CALIFORNIA
INSTITUTE OF
TECHNOLOGY

ENGINEERING & SCIENCE

Volume LXIII,
Number 2,
2000

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Entangled States

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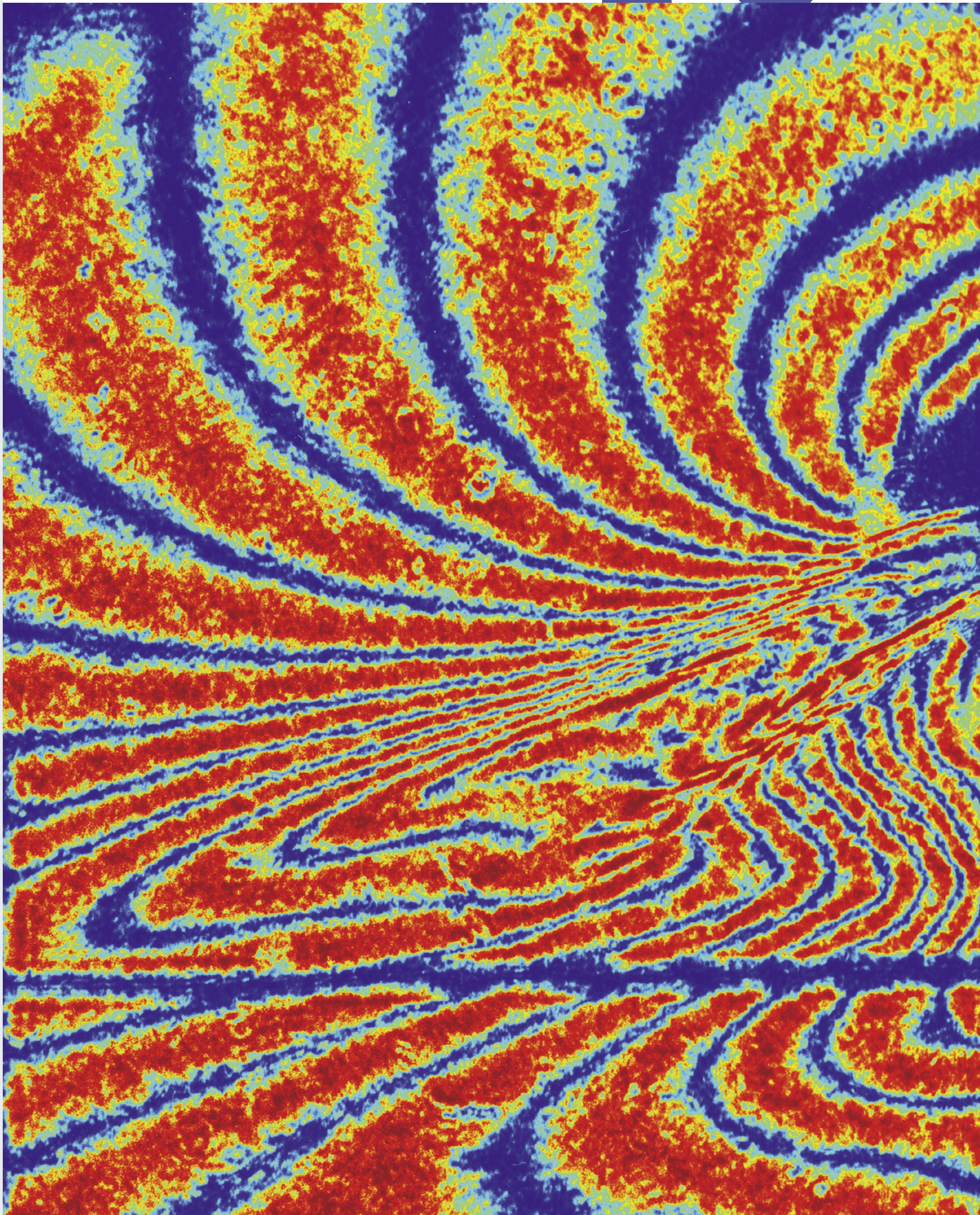

Knights of the Middle Ages fought their battles on horseback with lances and swords, as do these 11th-century knights storming the city of Antioch during the First Crusade. This manuscript of the *Conquest of the Holy Land* comes, however, from the 14th century, when this type of warfare, as well as the Middle Ages themselves, was drawing to a conclusion. An article beginning on page 8 discusses what actually defines the Middle Ages, when they began and when they ended, and why we should care. (Scala/Art Resource, NY)

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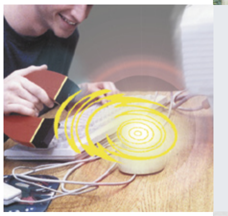
ENGINEERING AND SCIENCE
E&S

Volume LXIII, Number 2, 2000



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On the cover: This work of abstract art is really a false-color, high-speed photograph, using a technique called dynamic photoelasticity, of a metal-polymer composite splitting apart at the seam between the two materials. The crack is moving along the right edge of the page from bottom to top. (The technique works best with transparent solids, so only the polymer is shown.) For more breaking news, see the story beginning on page 30.

Engineering & Science (ISSN 0013-7812) is published quarterly at the California Institute of Technology, 1200 East California Boulevard, Pasadena, CA 91125. Annual subscription $10.00 domestic, $20.00 foreign air mail; single copies $3.00. Send subscriptions to Caltech 1-71, Pasadena, CA 91125. Third class postage paid at Pasadena, CA. All rights reserved. Reproduction of material contained herein forbidden without authorization. © 2000, California Institute of Technology. Published by Caltech and the Alumni Association. Telephone: 626-395-3630.

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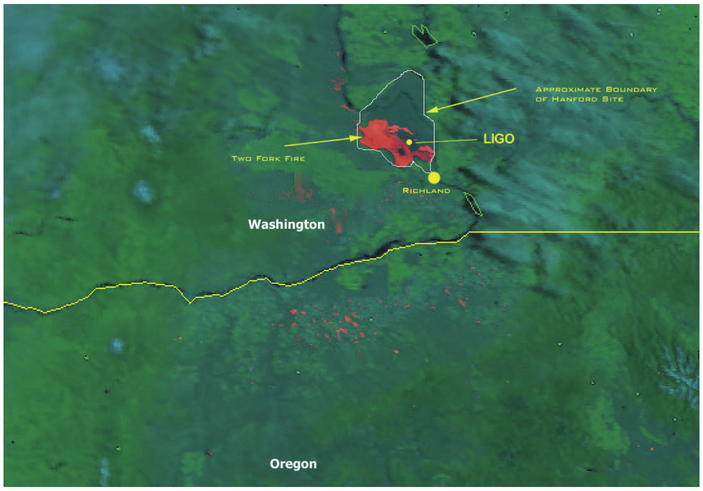
I SURVIVED THE HANFORD FIRE



Above: The heat signature (red) generated by the fire dominates this image taken by the National Oceanic and Atmospheric Administration on June 29. The tiny red spots near the Washington–Oregon border are caused by sunlight.

Below: In this 90-degree, postfire panorama, shot from an overpass on the Y arm near the corner station, the burn area and the red-orange fire-retardant residue are clearly seen. Sharp-eyed readers will also spot an elk in front of the clump of sagebrush near the intersection of the dirt roads.

Well, they haven't printed up commemorative T-shirts yet, but the LIGO Hanford Observatory has passed an unscheduled facilities test. On Tuesday, June 27, a brush fire was sparked by a fatal head-on collision on rural State Route 24 in the western reaches of the Department of Energy's Hanford site in eastern Washington. High winds and low humidity gave firefighters a run for their money, and before the fast-moving fire was finally controlled five days and 163,884 acres later, it had burned 11 houses and a number of other buildings. It also swept over the concrete and steel structures of the Laser Interferometer Gravitational-Wave Observatory (LIGO).

LIGO, a joint project of Caltech and MIT funded by the National Science Foundation, seeks to verify the last of Einstein's predictions that remains unproven—the existence of ripples in the fabric of space-time caused by colliding black holes, exploding supernovas, and other massive, violent cataclysms. (See *E&S*, 1998, No. 2.) The observatory, and its twin in Louisiana, consists of two two-and-a-half-mile-long arms joined in an L. Running the length of each arm (called the X and Y arms, since they aren't oriented north–south, east–west) is a four-foot-diameter stainless-steel pipe containing a laser beam. The pipes are the world's largest vacuum system, and protect the lasers and mirrors from being jostled by stray air molecules. The pipe, in turn, is shielded by a six-inch-thick concrete shell—in essence a long, long culvert. Buildings housing

vacuum chambers two stories tall straddle the midpoints and far ends of the pipes; a larger building where the pipes join houses the rest of the interferometery equipment as well as offices and workshops. The observatories are slated to become operational in 2002.

The view from the corner-station roof Wednesday night.

Fred Raab, the head of the LIGO Hanford Observatory, gave a play-by-play account of the fire in an e-mail back to campus:

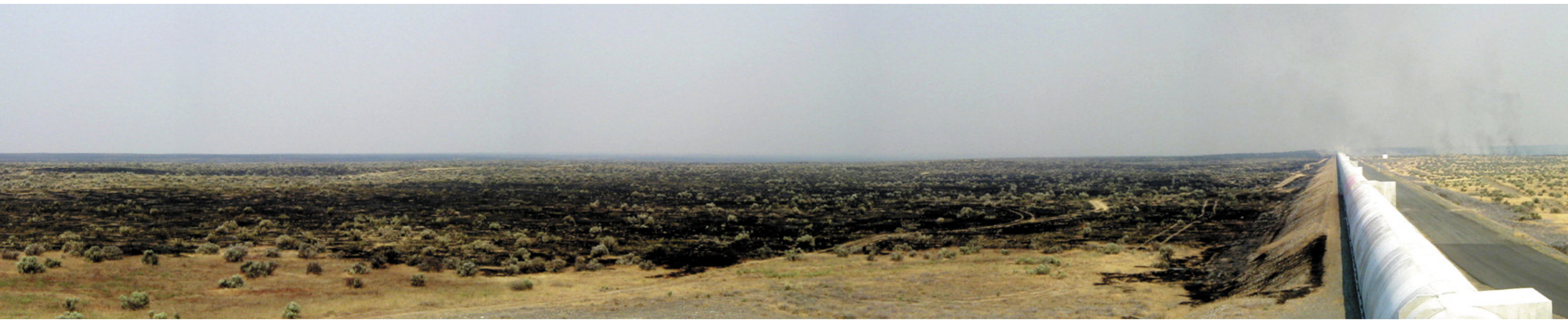
"At 6 p.m. [Wednesday], with the fire still about 10 miles west of LIGO and heading northerly I went home [to the nearby city of Richland] for dinner. Sometime after 7 p.m. I noticed the sky grow ominously dark.... Richard McCarthy and I learned through Hanford emergency personnel that the fire was racing toward LIGO. Richard called the lab to tell the people working inside, and a touring Boy Scout group, to evacuate the site. I drove in to ensure that all personnel were out and Richard followed shortly to actuate our groundwater pumps and valves to recharge our fire-water tanks.

