confirmed that the light from 3C273 had a very high redshift, and must have been moving away from the earth at one-sixth the speed of light. The discovery caused a sensation at the time.

"For as long as I knew him, he would be either building an innovative instrument or planning the next one," says Schmidt. And indeed, in 1968, Oke's multichannel photoelectric spectrometer was ready for use on the 200-inch. Its ability to measure the absolute spectral energy distributions of extremely faint objects benefited many astronomers over the years; Oke himself used it to measure the spectra of stars, Seyfert galaxies, and quasars.

In the late 1970s, he designed and built an innovative double spectrograph that split the light beam to go through two separate spectrographs, one fitted with a charge-coupled device (CCD) optimized for blue light, the other with a CCD optimized for red. This instrument, now with upgraded CCD technology, is still in use at Palomar.

More recently, a low-resolution imaging spectrograph that he designed and built with astronomy professor Judith Cohen for one of the twin 10-meter Keck Telescopes in Hawaii produced many of the telescopes' early successes, including the discovery and analysis of hundreds of galaxies at very high redshifts.

Despite building instruments and teaching, Oke found time to publish a large number of scientific papers, recounts Sargent. One of his main achievements was his fundamental work in calibrating the magnitude system used by astronomers to measure starlight. This calibration is still the standard in use today.

"He was as much a workaholic as anybody at Caltech, but seemed in the midst of it all to have much more time for students and really enjoyed interacting with students more than anybody else," says Gunn. "I, for one, benefited enormously from his attention when I was a student, and I was certainly not alone. I had a special relationship with him which began in the '60s while I was still a graduate student and which continued for many years later, because I was also keenly interested in instrumentation, and passed from apprentice and friend to very close colleague and friend. I think we have lost someone who was vastly important to the field in ways we will probably never properly recognize." In *Nature*, Sargent describes him as "a modest, phlegmatic man with a laconic sense of humor. His lectures were clear, matter of fact and unadorned with fanciful speech. He led by example, not by fine words."

On retiring from Caltech in 1992, Oke returned to his native Canada to continue his research at the Herzberg Institute of Astrophysics in Victoria. At the time of his death, he was working on the design of a spectrograph for the proposed Thirty-Meter Telescope, a joint venture between Caltech, the University of California, the Association of University Research in Astronomy, and its Canadian equivalent. He is survived by his wife, Nancy; sons, Christopher and Kevin; and daughters, Jennifer and Valerie. "His greatest indulgence was his MG sports car, which he delighted to drive along the S6 'highway to the stars' up to Palomar Mountain," Sargent writes. He was still working on it the day before he died. □—*BE*

William Hayward Pickering 1910 – 2004

Bill Pickering, "Mr. JPL," the father of American space exploration, died March 15 of pneumonia at his home in La Cañada Flintridge. He was 93.

Pickering was born in Wellington, New Zealand, and grew up in the province of Marlborough. Marlborough was also where Ernest Rutherford, "another giant of world science," was born and grew up, noted the Honorable Darryl Dunn, New Zealand's consul general, at the memorial service for Pickering in Beckman Auditorium March 20. "Like Rutherford, he had to go overseas to pursue his career," said Dunn. "Like Rutherford, Bill found a new home that he loved greatly. And like Rutherford, Bill never forgot the land of his youth."

While studying electrical engineering at the University of Canterbury in Christchurch, New Zealand, Pickering was encouraged by an uncle to study at Caltech. He emigrated to the United States in 1929, earning his BS at the Institute in 1932 and MS in 1933. After finishing his PhD in physics in 1936, he joined the Caltech electrical engineering faculty. In 1941 he became an American citizen.