"I found the site evacuated, except for Doug Cook, our laser-safety officer, who had just completed a walk-through of all the labs and assured me that all personnel and visitors were gone. Hanford Fire had set up a command post on the site, with a large number of fire engines, earth-moving equipment attempting to trench firebreaks around the 10-mile perimeter of LIGO, and aircraft dropping fire retardant.... By this time the winds had grown extremely strong [gusts of up to 30 miles per hour were reported] with a wildfire out of control and bearing down on the observatory. For a time, the Y arm of LIGO served as a firebreak, but the winds eventually blew the fire over the arm.... The fire started racing along the Y arm past the mid and end stations.... I was able to inspect the site from the platform on the corner-station roof and could see a line of fire advancing toward the X arm, but then a wall of smoke and high winds drove me off the roof.... By this time I could see fire extending several miles to the east, about 15 miles to the west, about 10 miles south and ascending Rattlesnake Mountain. The corner station was about the safest haven around, so we remained there.

"As the fire [burned] away from the corner station, the firefighters rapidly left our site. I later found out that this was when the fire jumped the Yakima River and headed for populated areas of West Richland and Benton City, which were under evacuation orders. We remained, predominantly at the corner station, inspecting fire conditions with binoculars as the fire burned along the X arm toward the end station."

In between wind shifts, they were able to drive the full distance along both arms and found no obvious damage to the concrete culvert or the buildings.

"By morning the fire was mostly contained on the Hanford site, but was burning near populated areas.... According to radio reports, about 500–1,000 firefighters were on the fire, which had by now burned about 150 square miles of land. We instructed staff to remain at home while a few of us drove out to do an inspection under daylight conditions.... [We found that a] power surge around midnight had taken down our turbo pumps (without any danger to the vacuum system).... The X end station was partially covered with fire-retardant compound, whose sticky surface had a layer of ash glued onto it. I think the worst damage we may have is if the fire retardant damages the underlying paint.... The ventilation systems prevented smoke damage within the critical experimental areas



although there is a slight smoke smell and dust levels were exceeded.... None of the critical optics were exposed. Vacuum system operation has been restored to normal.

"The DOE contractors, especially Hanford Fire and Hanford Patrol, were exemplary in their efforts to keep us informed, to let key people into the affected areas while providing for public safety, and most importantly to bring tremendous resources to bear on protecting our structures."

The wide gravel foundation on which the arms are emplaced, coupled with LIGO's assiduous tumbleweed-removal program (the fool things pile up against the beam tubes with astonishing rapidity) also helped the observatory sail through what could have been a very nasty mishap indeed. The fire retardant was washed off the X end station without incident, although it doesn't seem to want to come off the concrete culvert housing the beam line. Meanwhile, the commissioning and installation work is back on schedule.

"As fires go, this one was spectacular but it was really no big deal compared to Southern California wildfires," Assistant Engineer Tom Mahood says. "The dry grass burned so rapidly it didn't have a chance to do any serious damage. This time next year, you won't even know it burned." ☐—*DS*

ART ERUPTS ACROSS CAMPUS

Right: Physics and geophysics major Wren Montgomery's Ditch Day stack set in stone an already worn path through a bit of garden between Avery House and the rest of campus. The mosaic is not literally "stone," but crockery shards from each of the seven undergraduate houses and Avery, plus bits of tile.

Above: Welded out of copper triangles by Nate Austin, a Blacker House sophomore majoring in engineering and applied science, these dolphins leaped over the Millikan Pond bridge for a few weeks in May and early June. (Someone climbing on the scaffolding caused their demise.) Physicist David Goodstein, the Gilloon Distinguished Teaching and Service Professor and vice provost, remarked: "One morning these three beautiful dolphins appeared, as if to remind us of the endless creativity of Caltech students. What a great place to work!"

An installation called *Primordium: Leafy, Superman and Flo10* (names of plant mutations) by Los Angeles artist Marcos Lutyens opened at Caltech's outdoor art space July 22. Touching the (live) cactus triggers the recorded musings of subjects hypnotized by the artist and asked to describe their first memory of a plant. Here Institute Professor of Chemistry, Emeritus, Jack Roberts (right) and his wife, Edith, test it out, along with an unidentified visitor—who was later hypnotized as part of the show.

WORMBASE: ANOTHER SEQUENCED GENOME

In a major follow-up to the sequencing of the human genome, Caltech has received a $1-million grant from the National Institutes of Health for a genome database to aid in biomedical research as well as basic biology.

Known as the Worm Genome Database, or simply "WormBase," the project will link the already-completed genome sequence of the experimental organism *C. elegans* to the functions that the genes perform, says Caltech biology professor Paul Sternberg, leader of the project. Also, the information in WormBase will contribute to advances in understanding how the genes of all animals are related so that underlying genetic interactions can perhaps be exploited for future treatments of human disease.

More commonly known as a roundworm or nematode, *C. elegans* has a genome that comprises about 19,000 genes. As a consequence of evolution, the roundworm shares a huge number of genes with human beings—as do all other organisms on Earth, including plants.

The reason this fundamental relationship will be important to 21st-century medicine is that these commonly shared genes, or homologs, often have the same functions in their respective organisms. In Sternberg's own lab, for example, researchers found that several genes that control what cells do during the

development of the worm are worm versions of human genes that mutate to cause cancer.

This finding has two implications, Sternberg says. Genes that work together in the worm are likely to work together in the human, and the normal function of "oncogenes" is to control normal cell behavior, not to cause disease.

Thus, improved knowledge of the roundworm at the molecular level could lead to new and improved approaches for dealing with human disease, or even result in a cure.

And as a side benefit, Sternberg says, knowing the differences between ourselves and a roundworm could lead to new approaches to eradicating the creature, which is an agricultural nuisance.

"I think one of the important things about WormBase is that it will lead to new ways to study basic mechanisms," says Sternberg, adding that the sequencing of several other experimental organisms will be important for the same reason. Among the other organisms are the laboratory mouse, the mustardlike flowering plant *Arabidopsis*, the fruit fly, and the yeast cell.

"We could see patterns emerge from information in different organisms," Sternberg says. "Now that we have the human genome, we can start asking what a certain gene does in humans, what the homolog does in yeast, or fruit flies, or worms, and what's the common denominator."

WormBase's more immediate goals will be to make the genetic information more computer-accessible to anyone interested, Sternberg says. "The standard of success would be that the bench researcher could get within a minute or two the relevant data for his or her own research, rather than go to the library and pore for hours or days through reading material."

WormBase will continue an existing database developed by Richard Durbin of the Sanger Centre in the United Kingdom, one of two centers that sequenced the worm genome; Jean Theirry-Mieg, now at the National Center for Biological Information; and Lincoln Stein of the Cold Spring Harbor Laboratory. These researchers will remain involved, Sternberg says, as will John Spieth of the Genome Sequencing Center at Washington University in St. Louis, the other sequencing center.

The new phase of the work will involve biologists in curating new data, including cell function in development, behavior, and physiology; gene expression at a cellular level; and gene interactions—in much the same manner that the Human Genome Project will continue now that the genome itself has been completely sequenced. The National Human Genome Research Institute, which is funding this project, also supports databases of other intensively studied laboratory organisms. ☐
—*RT*

KIP, AHOY!

Kip Thorne turned 60 on June 1. Thorne, BS '62, the Feynman Professor of Theoretical Physics, has been a fixture on campus for most of his adult life. (He did tear himself away long enough to get a PhD from Princeton, but even then he didn't linger; he hustled it out in a very brisk three years.) So, of course, Caltech threw him a party—a three-day KipFest, in fact, featuring two days of technical sessions by a parade of heavy hitters from physics, math, and astronomy. Of the 14 speakers, 9 were alumni, several of them Kip's former students. Among the speakers were Rainer Weiss of MIT, Carlton Caves (PhD '79) of the University of New Mexico, and James Hartle (PhD '64) of UC Santa Barbara's Institute for Theoretical Physics.

The talks were part serious science and part roast. For example, Clifford Will (PhD '71), now at Washington University in St. Louis, said he had "backed into Thorne's group when, registered for Astronomy 105, I discovered to my horror that the class involved experiments at night." He quickly dropped that course and signed up for Thorne's relativity class. Those were exciting times, he reminisced, as new experimental tests of Einstein's theory of general relativity were just being designed. He quoted Thorne's tag line from that period: "On Mondays, Wednesdays, and Fridays, we believe in general relativity; on Tuesdays, Thursdays, and Saturdays, we believe the Brans-Dicke theory of gravity; on Sundays we go to the beach." Will concluded with a transparency of a passage of "bad poetry Kip wrote me for my 30th birthday; and in this audience, I can't show you the last stanza."

The serious science drew from several fields on which Thorne has left his mark. Among these are black holes, neutron stars, wormholes, quantum cosmology, gravitational physics, and experimental relativity—the latter focusing primarily on gravitational waves. A lot was said about LIGO, of which Thorne is one of the fathers. Panelists praised

Thorne for working tirelessly on many levels for several decades to get it built, and there was a general feeling that this entirely new way of seeing the universe will be his greatest legacy.

The symposium was followed on Saturday by a day's worth of lighter, Watson-lecture-type talks aimed at the general public. The all-star lineup here included bestselling authors Stephen Hawking, Thorne's sometime betting partner; Alan Lightman (MS '73, PhD '74); Timothy Ferris; and Thorne himself. A book based on these talks is slated to be published by W. W. Norton. The program ended with a family-oriented musical performance by Lynda Williams, the "Physics Chanteuse," who by day is a physics instructor at San Francisco State. □

> "On Mondays, Wednesdays, and Fridays, we believe in general relativity; on Tuesdays, Thursdays, and Saturdays, we believe the Brans-Dicke theory of gravity; on Sundays we go to the beach."

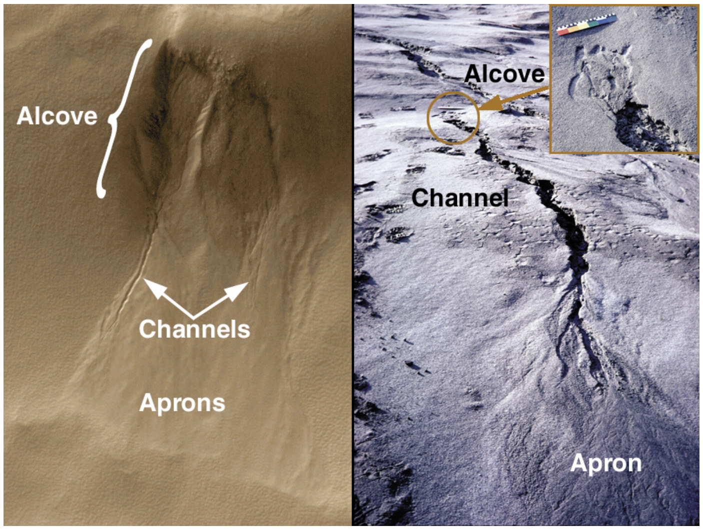
Above: Thorne (left) and fellow faculty member and physicist David Goodstein relish a zinger.

WHEN THE LEVEE BREAKS

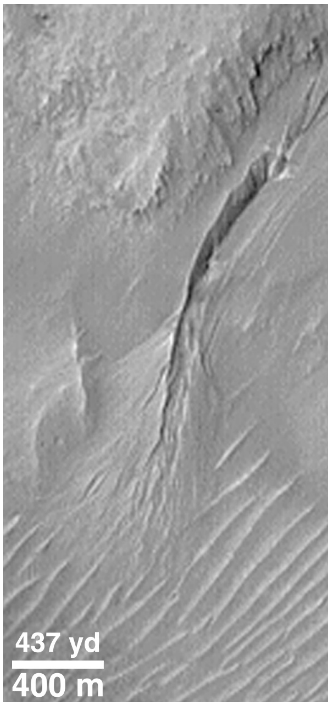
Mars just seems to get wetter and wetter every time you turn around. A paper by Michael Malin (PhD '76) and Kenneth Edgett in the June 30 issue of *Science*, and announced at a press conference on June 22, says that images from the Mars Orbiter Camera on JPL's Mars Global Surveyor show signs that liquid water may lie very close to the Martian surface in some places. "We see features that look like gullies formed by flowing water and the deposits of soil and rocks transported by these flows. The features appear to be so young that they might be forming today. We think we are seeing evidence of a groundwater supply, similar to an aquifer," said Malin, who is principal investigator for the Mars Orbiter Camera and president of Malin Space Science Systems in San Diego.

The gullies are seen on cliff faces, usually on the less-sunlit wall of the crater or valley in which they are found, and begin at a depth of about 100 to 400 meters from the top of the cliff—the depth at which the water is presumed to be trapped. All of them have the same general form, which resembles gullies on Earth where water emerges from beneath a layer of loosely consolidated rock or soil. A collapse zone, called an "alcove," is seen just above where the water is presumed to be seeping out of the Martian rock. (On Earth, such alcoves are formed as the emerging water erodes the aquifer that is carrying it back into the cliff face, eventually causing the material above the aquifer to collapse into the void.) The alcove leads to a channel that in turn ends in an "apron" of accumulated debris washed down the channel.

Not only does this imply that significant volumes of liquid water may exist much closer to the surface than anyone had believed, the kicker is that the features appear to be so young that the water may still be there. The most persuasive evidence offered was an image that showed a gully's debris apron partially covering a field of sand dunes. There are no



Right: Although the scale is different (note the footprints in the right-hand photo), the essential features are the same. The left-hand image is of the south-facing wall of an impact crater on Mars at approximately 54.8° S, 342.5° W and covers an area 1.3 kilometers wide by 2 kilometers long; the one on the right was taken by Malin on an ash field on the flanks of Mount St. Helens. The colored bar in the inset is 30 centimeters long. Below: This Martian dune field lies at the foot of a south-facing wall in the Nirgal Vallis near 29.4° S, 39.1° W.



craters on the dunes, so they are quite young, and the apron is on top of the dunes, so it must be even younger. It's not known for sure that these dunes are still active, but if they are, the apron would have to have been formed within the last few centuries. Said Malin, "They could be a few million years old, but we cannot rule out that some of them are so recent as to have formed yesterday."

Because the atmospheric pressure and surface temperature on Mars is so low, any water emerging from underground would immediately boil away or freeze before having a chance to flow downhill, so the thinking is that these channel-carving outbursts must have been flash floods. "When water evaporates, it cools the ground," said Edgett. "That would cause the water behind the initial seepage site to freeze. This would result in pressure building up behind an 'ice dam.' Ultimately, the dam would break and send a flood down the gully." The average water release per event is estimated to be about 2,500 cubic meters—enough to fill seven community-sized swimming pools.

The gullies are still quite rare, having been seen so far at only a few hundred sites among the many tens of thousands the orbiter has looked at. Most lie between 30 and 70 degrees south latitude, which on Earth roughly corresponds to the region between Sydney, Australia, and the Antarctic coast. □—*DS*

In other Mars news, on July 28 Edward Weiler, associate administrator for NASA's Office of Space Science, announced that JPL's Mars Rover concept was his choice from two mission options under study for the 2003 launch window. (The other option, proposed by Lockheed Martin Astronautics, of Denver, Colorado, was an orbiter featuring a camera capable of spotting objects 60 centimeters across—about the size of a footstool—as well as an imaging spectrometer designed to explore the role of ancient water in Martian history.) As *E&S* was going to press, NASA had decided to send *two* identical rovers to vastly different sites—perhaps one safer and one riskier—to be selected in the next couple of years.

These offspring of the Sojourner rover (see *E&S* 1997, No. 3) will land in January 2004 using the Mars Pathfinder's "drop, bounce, and roll" technology, but will be able to travel up to 100 meters per Martian day—nearly as far as Sojourner did over its entire lifetime. And this time around, the rovers will carry *all* of the science instruments, rather than having some on the lander and some on the rover. Consequently, the rovers will weigh about 150 kilograms (some 300 pounds) compared to Sojourner's 11.5 kilograms, and while Sojourner was about the size of a microwave oven, these babies will be more along the lines of a coffee table.

The robot geologist's tool kit will include a panoramic camera, three times sharper-eyed than Pathfinder's, and a miniature thermal-emission spectrometer, both to be mounted on a mast near the front of the rover. The rover will also carry magnetic targets that will collect magnetic dust for the various instruments to study. And a robotic arm that would make Inspector Gadget jealous will feature three more instruments plus an abrasion tool. The latter will grind away weathered rock surfaces to expose fresh material for scrutiny by a Mössbauer spectrometer, an improved version of Sojourner's alpha-proton X-ray spectrometer, and a microscopic imager. Cornell University will be the lead institution for the science payload, which—surprise!—is designed to search for evidence of liquid water in Mars's past. □—*DS*

The Middle Ages live on in popular culture today. The Black Knight, with most of his limbs still attached, fights it out with King Arthur in *Monty Python and the Holy Grail* (above left), a 1974 spoof of medieval romances, now a cult classic. (Courtesy of Python (Monty) Pictures, Ltd.) *Chant*, a recording of medieval church music, topped the charts in 1994. (Courtesy of Angel Records) Tourists visit the physical remains left by the Middle Ages not only in Europe but also in the United States. This late-12th-century cloister (right), from Saint-Guilhem-le-Désert in southern France, was transported and reerected intact at the Cloisters in Manhattan in the 20th century.

IMAGE NOT LICENSED FOR WEB USE

(The Metropolitan Museum of Art,
The Cloisters Collection, 1925.
(25.120.3-4)
Photograph © 1979
The Metropolitan Museum of Art)

If we look at movies, newspapers, and magazines, or on the Internet, we find that the Middle Ages are for us first and foremost an almost mythical time in Europe's distant past. "Middle Ages" means kings and queens, knights and castles, and glorious, unfettered, joyous violence.

What's "Middle" About the Middle Ages?

by Warren C. Brown

In 1986, the physicists Paul Ginsparg and Sheldon Glashow used the Middle Ages as a metaphor to express their concern with the way that string theory seemed to be increasingly divorced from verifiable reality. They charged string theory with being a kind of "medieval theology" that would undermine science itself: "For the first time since the Dark Ages, we can see how our noble search may end up with faith replacing science once again."

Ginsparg and Glashow's comments reflect one of the more common popular images of the Middle Ages. From a modern perspective, the term "medieval" frequently connotes either religion carried to the point of superstition or religious and intellectual intolerance: the Inquisition, faith smothering reason, and Joan of Arc burning at the stake. In other words, the adjective "medieval" is often used to represent the antithesis of our post-Enlightenment/post-scientific-revolution way of viewing the world.

American popular culture contains other images of the Middle Ages as well. If we look at movies, newspapers, and magazines, or on the Internet, we find that the Middle Ages are for us first and foremost an almost mythical time in Europe's distant past. "Middle Ages" means kings and queens, knights and castles, and glorious, unfettered, joyous violence. It means dragons, damsels in distress. It means oppressed peasant serfs, exploited by their rapacious lords. The Middle Ages have inspired not only movie-makers, but also legions of historical reenacters and war gamers who have turned to medieval history and mythology in search of a simpler and more direct world with fewer rules than, or perhaps rules different from, our own.

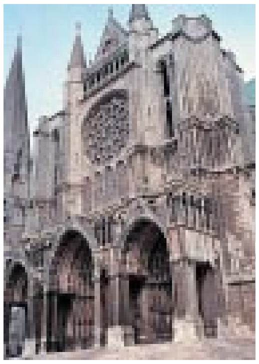
As I indicated above, there is, of course, also a strong religious component to the popular idea of the Middle Ages. "Middle Ages" means Christian churches, Christian monks. Popular destinations for tourists interested in the period include not only castles but also great cathedrals and monasteries—and not just in Europe, but sometimes moved to this continent, like the pieces of various monasteries incorporated into the Cloisters in Manhattan.

But what *were* the Middle Ages, really, and what was "middle" about them?

To answer this question, we need to get away from popular conceptions and preconceptions and look at what the term "Middle Ages" actually means. Literally, it means a set of times that lies between other times. The question then becomes: which times are they, and what times do they lie between? To find out, we need to look at where the term originated and what it was first used for.

The term first started appearing in Europe in the mid 15th century, a period when European intellectuals were beginning to feel that their world was somehow different from the world that had come before it. This sense of difference translated into a sense of revival or "renaissance"; that is, a sense that European civilization was recovering from something. These early-modern intellectuals measured that recovery by a set of even older standards: the intellectual, political, and artistic glories of classical Rome. They used the term "middle age" to describe the period between classical antiquity and their own present, which they sought to connect to classical antiquity—that is, to refer to the in-between "not antiquity." The term was, therefore, not flattering. "Middle" used in this way meant not only "between" but also "lesser."

By the 18th century, European historians were using "middle age" to label a discrete historical period from roughly the 4th through the mid 15th century. This "time in between" was like a dark valley between two shining hills, hence the corresponding term "Dark Ages." In the view of these historians, in the late 4th and the 5th centuries barbarian hordes (most visibly Goths and Vandals) swept across the Western Roman Empire.



Early-modern historians considered the ornate gothic architecture (right: Chartres Cathedral) and script of the Middle Ages "barbaric"—an unfortunate departure from the purity of classical Roman forms.

These barbarians destroyed ancient civilization; they wiped out ancient learning, art, and architecture. While Roman civilization survived for many more centuries in the Eastern Roman, or Byzantine, Empire centered in Constantinople, civilization in western Europe reverted to a rudimentary level. The only light flickering in the darkness was kept alive by monks working desperately in remote monasteries to salvage what they could of the wreckage.

The cultural handiwork of the Middle Ages was seen accordingly as "barbaric" in comparison to the things Rome had produced. For example, medieval buildings were much too ornate and complicated; medieval handwriting was equally incomprehensible. These things had to have come from the barbarians, hence the terms "gothic" architecture and "gothic" script.

Attitudes toward the Middle Ages among historians have improved since then, but the sense that the period was different, unique, even "middle," has remained. Looked at from the eyes of modern medieval historians, then: what is "middle" about the Middle Ages?

First I must issue a disclaimer: what I'm presenting here is *my* Middle Ages. The picture I will lay out for you here is shaped by my training and by the questions that interest me. It is also shaped by my interaction with my professional colleagues and with my students—who have helped me to understand just what it is that I study. Someone else might present a very different picture. Due to the limits of space, my picture will also be incomplete; I could write an entirely new essay from the things I have had to leave out. Nevertheless, I want to use the space I do have to suggest some particular points that might help us understand what makes this time worth studying.

The story undeniably starts with the end of the classical world. The Roman world was profoundly Mediterranean. Plato's famous comment about the ancient Greeks that they lived on the shores of the Mediterranean like "frogs about a marsh" applied equally well to most of Roman civilization. The Roman Empire would remain to its dying breath a loose aggregate of independent city-states, most of which were grouped around the shores of the sea that the Romans proudly called *mare nostrum*—our sea.

Roman society was also polytheistic, marked by a bewildering array of religious cults of various shapes and sizes that Roman governments cheerfully tolerated as long as they didn't interfere with the established state pantheon of gods.