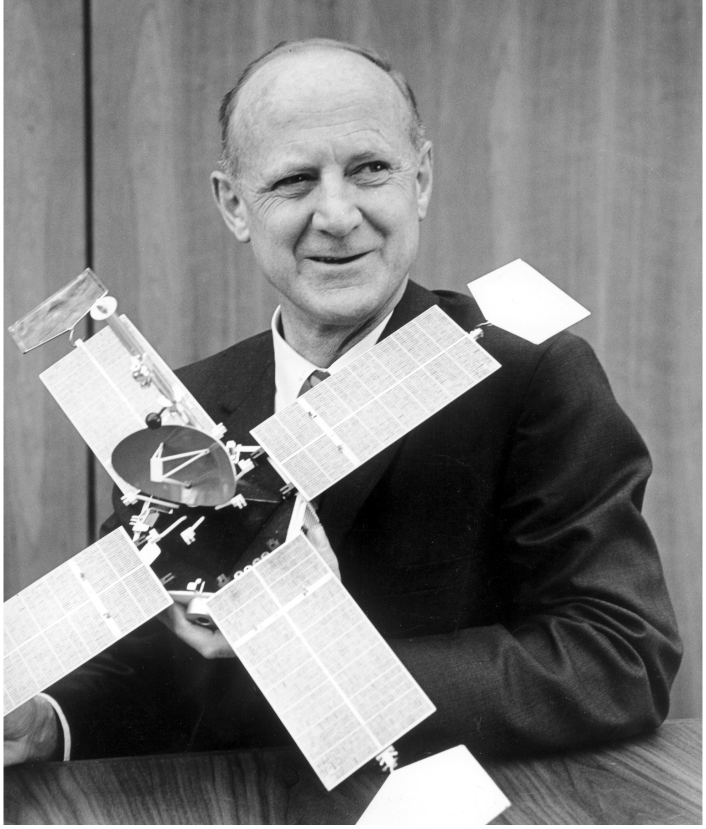
Then in 1944 Pickering began his long, distinguished career at the Jet Propulsion Laboratory; he became its director in 1954 and led it through the decades of the Cold War and the space race. JPL was originally set up under the U.S. Army to support guided-missile research and development, and Pickering worked on the Private and Corporal rockets in the Lab's early days. It was Pickering, said Charles Elachi, the current JPL director, "who made the critical move in the late 1950s to have JPL do more than building the rocket—build what's on *top* of the rocket. Without that foresight, that vision, and that boldness, JPL would not be what it is today."

When the Soviet Union launched Sputnik in the fall of 1957 and the space race began, Pickering led the JPL team that, in a mere 83 days, launched the first U.S. satellite, Explorer 1, on January 31, 1958. And also in 1958, when JPL, under Caltech's management, was transferred to the newly established National Aeronautics and Space Administration, Pickering, when offered the choice of either human or robotic exploration of space, chose the role of sending unmanned spacecraft out into the solar system. There followed subsequent Explorer missions, the Ranger and Surveyor missions to the moon, and the several Mariner flybys of Venus and Mars. He appeared on the cover of *Time* magazine twice—in 1963 and again in 1965. When he retired as director in 1976, the two Voyager missions were being prepared for launch on their spectacular tour of the outer planets, and Viking 1 was about to land on Mars. And when Spirit and Opportunity landed on Mars last January, Pickering was there at JPL, celebrating the triumph.

Pickering brought to the Lab strong leadership, good engineering, and good management, said Elachi at the memorial service. "He was unflappable," and "ran the lab with a steady hand." And a sense of humor. Elachi spoke of how Pickering used to describe the lab "as a graduate student project that got out of hand," whose main task in the early days was to figure out "how to make a rocket that won't blow up."

Several former JPL administrators also spoke at the memorial, each in his own way praising Pickering's role in setting JPL on its trajectory to the planets. Lieutenant General Charles H. Terhune Jr. an Air Force rocket man who was JPL's deputy director from 1971 to 1983, noted the Lab's first rocket projects and said, "There was no doubt that he wanted to go into space as opposed to simply making weapons. He inspired vision in people. He tried out new ideas. He didn't lose sight of his objectives."

Eberhardt Rechtin (BS '46, PhD '50), assistant director of JPL from 1958 to 1967 and chief architect of the Deep Space Network, was a student of Pickering's and spoke of "Pickering's boys"—his Caltech students. "He taught by example; he taught us



Bill Pickering shows off a model of a Mariner spacecraft in 1967.

discipline; he taught us precision; he taught us about humility." He was everyone's favorite professor and also taught his students "how important it was that things had to work, not just be."

Rechtin described how the Deep Space Network was born—not in 1963 as officially stated, but back in the days before Explorer's launch. Pickering understood "about the importance of that particular flight, of the interest that the world would have, and how important it was to measure it." And when the Army declared a tracking system unnecessary, Pickering sent his tracking stations ("all we needed was a suitcase full of stuff and we could do anything") to British Commonwealth friends around the world—the first international network, said Rechtin. "And it was the Nigerian station that first heard the signals from Explorer that told us of the existence of the Van Allen ionization belts. The Nigerians were listening at the right time at the right place and they heard us."

Tom Everhart, president of Caltech from 1987 to 1997, also mentioned the discovery of the Van Allen belts. For Pickering, he said, "it wasn't enough to have a beeping satellite as the Russians had. Ours needed to do something useful and it did." Everhart put that down to Pickering's Caltech education. "He has stated that when he knew that Explorer I was successfully orbiting the earth, that was one of the proudest moments of his life."

"I believe Bill Pickering will go down in Caltech history as a man who demonstrated that the Institute could take on a new role, leading a government-funded mission laboratory to make unprecedented discoveries about our planetary system," said Everhart. "He emphasized the synergy and mutual dependence between science and engineering."

Pickering received many honors during his long life, among them the National Medal of Science, NASA's Distinguished Service Medal, and the New Zealand Order of Merit. He was awarded an honorary knighthood by, as Dunn, the consul general, called her, "the Queen of New Zealand."

New Zealand always claimed him as a "beloved son." Dunn remembered seeing the first Mars pictures in 1965 and "the distinguished man with the odd American accent" presenting them. "I still remember my mother pointing to him and saying with pride, 'That's Dr. Pickering. Did you know he's a New Zealander?'"

Donations in his memory may be made to the William H. Pickering Scholarship for New Zealand Graduate Students at Caltech.

He is survived by his wife, Inez, and his daughter, Elizabeth Pickering Mezitt. His son, William Balfour, died two days before him. □
—JD

Honors and Awards

David Baltimore, president of Caltech and Nobel laureate, was chosen by the Israel Academy of Sciences and Humanities to deliver the Albert Einstein Annual Lecture at the academy's headquarters in Jerusalem on March 14, when he spoke on "Biotechnology—An Industry with a Future."

Andrew Blain, assistant professor of astronomy; **Nathan Dunfield**, associate professor of mathematics; **Sunil Golwala**, assistant professor of physics; **Vadim Kaloshin**, associate professor of mathematics; **Re'em Sari**, associate professor of astrophysics and planetary science; and **Tapio Schneider**, assistant professor of environmental science and engineering have all received 2004 Sloan Research Fellowships. Intended to enhance the careers of the very best young faculty members nationally in the fields of chemistry, computational and evolutionary molecular biology, computer science, economics, mathematics, neuroscience, and physics, the highly competitive two-year, $40,000 awards are available for any activity directly related to a Fellow's research, including equipment, technical assistance, professional travel, or trainee support.

David Charbonneau, Millikan Postdoctoral Scholar in Astronomy, has been selected to receive the Astronomical Society of the Pacific's Robert J. Trumpler Award, which "is given each year to a recent recipient of the PhD degree in North

America whose research is considered unusually important to astronomy." The award consists of a plaque and a check for $500. He has also been named to receive the Bar J. Bok Prize for "outstanding research by a recent graduate of the Harvard Department of Astronomy."

Serguei Denissov, Taussky-Todd Instructor in Mathematics, has been selected to receive the Vasil A. Popov Prize in Approximation Theory. Established in honor of the late Professor Vasil A. Popov of Bulgaria, the prize is awarded every three years to an outstanding young approximation theorist with at most six years of professional experience. This year's prize will be awarded in May at the Eleventh International Conference in Approximation Theory, in Gatlinburg, Tennessee.