Historians are now divided about when the Roman world came to an end. One of the hottest new areas of research in the last few decades has concerned how to define the end of antiquity and the beginning of the Middle Ages. The problem is that the lines are blurred. Change happened at different rates in different arenas. If we focus on any one point in time we see both signs of the future and signs of the past.

For example: is the dividing line Christianity? Not to the Roman emperor Constantine, who legalized and promoted Christianity at the beginning of the 4th century and who oversaw the Council of Nicaea in 325, which promulgated the statement of belief, or creed, that is still the central statement of faith for Christian churches.

The Roman Empire in the 3rd century stretched northward as far as Britain, southward into North Africa, and eastward into Asia, but its center remained the Mediterranean Sea.

During the 4th and 5th centuries, barbarian peoples gradually infiltrated the western Mediterranean lands and established their own kingdoms. The Byzantine Empire succeeded what was left of the Roman Empire in the east, while in the west, Roman and barbarian governments and cultures became inextricably fused.

Neither the Christian Constantine (top), who ruled as emperor in the 4th century and moved his capital eastward, nor Romulus Augustulus (bottom), who was deposed by barbarians in 476, was responsible for the "fall" of the Roman Empire.

Constantine was Roman. He acted in the best interests of the Empire as he saw them in promoting a youthful and vigorous religion that could help him unite a polity that had been battered by invasion and civil war for most of the previous century.

Or is the dividing line economic or social, perhaps marked by transition from gangs of slaves working huge plantations to quasi-free or unfree serfs working their own fields and paying dues of produce or labor to their lords? Again, it's not easy to say. Clear antecedents of medieval serfdom were already visible in the Roman world by the end of the 3rd century.

Perhaps the greatest example of the difficulty is pinning down the "fall" of the Roman Empire itself. Recent research on late antiquity has contributed the recognition that the Roman Empire did not so much fall as become gradually transformed out of existence. Most textbooks give the date of the fall as 476. In this year, the last "legitimate" western Roman emperor, Romulus Augustulus, was deposed by a barbarian military commander. A leading scholar of the period, however, has characterized this as the greatest nonevent in western history. The deposition of Romulus Augustulus is now understood as entirely typical late-Roman power politics in a world where barbarian and Roman had become irreversibly blended. This was a world in which Germanic barbarians had served as Roman soldiers and even generals for centuries; a world in which Roman emperors freely used entire barbarian peoples as armies to make up for a shortage of army recruits. Many contemporaries hardly noticed the event that now looms so large in history books. To them it looked simply like a coup d'état by a Romanized barbarian general, similar to countless others carried out over the preceding centuries by Romanized barbarians or barbarized Romans.

Nevertheless, with hindsight we can see that a critical transformation was taking place. By 500 political competition no longer focused on control of the imperial office itself, but rather on carving out local or regional spheres of domination within the western territory that had formerly been under direct imperial rule.

What followed was a long period of what historians now call "sub-Roman" society. Traditions of classical aristocratic culture and lay Latin education continued in the West. Descendants of Roman soldiers still occupied the bases and used the weapons of their great-grandfathers. Barbarian kings still nursed Roman titles that their forefathers had borne in Roman service; they issued law codes drawn up by Roman legal experts and still paid lip service to the eastern emperor in Constantinople.

These continuities, however, existed side by side with profound change. For example, in the classical empire, a local aristocratic bigwig would have shown his wealth and power by serving on his town council, by promoting the political careers of promising young men, and by building lots of great secular buildings with his name on them. In the sub-Roman world, a local aristocrat (probably of mixed Roman and barbarian heritage) exercised the same kind of power over local affairs, but as a Christian bishop building churches or monasteries. This sub-Roman local aristocrat could also be female. Christianity opened the doors wide for aristocratic women, through their patronage of churches and monasteries, to wield considerable influence on a local or regional scale, or even on the scale of a kingdom.

One of the most important changes that took place was the separation of western Roman society from its southern half. Starting in the 7th century, Islamic troops spread out from Arabia into the Mediterranean basin. By 711, they had overrun North Africa and jumped across the Straits of Gibraltar into Spain. These Islamic conquests helped shift the center of gravity of European civilization to the north and west.

So when do we finally get to the Middle Ages? My personal favorite as a symbolic date for the end of sub-Roman late antiquity and the arrival of something really different is Christmas Day of the year 800. On that day, Charlemagne, a Frank—that is, a descendant of the barbarian group that had taken over the rule of Roman Gaul—was crowned emperor of a revived Western Roman Empire.

Yet this new western empire was not really Roman. It was clearly European; its center of gravity was *not* the Mediterranean. Moreover, Charlemagne's empire (which historians now call the Carolingian Empire, from Charlemagne's name in Latin—*Carolus*) had no bureaucracy or standing army as the old empire had. It was held together by ties of loyalty and self-interest binding emperor to aristocrats to local freemen. It was maintained by constant warfare carried out on a seasonal basis (almost like football season) by the emperor, the aristocrats and their armed followers, and levies of local freemen carrying out required military service.

Even more important was that fact that although Charlemagne was crowned emperor in Rome, the coronation was performed in a church, by a bishop of Rome, Pope Leo III. This act reflected Charlemagne's efforts to unify his empire by promoting a centralized western Christian church that looked to the papacy for spiritual authority—something very unlike the Christian churches of antiquity.

Charlemagne's empire was also held together by a common written culture based on a backward looking, revived classical Latin, which by this point was very different from spoken late-Latin vernaculars. Charlemagne and his successors promoted this written culture as a way to standardize and ensure the quality of religious training and to enable government and church officials to communicate over long distances in an empire that was a hodgepodge of different peoples, cultures, and legal traditions.

After the Islamic conquest of North Africa and Spain in the 7th and 8th centuries, Charlemagne consolidated his Western Roman Empire in the north in the 9th century. The orange area represents the mainly Frankish lands he started with; bluish green, the territories added before Charlemagne's death in 814; and greenish yellow, the tributary Slavic states. Although "Roman" in name, it was not centered around the Mediterranean; historians now refer to it as the Carolingian Empire.

So these are the things that make the Middle Ages "middle": a coherent Latin Christian civilization, centered in western and central Europe and distinct from the Islamic world and the Greek Christian Byzantine Empire. The written language of this civilization was Latin. The bonds between its members depended more on kinship, loyalty, and self-interest than on bureaucratic or contractual relationships. This "Latin West" as a visible civilization maintained its coherence even after Charlemagne's empire broke up in the mid 9th century.

Looking closely at the centuries that followed, it's possible to identify other things that made medieval civilization different from what came before and what came after. In particular, we find things living comfortably together that people in modern western societies might consider mutually exclusive. For example, the natural world and the supernatural world were completely and organically intertwined. As far as medieval people were concerned, miracles happened. These two worlds intersected in saints—that is, holy men and women—and especially in their relics (bits and pieces of their physical remains or items that had once belonged to them). People prayed to saints as personified in relics, and expected in return protection or intercession with God, just as one expected one's earthly lord or patron to provide protection or intercede on one's behalf with a higher lord.

Saints' relics, accordingly, were given royal treatment; relic cases, or reliquaries, include some of the most ornate and beautiful works of art to survive the Middle Ages. Saints responded to this treatment with miracles. The most common ones were a direct reflection of much of Christ's activity in the New Testament: healing miracles. One example among innumerable others occurred in the early 13th century. Brother Paul of Venice, a member of the Dominican order of friars, wanted to testify in the canonization process of the order's founder, Dominic. Paul had such bad kidney pains, however, that he was afraid he could not. So he prayed at Dominic's tomb. Sure enough, his pains vanished and he was able to testify—and the miracle conveniently gave him something to testify about.

The supernatural world also communicated with the natural world through visions and voices. The following example demonstrates the huge gulf between the medieval world view and our own. A friend of mine served as a historical adviser on a recent TV movie about Joan of Arc, the 15th-century French peasant girl who claimed to hear voices telling her to go and rally the French to drive the English from France. My friend showed up at the first meeting with the heads of the project to find them still trying to sort out their script. The main question that they were strug-

The medieval mentality was dominated by the concept of right or truth; everyone had his own—and it frequently came into conflict with someone else's.

Voices, visions, and miracles were part of the "truth" in the Middle Ages. Joan of Arc (top, right; 15th century; Giraudon/Art Resource, NY) heard voices from God directing her to lead her countrymen against the English; and a grateful Saint Faith (her ornate jewelled reliquary is shown above) performed miracles after her relics were moved to a different church.

gling with was: how do we portray why Joan did what she did?

Among the possible explanations they had come up with were: 1) Joan wanted to prove that as a girl she could be powerful in a man's world; 2) she wanted to prove that a country girl could make it big on the national stage; and 3), my personal favorite, her father hadn't wanted a girl and had tried to abandon her to die when she was born, so Joan spent the rest of her life trying to prove to her father that she wasn't worthless. After the discussion had gone on for a while, my friend finally raised his hand and ventured: "Perhaps Joan heard voices, and, given the 15th-century perception that the divine world communicated through voices, she interpreted them as a sign from God that she should go help drive the English out of France." Their response was dismissive: "We're not interested in the God angle."

Similarly, the boundary between truth and fiction in the Middle Ages was not how we would understand it today. Medieval writers have bedeviled generations of medieval historians with documents and stories that to us often seem to be fantasies or outright lies. But they weren't lies. The medieval mentality was dominated by the concept of right or truth; everyone had his own—and it frequently came into conflict with someone else's. If the documentation to support what you knew to be true didn't exist, then you produced it, by altering old documents, by writing new ones, by writing down old orally transmitted legends, and so on, to document what you knew must have been because it was right that it was so.

This activity produced tales that from a modern perspective seem very strange. One staple of medieval literature, for example, is the so-called "translation story"—the story of how a particular saint's relics were moved, or "translated," from one place to another. A bald reading of many of these stories from a modern perspective would suggest that some monks wanted relics they didn't have, so they went out and stole them. But the storytellers told it differently: the saint sent out a vision that he or she (that is, his or her relics) was being mistreated. The monks went out and liberated the saint from prison and brought the relics back to where the saint really preferred to be—that is, to their monastery. The saint then showed his or her approval by performing a host of miracles.

One prominent example concerns St. Faith, a late-3rd-century Roman girl who was martyred for her Christian beliefs. Faith's relics spent most of the Middle Ages at the monastery church at Conques, in southern France. According to an 11th-century translation account, they came to Conques in the second half of the 9th century from the church at Agen, likewise in southern France. A monk from Conques went to Agen and signed up with the church community there as an ordinary priest. He spent the next 10 years gaining the trust of the community and finally a position as guardian of the church treasury (where the relics were kept). One night, finding himself alone in the church, he broke open St. Faith's tomb, took her body, and ran back to Conques. The monks of Conques rejoiced, and St. Faith showed her approval by performing a battery of miracles over the next few centuries that turned Conques into a major pilgrimage destination.

Despite stories like this, the Middle Ages were also a period when two other things that some might see as diametrically opposed, Roman Catholic Christianity and rationalist Greek philosophy, could live in harmony. It was the 13th-century theologian Thomas Aquinas who took the logic and natural philosophy of Aristotle, reintroduced into the West from the Islamic world, and reconciled it to revealed religion. Aquinas's basic assumption was that, since both reason and faith are God-given, they cannot contradict each other. Natural philosophy is therefore valid within its own sphere and can even help correct errors in the interpretation of scripture.

Perhaps the most striking contrast between medieval society and our own is that large segments of medieval society saw no contradiction between Christianity and violence. The dominant social class during much of the Middle Ages was the warrior aristocracy, which by the 12th century was labeling itself as knighthood. The knights' military and social power derived from their practice of heavily armed and armored warfare on horseback and their control of local fortifications—that is, castles. Knights saw their brand of warfare in and of itself as a religious vocation. Properly carried out, according to the rules, violence was work pleasing to God.

In medieval chivalric literature, such as the romances about Arthur and the Knights of the Round Table, the path to God is to be found through the use of violence to protect women and orphans, to uphold justice and right order (here's that passionately and partisanly held vision of "right" again), to uphold the Christian faith, and to display the military prowess on which social and political power ultimately depended.

What about dragons and damsels in distress? It is hard to say that there were dragons (although we do have medieval accounts of people having seen them), but there were certainly damsels in distress. One of the most famous knights of the 12th century, the Englishman William Marshall, as a young man got his start up the ladder that would lead to fame and a position as regent of England by trying to protect the Queen of England, the famous beauty Eleanor of Aquitaine, from ambush as she led an expedition to put down a rebellion in her continental territories. William got himself badly wounded and captured; a grateful Eleanor ransomed him and made him part of her own household.

Battles among the warrior aristocracy of the Middle Ages were fought on horseback with lances and swords, as portrayed in the scene below of William killing Harold at the Battle of Hastings (1066), from a 14th-century manuscript, *Decrees of Kings of Anglo-Saxon and Norman England.* (Art Resource, NY)

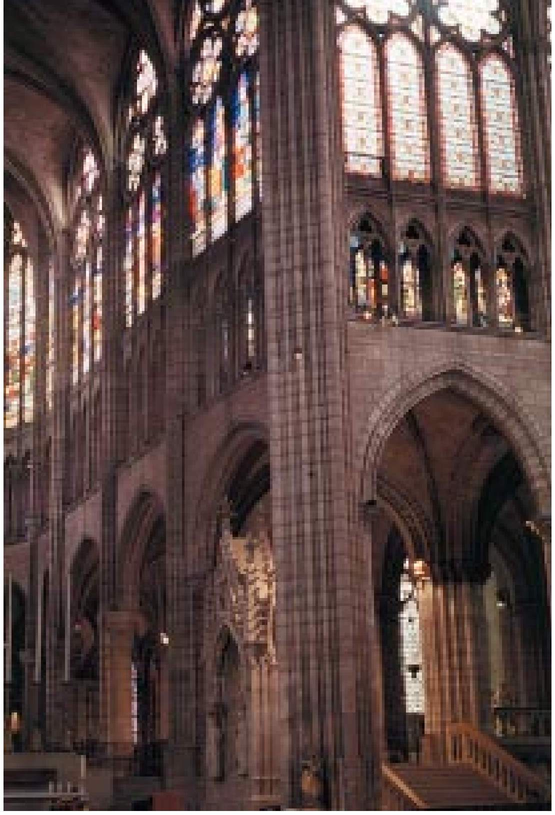
IMAGE NOT LICENSED FOR WEB USE

The church, of course, had some problems with a lot of knightly violence. Beginning in the 10th century in France, church councils tried to proclaim the "Peace of God"—a set of limitations on the use of violence whose basic upshot was: "You can bang each other on the head all you want, but leave peasants and merchants alone, as well as church property and churchmen" (as long as these were unarmed; according to extant Peace Council acts, armed clerics were apparently legitimate targets).

Yet the church and individual churchmen, who themselves generally came from the ranks of the warrior aristocracy, were not interested so much in shutting down violence as in using it to uphold their version of right order—especially as it concerned church interests and church property—and in channeling violence to achieve their aims. This especially held true if knights were attacking the enemies of Christendom. Hence the Crusades and the theme present in so much of chivalric literature that the knightly work most pleasing to God was killing Muslims or other heretics if you couldn't force them to convert or recant.

Despite all of these differences between the medieval world and our own, there are also things that look familiar to us. Above all, we see humanity just being humanity. For example, there was plenty of bigotry and persecution. During the First Crusade, which began in 1095–96, loosely organized gangs heading south down the Rhine River to join the Crusade massacred Jewish communities along the way, despite heroic efforts by some churchmen to save them. They murdered on the theory that if they were going off to kill the infidel, they might as well get the ones at home first.

Another example is the so-called "feudal anarchy," that is, lawless violence by unruly knights, that has long been seen as characteristic of early France, especially before the 12th century. Many medievalists now do not view knightly violence as anarchic at all, but rather as somewhat familiar. Knights seem often to have behaved like members of the modern Mafia, or like members of urban gangs. Although violence was a way of life, it was regulated and limited by ritual and custom, and by unstated rules of behavior about



Romanesque churches such as the one in Maria Laach in southern Germany (right) were characterized by solid walls and "Roman" arches supporting a round vaulted ceiling. Maria Laach was begun in the late 11th century, and its construction continued through the 12th. Meanwhile, in France, the load-bearing walls were being replaced by outside buttressing, freeing up space for glass and light. The monastery church of St. Denis, outside Paris (far right), built in the middle of the 12th century, is considered the first gothic church.

whom you could injure or kill and how. It was carried out less for the purpose of simple destruction than to send messages about honor, prowess, or relative power relationships between individuals and groups.

In other words, although knights lived by and for violence (and although they frequently took out innocent bystanders, such as peasants, in their efforts to get at each other), their behavior—like the Mafia's—nonetheless possessed an internal logic and order. This order enabled early French society to function and survive in a time of weak to nonexistent central authority. Scholars trying to understand knights have abandoned the assumption that the absence of a state-sponsored, law-based order means anarchy. Instead, they are looking for other kinds of social and political order and are finding insights by looking at urban gangs or at non-Western societies that operate on different principles than those we are conditioned to expect in modern Western states.

It's also important to recognize that, while other European languages, such as French and German, call this period "the Middle Age" (*le moyen âge*, *das Mittelalter*), the English language got it right: there were many "middle ages." We are talking about centuries in which changes took place every bit as profound as those that separate us from the United States of the late 19th century, or even the 1930s or 1960s. Students taking my early medieval history course (which covers the period from roughly 300 to 1000) go through the end of late antiquity, the development of the Frankish kingdoms, and the rise and disintegration of Charlemagne's empire, and are surprised that only at the end do we end up with knights and castles. A warrior aristocracy whose self-identity rested solely on mounted combat and who operated from small, fortified bases was the product of a particular historical moment within the broader Middle Ages: in the 10th century, the combination of weakening royal power in what was becoming France, and invasions by Vikings and others, placed a premium on local, heavily armed, and mobile military power.

We can also see changes over time in architecture. The architecture of the early Middle Ages (roughly through the 11th century) is called "Romanesque," meaning "like the Romans." In the 12th century, however, comes something really new. Between 1140 and 1150, Abbot Suger of the monastery of St. Denis outside Paris set out to restore his monastery's traditional role as guardian and promoter of the sacred image of the French kings. As part of this program, he built a new monastery church in a revolutionary architectural style, which is now seen as the first Gothic church. By the use of outside buttresses, walls were liberated from the need to bear loads and could become frames for huge windows that let light through stained glass into a space conceived of as a meeting place between the human and divine worlds.

Economic and political structures also underwent changes. Before the year 1000, European rulers could rule in a profoundly rural and agricultural world only by engaging the loyalty and self-interest of coalitions of warrior aristocrats. By the 12th century, however, the rulers of France and England, increasingly flush with money taxed from thriving commercial economies, were able to start slowly territorializing their power with paid bureaucrats and mercenaries. As a result, by the 14th century, we can see glimmerings in France and England of what we might term national states.

So how did the Middle Ages end? How did all these things transform into something else? The

If the defining image of the Middle Ages for many is the knight on horseback, operating from his castle, defeating opponents by charging at them with his lance, and holding tournaments and wooing ladies in his spare time, perhaps the Middle Ages could be said to have ended when the knight was no longer militarily or culturally dominant.

boundary at this end is just as fluid and difficult to pin down as at the beginning. Nevertheless, we can find some markers.

An obvious one is the Protestant Reformation. In October 1517, the theology professor Martin Luther nailed his 95 theses on the door of the castle church in the small German university town of Wittenberg. An attack on the sale of indulgences, this act set in motion a chain of events that brought a uniform Latin Christian church in Europe to an end. Yet Luther's challenge to the Roman church was the culmination of a long series of church reform movements visible from the 12th century on. Various heresies, as well as wandering preachers sworn to poverty such as the Franciscan Friars, tried to divorce the Roman church from its wealth and involvement in worldly affairs and reconnect it to the basic Christian message. The Roman church succeeded in either suppressing or absorbing such reform movements until the point when princes and kings ruling developing territorial states, or wealthy urban elites, found it to their advantage to support religious rebellion for their own purposes (for example, Luther owed his survival to the protection of Prince Frederick III of Saxony).

The gradual end of the Middle Ages is also visible in the slow decline of Latin as the dominant European written language. Written vernaculars had already appeared before the millennium; by the 12th century they were used in texts written for the entertainment of the aristocracy. The development of written vernaculars was driven above all, however, by businessmen, who needed to write the language they spoke in order to carry on commercial transactions and relationships. By the 14th century, a class of people had arisen literate in the vernacular, who wanted to read religious or historical texts that previously could have been written only in Latin (such as Dante's *Divine Comedy,* which the Florentine poet began around 1308).

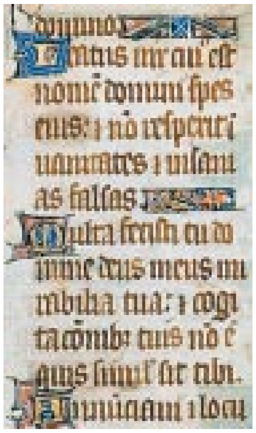
IMAGE NOT LICENSED FOR WEB USE

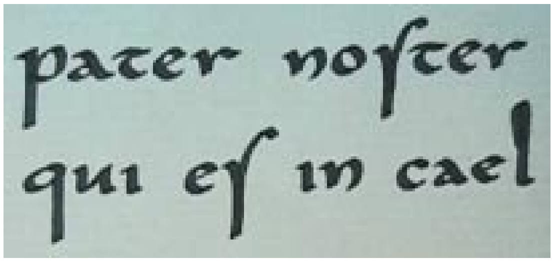
The Hundred Years War in the 14th and 15th centuries changed knightly warfare forever. English archers defeated French mounted knights, and cannon besieged the castles. (From Froissart's *Chronicles*; Giraudon/Art Resource, NY)

Hand in hand with both of these changes went the development of printing. Craftsmen such as Johannes Gutenberg in Mainz developed printing in the mid 15th century in response to the growing demand for books at ever-lower levels of society. This demand reflected not only increasingly widespread literacy but also the intellectual ferment and desire for religious knowledge that would lead to Martin Luther. Once printed books became available, a flood of Bibles, both in Latin and in vernacular translations, as well as religious tracts and pamphlets, helped spread Protestant ideas and arguments and left the religious and cultural landscape of Europe changed forever.