James Heath, the Gilloon Professor and professor of chemistry at Caltech and one of the scientific founders of Nanosys Inc., has been recognized "for devising a method for producing ultra-high-density arrays of aligned nanowires and nanowire circuits," which constitute "a key architecture and technique in several of Nanosys's electronic systems." The recognition came as part of the *Chemical and Engineering News* Nanotech & Molecular Electronics Highlights for 2003.

Charles Elachi, Caltech vice president, director of the Jet Propulsion Laboratory, and professor of electrical engineering and planetary science, was named to the William Gould Dow Distinguished Lectureship, which is "the highest external honor" bestowed by the University of Michigan's department of electrical engineering and computer science, and recognizes the accomplishments of individuals outside the university system "who have made outstanding contributions" in the field of electrical engineering and computer science. Elachi spoke on "Space Exploration in the Next Decade—Challenges and Opportunities."

Alexander Kechris, professor of mathematics, has been elected president of the Association for Symbolic Logic, an international organization supporting research and critical studies in logic by providing a forum for the presentation, publication, and critical discussion of scholarly work in this area. He began his term in January and will hold the presidency for three years.

Joseph Kirschvink, professor of geobiology, and **Yuk Ling Yung**, professor of planetary science, have been elected fellows of the American Geophysical Union. The honor recognizes scientists who have achieved eminence in the geophysical sciences and is bestowed on only a tenth of a percent of the union's membership in any given year.

Christof Koch, the Troendle Professor of Cognitive and Behavioral Biology and professor of and executive officer for computation and neural systems, and **Melissa Sáenz**, postdoctoral scholar in biology, have been selected by the Mind Science Foundation to receive a 2004 Tom Slick Research Award in Consciousness. Named after the late entrepreneur, explorer, philanthropist, and author Tom Slick (1916–1962), the awards were initiated "to fulfill his vision of studying the mind as a means for improving the condition of humankind."

Mark Konishi, the Bing Professor of Behavioral Biology, has been selected to receive the first Edward M. Scolnick Prize in Neuroscience, the highest award of the McGovern Institute at MIT. Named in honor of the former president of Merck Research Laboratories, the award was created in 2003 to recognize an outstanding discovery or significant advance in the field of neuroscience.

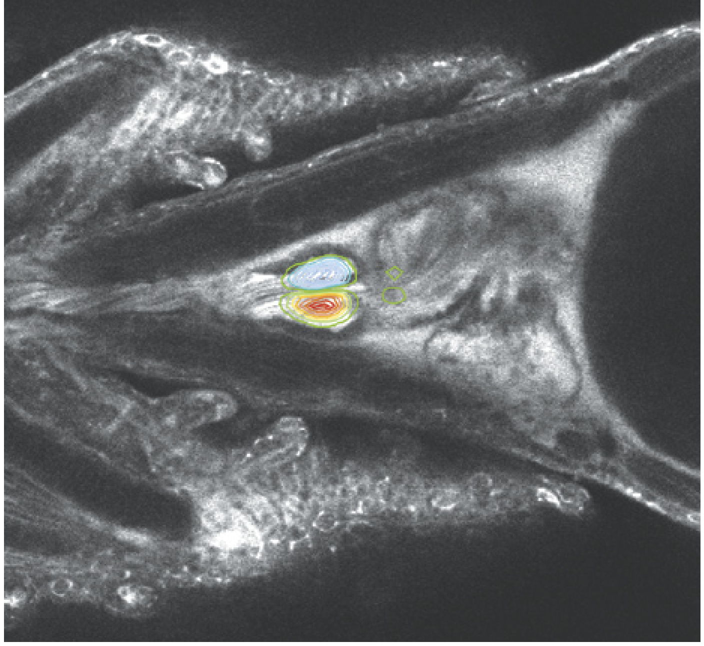
Richard Marsh, senior research associate in chemistry, emeritus, has been selected by the American Crystallographic Association (ACA) to receive its first Kenneth N. Trueblood Award, which "recognizes exceptional achievement in computational or chemical crystallography." As part of the award, Marsh will give the keynote lecture in the Trueblood Symposium, to be organized in his honor during the 2004 ACA annual meeting. □

George Rossman stands alongside a poster of rossmanite, a tourmaline mineral species named in his honor.