Perhaps the most poignant change came in the nature of warfare. If the defining image of the Middle Ages for many is the knight on horseback, operating from his castle, defeating opponents by charging at them with his lance, and holding tournaments and wooing ladies in his spare time, perhaps the Middle Ages could be said to have ended when the knight was no longer militarily or culturally dominant. The end was already in sight during the Hundred Years War between France and England, which occupied most of the 14th century and part of the 15th. At the Battle of Crécy (1346) a charge by the cream of French chivalry was broken up by an army of highly

The clearly readable alphabet of Carolingian minuscule (bottom), which is the basis of our modern letter forms, was supplanted for several centuries by florid gothic writing (top), until the 9th-century script was rediscovered by Renassiance scholars—who thought it Roman.





pater noſter
qui eſ in cael

trained English archers and foot soldiers. By the 15th century, gunpowder weapons were knocking down the walls of the knight's refuge—his castle. The French turned these weapons on the English in their successful effort to finally drive the English off the continent.

So perhaps another symbolic marker for the end of the Middle Ages (to place alongside Martin Luther in 1517) would be the fall of Constantinople in 1453, when the walls of the ancient East Roman capitol were breached by Turkish cannon. This event proved a huge psychological blow to western Europeans, because it removed the bulwark that had stood for centuries between western Christendom and Islam.

So why do we care? What do the Middle Ages matter to us? Why study them?

Well, for one thing, they're intrinsically interesting. Medieval history provides great hooks to get students engaged so I can teach them other things. For example, Caltech students, particularly males, seem to enjoy military technology and lots of carnage. Medieval sources provide these in abundance, so I can teach students how to approach history and historical sources while they're not looking.

All my students get caught up in the differences between medieval society and our own, in the things that seem to be incompatible to us but coexisted naturally in the Middle Ages. This makes the Middle Ages an excellent vehicle for driving home the idea that the past really is a foreign country—that there are many different ways that societies can function, many different ways of understanding the world, and that Western civilization has tried out a lot of them.

Another extremely important reason for studying the Middle Ages: that part of our collective identity that is European, and therefore our collective sense of who we are, has been shaped by the decisions of medieval people about what to preserve from their own past and how to preserve it. For example, much of classical literature and history—that is, works by Roman authors—was preserved by 9th-century copyists responding to an imperative from Charlemagne to preserve models of good Latin for education, as well as the most accurate texts of ancient Christian writings. To these copyists, and to their decisions about what to copy, we owe much of our picture of what classical antiquity looked like.

Finally, the Middle Ages are all around us. We can see this physically in Europe, of course, but we don't have to go there to appreciate the period's influence. Our language, for instance—modern English, both British and American—is a blend of old Anglo-Saxon with Danish imported into the British Isles by Vikings in the 10th century and with a French dialect brought into England by the Normans (themselves descendants of other Vikings) in the late 11th century.

One further interesting example illustrates how the Renaissance humanists utterly failed to appreciate the Middle Ages even when they were looking straight at it. In the 15th century, Italian intellectuals combed Europe for the oldest surviving texts of classical authors. They found that the oldest manuscripts were written not in the dense and obscure Gothic handwriting but in a remarkably clear and elegant script. Assuming that, since these were the oldest manuscripts, they must be the Roman originals, they copied the handwriting and named it Roman script. But it was not Roman. The manuscripts were late 8th- and 9th-century copies produced during the reign of Charlemagne and his immediate successors in the burst of copying mentioned above. The easily readable script was developed in the context of Charlemagne's effort to standardize and rationalize church education and the royal bureaucracy. Historians now call it "Carolingian minuscule." Because of how Carolingian script was understood and transmitted by the early modern period, it became the standard for modern letter forms. It is still called the "Roman" font, but most of our basic modern lowercase letter forms go back essentially to 9th-century Carolingian writing.

In short, we live, even here in the United States, amid all the other complex threads that combine to create the world we live in, surrounded by what medieval European society left behind. The lives of medieval people are all around us, like ghosts whose presence we are entirely unaware of. What they did, what they thought, what they wrote and built, are an important part of the streams of past experience that shape how we lead our own lives. They deserve not to be forgotten. □

Assistant Professor of History Warren Brown holds a BS in physics from Tufts (1985) and is also a graduate of the New England Conservatory with a major in French horn performance. After several years playing horn in Europe, Brown followed his own internal "voices," returned to the United States, and took up history as his profession. Brown earned his MA in history in 1993 from the University of Cincinnati and his PhD in medieval history from UCLA in 1997, the same year he joined the Caltech faculty. This article was adapted from his popular Seminar Day talk this past May. His own work focuses on an area he mentions only briefly here—knightly violence and the internal order of medieval societies.

PICTURE CREDITS:
10, 11, 12 — Bob Turring; 15 — Warren Brown

We're sorry we don't have a quantum computer to show you, but here (from left) Gillian Pierce; Brock Beauchamp, a junior in electrical and computer engineering; his mentor, James Arvo, associate professor of computer science; and John Preskill, professor of theoretical physics and mentor to Jacob West, a junior in physics, pose with Caltech's Center for Advanced Computing Research's Exemplar, the biggest machine Hewlett-Packard has yet built.

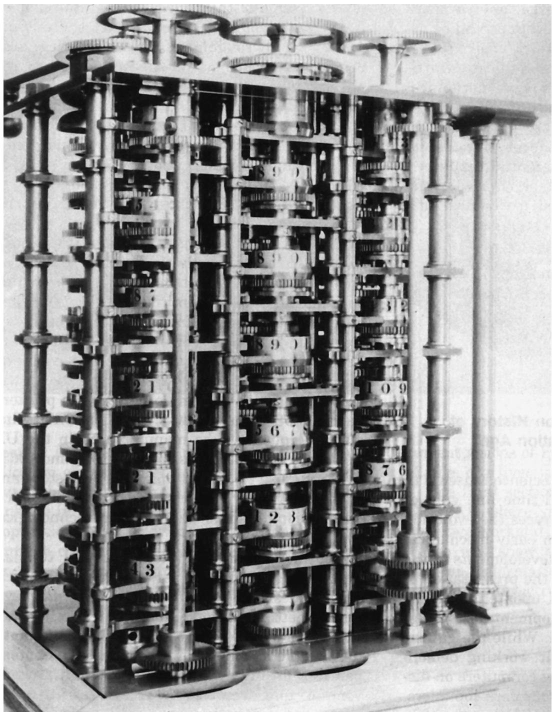
Who is going to be the next Carl Sagan? The next Stephen Jay Gould? This year, the Institute added a new course to the core curriculum: Core 1ab, Science Writing. To quote from the course's Web site, "Communicating scientific ideas is one of the most fundamental tasks that a scientist or engineer undertakes, and nonscientific audiences provide one of the most challenging groups to write for." During the two-quarter course, students write (and rewrite!) a 3,000-word essay on any topic in science, broadly defined. Since it's a writing course, not a lab course, they do not have to write about their own research but about any subject that appeals to them. This year's topics ranged from the history of science to flaviviruses, Fermat's Last Theorem, and the origin of the universe. The essays, according to program coordinator and editor Gillian Pierce, are supposed to be comparable to an article in Scientific American *or our own* E&S, *several of whose past stories were posted on the Web site as models.*

Science writing has been taught at other colleges, but never with so much faculty involvement. Each student picks a faculty mentor who is responsible for critiquing the essay's science content, while Pierce works on improving the writing. The faculty input adds an element of peer review to the process, making the course a good exercise for those students who will actually go on to publish academic papers.

*The course, which will be required of all undergrads next year, was offered this year as an option. Fifteen adventurous students signed up. All of their papers will be published in an on-line journal (*http://www.its.caltech.edu/~sciwrite/ejournalhome.htm*), but we thought you might like to see a couple of the best ones, as chosen by Pierce and the staff of* E&S. *What follows are two very different looks at a hot research topic. And for what some people at Caltech are doing, see the sidebar on page 29.*

The Dawn Of Quantum Computation

by Brock Beauchamp



The largest surviving portion of Charles Babbage's Difference Engine, built in 1832, is in the Science Museum, London. Photo from "The Science Museum, London History of Computing and the 'Information Age,'" by Doron Swade, in the *Annals of the History of Computing*, volume 10, number 4, page 316, 1989. Copyright © 1989 IEEE.

In what now seems to be the dawn of time, around 500 B.C., the Babylonians invented a primitive "computer"—the lowly abacus. Over two thousand years later, in A.D. 1614, Scotsman John Napier, the inventor of the logarithm, renewed the interest in creating more advanced mechanical computers. The most famous of these improbable devices was the Babbage Difference Engine, which was drafted as a steam-powered apparatus that could solve one fixed problem, using thousands of gears and dials. It would have done these calculations with 20-decimal-place accuracy, but it was a costly and unwieldy feat of engineering that eventually lost funding. Such was the fate of most mechanical computers, which history remembers as little more than novelties, albeit novelties with foresight. Computation did not truly come of age until machines powered by vacuum tubes appeared on the scene in the early 20th century. When these behemoths were scaled down by the advent of the transistor in 1947, computational power that was once restricted to testing theories behind the H-bomb was available to the masses.

Today's computers are certainly faster than their predecessors, but they share many of the same inherent weaknesses. For example, they are stymied by the significant problem of factoring large numbers. Using the best algorithm to date, the number-field sieve, one can factor a 130-digit number in a little more than a month. However, factoring a 260-digit number, just twice the length, would require over a million years on the same computer! Clearly, an entirely different kind of tool is needed to solve such difficult problems, and many hope the quantum computer will be just that panacea.

THE CHALLENGE AND THE NEW CONTENDER

In order to better appreciate these challenges, an understanding of computational complexity is helpful. To better systematize the difficulty of problems, they are often sorted into complexity classes. The gauge for complexity is how many steps it takes to solve a problem (the number of steps often being loosely called "time") with respect to the length of the input. Computer scientists are typically concerned with asymptotic complexity—that is, complexity as the size of the input grows very large. Using this criteria, many problems have been deemed intractable, meaning that any algorithm able to solve the problem has a prohibitive asymptotic complexity. (It is possible that there is some feasible way to approach "intractable" problems, but the evidence to date strongly suggests that the difficulty of these problems is unassailable.) In other words, making the problem just a little longer makes it considerably harder to solve. These "hard" problems are theoretically solvable on a computer, but quickly become impractical. For example, suppose that a company wanted to find the shortest route between all its regional offices. If there were 40 offices, If entanglement gives the quantum computer its voice, it is quantum parallelism that gives it its muscle.

a computer would have to examine 40!, or 40 × 39 × ⋯ × 1, which is approximately equal to 10^{45} different routes (that's a 1 followed by 45 zeroes), by first choosing one of the 40 offices, then one of the remaining 39, and so forth. Using current projections, the sun will supernova long before any computer could finish checking all of these possibilities! It seems as though there could not be a harder problem; however, there are well-formed problems that are uncomputable on any machine. The classic example is the halting problem: no program can be written that can tell whether or not any given program will eventually stop and return a value.

What new ammunition does quantum computation have to combat these difficulties? For one thing, quantum systems deal with information in an entirely different way. All information is represented in terms of an elementary unit called the qubit (short for "quantum bit," denoted in Dirac notation by "$|\phi>$"). Qubits, which have no classical analog, exhibit a sort of quantum indeterminacy: the qubit is not in *any* state in particular until it is tested, after which it has a definite state. Because nature is ordered according to these quantum principles, each qubit is a complete representation of the system it represents, without any extraneous data. Information scientists are wont to describe such properties in the context of a fictitious conversation between Alice and Bob, so we will not break tradition here. In the classical scenario, Alice would look at her information and write, "Dear Bob, I have the state $|0>$. Sincerely, Alice." Or, if it were a physical bit of information, she could simply make a copy and send it over to Bob. However, she cannot do this in a quantum information system. In the first case, Alice cannot simply measure her qubit and send the results as she did in the classical case. She might test her qubit $|\phi>$, and in doing so force it into state $|0>$, but she would not be sending *all* the information contained in the multiple states that were initially in $|\phi>$. Second, it has been proven that it is physically impossible to clone a qubit while leaving the original untouched. This means that Alice cannot simply copy her qubit and send the copy to Bob. This leads to a very important result: the information contained in a qubit cannot be transmitted without sending the qubit itself.

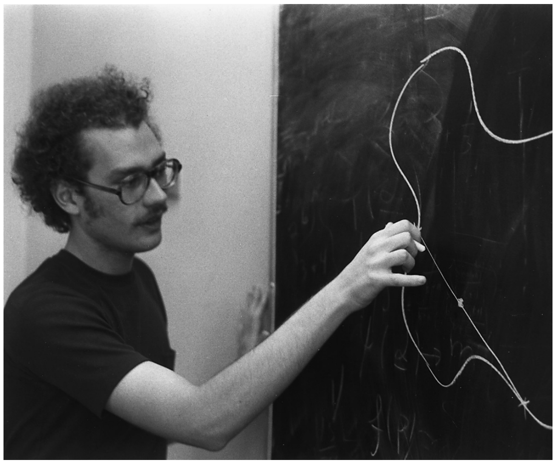
Taking Advantage of Quantum Quirks

The inability to transmit qubits is no small problem—in order for quantum computers to be very useful, they need to be able to send information to other computers (in a network) and to the user (as output) without losing the copy they possess. The solution to this problem turns out to be the quirk known as quantum entanglement. It is a disturbing fact of modern physics that pairs of particles may be produced such that the measurement of one particle has an effect on the measurement of the other, even if they are separated by a great distance. At most, all Alice has to send to Bob is an explanation of what kind of measurements she performed on the "quantum twin" in her possession, which may be sent classically. The information that Bob gets is complete; his information perfectly reflects the state of Alice's qubit. However, because of the "no-cloning" theorem, Alice's qubit is destroyed in the process. Because of these properties, many refer to the process as quantum teleportation. According to Jeff Kimble, an expert in quantum optics at Caltech who demonstrated the first bona fide teleportation in 1998, "entanglement means if you tickle one, the other one laughs." Or, one could view entanglement like a pair of quantum dice that always add up to seven. Before one of the dice is rolled, neither die can be said to have a value. But when one is rolled, say as a three, that act determines the value of the other (to be a four, in this case). It's no surprise that Einstein called this behavior “spooky action at a distance.” While the mysteries of entanglement have stymied physicists for years, they are the keys to the quantum computer’s ability to transfer and process information.

If entanglement gives the quantum computer its voice, it is quantum parallelism that gives it its muscle. Recall a fundamental property of the qubit: before it is tested, it is in many different states at the same time (technically speaking, a superposition of states). It is therefore possible that each one of these states could function like a separate computer, following a single computational path and coming up with a result. Each of these states then interferes with the others, like ripples on a pond, forming a peak that is interpreted as the final output. This is an important departure from the classical model, because it means that the right answer is only found with a certain probability. It will often take many trials before any degree of certainty can be established. Still, the ability to have so many parallel “computers” in one piece of hardware is what gives the quantum computer its unprecedented power.

THE BIRTH OF A SCIENCE

While there is no shortage of skepticism about quantum computation, there have been a number of early demonstrations of its promise. Like every other new technology, quantum computers began as a mere theoretical fascination, waiting in the wings for a practical application. In 1993, at the 35th Annual IEEE Symposium on the Foundations of Computer Science, Peter Shor delivered a groundbreaking paper that proved to be that “killer app.” (Pronounced “eye-triple-E,” IEEE stands for the Institute of Electrical and Electronics Engineers, a major clearinghouse for electrical standards and research.) More specifically, he presented an algorithm that can factor very large numbers, yet does so efficiently even as the input size grows bigger. Since many of the pieces that Shor incorporated into his algorithm have been known since 300 B.C., one may well wonder why his discovery was so remarkable. Although most of the methodology behind the algorithm is nothing new, Shor managed to use procedures from the classical realm that could benefit from quantum parallelism. This is particularly significant given that factorization is believed to be an intractable problem for classical computers. While it hasn’t been proven to be one of those “hard” problems, it has thus far been such a Herculean feat that most cryptography depends on its difficulty. The connection is no mere coincidence—the ability of the quantum computer to make and break codes is what has driven most of the interest in the field. The prospect of a drastic increase in the speed of code-breaking algorithms was enough to make the scientific community, not to mention government agencies, stand up and take notice.



Peter Shor (BS ’81, mathematics) won a national prize in the William Lowell Putnam Mathematics Competition as an undergraduate (see E&S, June/September 1981) and is now a big deal in quantum computing at AT&T Labs in Florham Park, New Jersey.

Though Shor’s procedure is certainly the most famous quantum algorithm to date, there have been a number of other similar speedups. For example, in the field of computational chemistry, one of the most fundamental calculations is the determination of the thermal rate constant. In fact, some have suggested that the rate constant is “the single most important number characterizing chemical reactions.” The rate constant is significant because it reveals how much energy a system must have for a reaction to proceed, as well as how quickly that reaction will take place. Recently, an algorithm has been published (Lidar and Wang, 1999) that computes the rate constant efficiently on a quantum computer. The resulting procedure drastically outperforms any exact classical calculation. A speedup has also been demonstrated for database searches in the field of information science. Searching a database is akin to looking for a forgotten client’s telephone number in the phone book in order to find the client’s full name. If there were N numbers in the phone book, one would have to flip through half the numbers on average before finding the right one. In 1996, L. K. Grover presented an algorithm that could perform the search in $\sqrt{N}$ steps on average. Although this is not a substantial speedup, it has been proven that the procedure is as fast as is possible, insofar as asymptotic complexity is concerned. Unfortunately, Grover’s search algorithm is somewhat odd in that it is randomized, and therefore only gets the answer right about half the time. Its faults notwithstanding, it has the distinction of being the first quantum algorithm actually implemented (on an NMR-QC) that beats the classical analog. Furthermore, Grover’s work has the potential to speed up a number of other seemingly unrelated problems.

In review, the power of the quantum computer is not the same across the board. Some problems get a modest speedup, like the search problem, while other problems get a drastic speedup, like factorization. Note, however, that the real power of this new breed of computer is an open avenue of investigation. Some scientists, such as Bennett et al., have argued persuasively that quantum computers cannot put a dent in a very special class of intractable problems called "NP-Complete." If their assertion is in error, and NP-Complete problems are susceptible to quantum speedups, a vast array of very important problems could be solved efficiently. Bennett states that while his paper conclusively rules out the most straightforward approaches, it cannot make the categorical statement that *no* approach is possible. In truth, no one can yet say with certainty where the boundaries of complexity ought to fall. It does seem to be the case, however, that the realm of uncomputable problems is far beyond even the capacities of the quantum computer.

More Than a Speed Demon

In addition to their ability to speed up calculations, quantum computers bring much more to the table. Another significant feature they have to offer is error correction. This is important if quantum machines are to be able to communicate with one another, since every communication channel has some degree of unwanted noise. This is a well-established principle from classical communications, in which computer modems constantly check for errors that are caused by the noisy "static" on the phone lines. Also, if information is to be stored in any medium, there will necessarily be errors that arise and must be suppressed. These sources of error have been so thoroughly probed in the classical realm, it is currently unclear whether quantum algorithms will prove superior. In one sense, the new algorithms are inferior, in that up to nine qubits may need to be stored and updated for every qubit of data that is to be guarded from error. This requires much more storage than the classical algorithms use. There is, therefore, another very significant reason why these new forms of error correction are vital. Due to the sensitive state needed to create parallelism, quantum computers are highly susceptible both to minor flaws in their implementation and to undesirable interaction with the outside world. Both of these difficulties will be discussed later, but suffice it to say that without error-correcting codes, quantum computers could not do basic multiplication, let alone anything more complicated.

Finally, given the significant influence of cryptography in this budding science, any discussion would be remiss to exclude it. Equally noteworthy is the fact that many of these remarkable security protocols can be implemented with current technology. In 1995, H. Zbinden and his associates at the University of Geneva were able to use laser pulses to transmit qubits in a secure fashion. The pulses were sent across 23 kilometers of standard telecom fiber optics under Lake Geneva. The error rate, around three percent, was low enough to establish the viability of the protocol. Considering that an eavesdropper would be likely to introduce errors in approximately 25 percent of the qubits, the demonstrated error rate was sufficient to guarantee the privacy of the channel. Further enhancements with error-correcting codes would make the data all the more difficult to tamper with or intercept. Zbinden's experiment highlights an important advantage that quantum cryptography has over classical models: because qubits are changed when they are measured and cannot be cloned, a wiretapper cannot simply intercept them midstream without being noticed. However, as was demonstrated by C. A. Fuchs et al. in 1997, an eavesdropper can potentially take advantage of entanglement to glean partial information from a "secure" conversation. In conclusion, even though quantum cryptography is not yet foolproof, it promises to provide much greater security than any existing classical protocol.

Fallen Soufflés and Other Maladies

With all of these exciting new capabilities, one might expect to find quantum computers on the shelves sometime soon. However, there are a number of technical difficulties that some scientists think may never be resolved. Almost always, an underlying theory makes some assumptions that are very difficult to implement in practice. For example, the idealized quantum computer would have no internal flaws and no interaction with its environment. In reality, though, such complicating factors are always present, and they lead to the disruptive phenomenon called decoherence. Recall that in order for the computer to work properly, all the qubits have to be able to interfere in just the right way. Unfortunately, little flaws in the system upset the process (technically speaking, the system becomes "out of phase"). In addition, an even greater problem is that the system loses energy, and hence information, to its surroundings. These are no minor difficulties—information is lost 10 million times too fast to allow for the factorization of a 130-digit number! In that particular instance, it may well be easier to wait for classical computers to get faster than to try to compensate for such loss. Serge Haroche and Jean-Michel Raimond, two of the most outspoken pessimists about quantum computation, write that "the fundamental phenomenon of quantum decoherence, whose probability increases exponentially [i.e., very quickly] with the system size, will make it impossible to 'push back' … the quantum/classical boundary." Early experiments at least confirm the difficulty of the task: the ratio of speed to decoherence needs to be around one billion, in place of its empirical value of about 10. At this point, scientists are split; some believe that error correction will save the day, while others conclude that it would only make an unstable system all the more unwieldy.

How many customers would buy a calculator that couldn't be interrupted while it was working, failed to announce when it was done, and only got the right answer 50 percent of the time?

Sadly, decoherence is not the only substantial problem. There is another wrench in the works, one that might be called the problem of the "quantum soufflé." In today's electronic computers, one could (carefully) probe around in all sorts of circuits and measure voltages at a whim. However, quantum machines find that kind of prodding very rude, and they will refuse to give an answer. This is because testing the qubits collapses them into a single state, and the parallelism needed to solve the problem is lost in an instant. The tendency of the "quantum soufflé" to collapse is only half the explanation for its name. Everyone who has baked a soufflé (or at least seen Martha Stewart do so on television) knows that the oven needs to be set at just the right temperature and that the haute cuisine must be removed at precisely the right time if the final product is to be edible. It turns out that quantum computers are finicky in a similar fashion. Consider Grover's search algorithm, the one that had a 50/50 chance of coming up with the right answer after around $\sqrt{N}$ iterations. Of course, running through the procedure a few more times should give an even more accurate answer, right? Unfortunately, this is much like the temptation to crank the oven up a few degrees—it seems to make sense but doesn't help in the end. The probability of getting the right answer actually drops precipitously over the next few trials. The greatest difficulty in getting a quantum computer to market might well lie in writing the owner's manual.