Rossman Wins Feynman Prize

"Best professor at Caltech." "Probably the best, clearest, and most exciting teacher I have ever had." "Such a great lecturer that he can make the class and each mineral very funny." Comments such as these from professor of mineralogy George Rossman's students gained him this year's Richard P. Feynman Prize for Excellence in Teaching, Caltech's most prestigious teaching award. According to the citation, "Rossman has been teaching with enthusiasm and with superb results since he joined the Caltech faculty in 1971. His style of teaching ex-ploits the beautiful and beguiling qualities of minerals and their relationships to geological processes. He employs a series of mind-stretching demonstrations, often including liquid nitrogen and irradiated crystals. He tells stories about minerals. He asks probing questions about their color, and then leads students to think in general about the proper approach to scientific ques-tions." "Rossman also originated the concept, and helped to fund the reality, of field trips to localities not easily accessible to students. Recently, undergraduate and graduate students have gone to Alaska, Greece, Turkey, South Africa, and Brazil." The award is made possible by the generosity of an endowment from Ione and Robert E. Paradise, along with additional contributions from Mr. and Mrs. William H. Hurt. □

Answer to puzzle on page 11: Pat, Lee, and Sydney are in the room with Renay.



Complex blood-flow patterns have been captured mid-beat in the embryonic heart of a zebrafish. A pair of vortices, one with low velocity (blue), the other high velocity (red and yellow) have just formed after systolic contraction of the ventricle.

Discovery Funds

Even a modest amount of funding can lead to far-reaching advancements at Caltech. Take, for example, the groundbreaking work of Morteza Gharib (PhD '83), Scott Fraser, and their colleagues.

As reported in the article "Shear Stress is Good for the Heart" (*Engineering & Science*, Volume LXV, Number 4, 2002), Gharib (the Liepmann Professor of Aeronautics and Bioengineering), Fraser (the Rosen Professor of Biology), Jay Hove (senior research fellow in bioengineering), and postdoc Reinhardt Köster teamed up to image the blood flow inside the heart of a growing embryonic zebrafish. The result was a triumph of bioengineering that landed the team's project on the cover of the journal *Nature* in January 2003. The interdisciplinary team demonstrated for the first time that the very action of high-velocity blood flowing over cardiac tissue is an important factor in the proper development of the heart—a discovery that could have profound implications for future surgical techniques and for genetic engineering.

Adding to the measure of this feat is the fact that the group was able to launch the project with a mere $20,000. Such funding is often drawn off of Caltech's annual operating budget—a limited resource. Financial resources made available through endowed Discovery Funds, however, provide a predictable source of restricted monies to support innovative research in perpetuity.

Discovery Funds free the provost and division chairs from budgetary restrictions and quickly allow faculty to explore novel ideas and unique opportunities that could lead to new knowledge and technologies offering significant benefits to society. What's more, a Discovery Fund has the ability to support many different projects over the life of the fund, providing a stable financial resource year after year. For this reason, endowing a Discovery Fund is one of the most meaningful ways a donor can invest in the advancement of knowledge and scientific discovery at Caltech.

A Discovery Fund can be created with a gift of $250,000 through a variety of gift arrangements. Recent gifts to establish Discovery Funds have come from the Estate of Leonard B. Edelman to support fundamental biology research, the Della Martin Foundation for research in mental illness, the Estate of Mr. John N. Fehrer to support biomedical research, and Mr. and Mrs. Irvin P. Seegman (BS '42) for research in chemistry. □

–*Vannessa Dodson*

The zebrafish, a common resident in home aquariums, has a number of features, such as transparent embryos, that make it a popular lab model.

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THE CAMPAIGN

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