The enthusiast would probably ask at this point, "Isn't it worth bearing with all these quirks to get a blazing fast computer?" The answer: not necessarily. It is important to realize that these speedups usually only outclass the classical computer on very large problems that require thousands of qubits and billions of logic gates. To make matters worse, it has been demonstrated that there are some problems that don't get any speedup from running on a quantum machine. As difficult as it is to build and operate a quantum computer, scientists would prefer to exploit alternatives whenever possible. After all, how many customers would buy a calculator that couldn't be interrupted while it was working, failed to announce when it was done, and only got the right answer 50 percent of the time?

Tomorrow and Beyond

Yes, there are a number of hurdles on the path to a large-scale quantum computer. However, this is to be expected in a field that has had most of its important questions posed within the last three or four years. Certainly, many of the questions are waiting to be asked in this realm of half magic, half science. At least for the foreseeable future, it appears that everyday silicon-and-wire computers will remain the standard. This conclusion is left tentative in hopes of avoiding the mistake of IBM chairman Thomas Watson, who forecast in 1943 that there would be "a world market for maybe five computers." After all, this nascent technology is already beginning to settle into its niche, poised to conquer problems previously thought to be invincible. Dawn has broken for the quantum computer, and it promises to be an exciting day.

A Limerick by Peter Shor

If the computers that you build are quantum,
Then spies everywhere will all want 'em.
Our codes will all fail,
And they'll read our e-mail,
Till we get crypto that's quantum,
  and daunt 'em. □

The Quantum Computer—An Introduction

by Jacob West

West (left) zips through a gnarly prime factorization problem with his quantum computer while Beauchamp (right) wrestles with his balky PC. Well, maybe someday…

WHAT IS A QUANTUM COMPUTER?

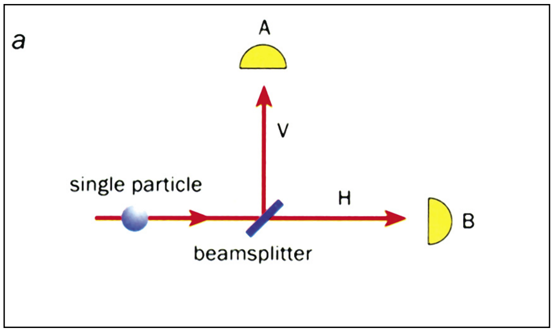
Behold your computer. Your computer represents the culmination of years of technological advancements beginning with the early ideas of Charles Babbage (1791–1871) and the eventual creation of the first computer by German engineer Konrad Zuse in 1941. Surprisingly, however, the high-speed modern computer sitting in front of you is fundamentally the same as its gargantuan 30-ton ancestors, which were equipped with some 18,000 vacuum tubes and 500 miles of wiring! Although computers have become more compact and considerably faster in performing their task, the task remains the same: to manipulate and interpret an encoding of binary bits into a useful computational result. A bit is a fundamental unit of information, classically represented as a 0 or 1 in your digital computer. Each classical bit is physically realized through a macroscopic physical system, such as the magnetization on a hard disk or the charge on a capacitor. A document, for example, comprised of *n* characters stored on the hard drive of a typical computer is accordingly described by a string of 8*n* zeros and ones. Herein lies a key difference between your classical computer and a quantum computer. Where a classical computer obeys the well-understood laws of classical physics, a quantum computer is a device that harnesses physical phenomena unique to quantum mechanics (especially quantum interference) to realize a fundamentally new mode of information processing.

In a quantum computer, the fundamental unit of information (called a quantum bit, or qubit), is not binary but rather more quaternary in nature. This qubit property arises as a direct consequence of its adherence to the laws of quantum mechanics, which differ radically from the laws of classical physics. A qubit can exist not only in a state corresponding to the logical state 0 or 1 as in a classical bit, but also in states corresponding to a blend or superposition of these classical states. In other words, a qubit can exist as a zero, a one, or simultaneously as both 0 and 1, with a numerical coefficient representing the probability for each state. This may seem counterintuitive, because everyday phenomena are governed by classical physics, not quantum mechanics—which takes over at the atomic level. This rather difficult concept is perhaps best explained through an experiment. Consider the figures on the opposite page: In an experiment like that in figure a, where a photon is fired at a half-silvered mirror, it can be shown that the photon does not actually split by verifying that if one detector registers a signal, then no other detector does. With this piece of information, one might think that any given photon travels either vertically or horizontally, randomly choosing between the two paths. However, quantum mechanics predicts that the photon actually travels both paths simultaneously, collapsing down to one path only upon measurement. This effect, known as single-particle interference, can be better illustrated in a slightly more elaborate experiment, outlined in figure b. Figure b depicts an interesting experiment that demonstrates the phenomenon of single-particle interference. In this case, experiment shows that the photon *always* reaches detector A, *never* detector B! If a single photon travels vertically and strikes the mirror, then, by comparison to the experiment in figure a, there should be an equal probability that the photon will strike either detector A *or* detector B. The same goes for a photon traveling down the horizontal path. However, the actual result is drastically different. The only conceivable conclusion is therefore that the photon somehow traveled both paths simultaneously, creating an interference at the point of intersection that destroyed the possibility of the signal reaching B. This is known as quantum interference and results from the superposition of the possible photon states, or potential paths. So although only a single photon is emitted, it appears as though an identical photon exists and travels the "path not taken," and is detectable only by the interference it causes with the original photon when their paths come together again. If, for example, either of the paths are blocked with an absorbing screen, then detector B begins registering hits again just as in the first experiment! This unique characteristic, among others, makes the current research in quantum computing not merely a continuation of today's idea of a computer, but rather an entirely new branch of thought. And it is because quantum computers harness these special characteristics that they have the potential to be incredibly powerful computational devices.

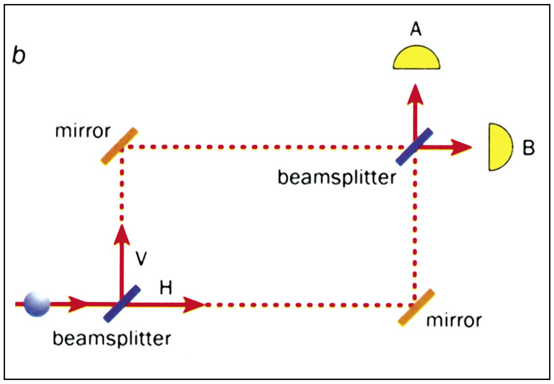
THE POTENTIAL AND POWER OF QUANTUM COMPUTING

In a traditional computer, information is encoded in a series of bits, and these bits are manipulated via Boolean logic gates arranged in succession to produce an end result. Similarly, a quantum computer manipulates qubits by executing a series of quantum gates, each a unitary transformation acting on a single qubit or pair of qubits. In applying these gates in succession, a quantum computer can perform a complicated unitary transformation to a set of qubits in some initial state. The qubits can then be measured, with this measurement serving as the final computational result. This similarity in calculation between a classical and quantum computer affords that in theory, a classical computer can accurately simulate a quantum computer. In other words, a classical computer should be able to do anything a quantum computer can. So why bother with quantum computers? Although a classical computer can theoretically simulate a quantum computer, it is incredibly inefficient, so much so that a classical computer is effectively incapable of performing many tasks that a quantum computer could perform with ease. The simulation of a quantum computer on a classical one is a computationally hard problem because the correlations

Illustrations from "Quantum Computation" by David Deutsch and Artur Ekert, *Physics World*, March 1998, p. 47. See http://physicsWeb.org/toc/11/3 for related articles.



Here a light source emits a photon along a path toward a half-silvered mirror. This mirror splits the light, reflecting half vertically toward detector A and transmitting half toward detector B. A photon, however, is a single quantized packet of light and cannot be split, so it is detected with equal probability at either A or B. Intuition would say that the photon randomly leaves the mirror in either the vertical or horizontal direction. However, quantum mechanics predicts that the photon actually travels both paths simultaneously! This is more clearly demonstrated in figure b.



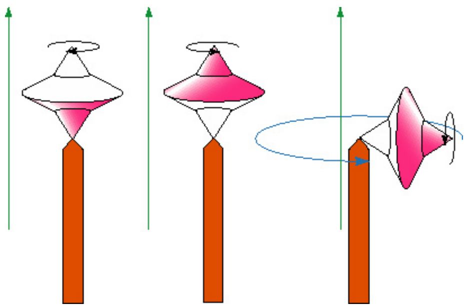
In this experiment, the photon first encounters a half-silvered mirror, then a fully silvered mirror, and finally another half-silvered mirror before reaching a detector; each half-silvered mirror introduces the probability of the photon traveling down one path or the other. Once a photon strikes the mirror along either of the two paths after the first beam splitter, the arrangement is identical to that in figure a, and so one might hypothesize that the photon will reach either detector A or detector B with equal probability. However, experiment shows that in reality this arrangement causes detector A to register 100 percent of the time, and detector B never! How can this be?

among quantum bits are qualitatively different from correlations among classical bits, as first explained by John Bell. Take for example a system of only a few hundred qubits. This exists in a Hilbert space of approximately 10^{90} dimensions, which in simulation would require a classical computer to work with exponentially large matrices (to perform calculations on each individual state, which is also represented as a matrix), meaning it would take an exponentially longer time than even a primitive quantum computer.

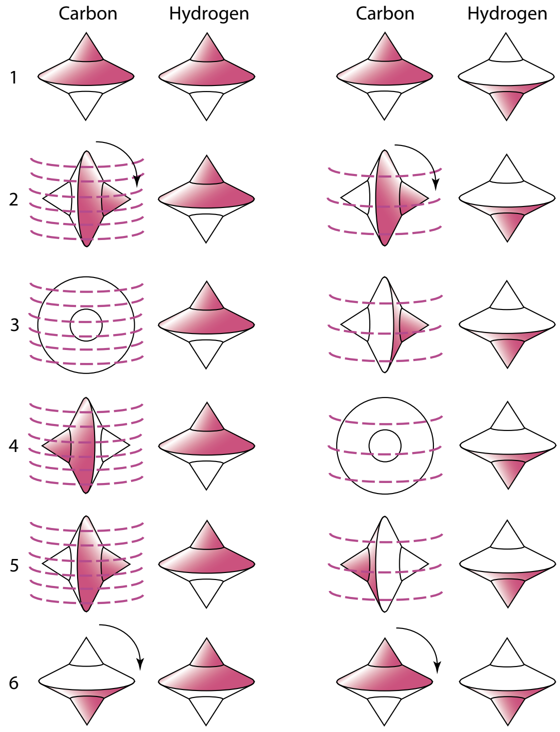
Richard Feynman was among the first to recognize the potential in quantum superposition for solving such problems much much faster. For example, a system of 500 qubits, which is impossible to simulate classically, represents a quantum superposition of as many as 2^{500} states. Each state would be classically equivalent to a single list of 500 1's and 0's. Any quantum operation on that system—a particular pulse of radio waves, for instance, whose action might be to execute a controlled-NOT operation on the 100th and 101st qubits—would simultaneously operate on all 2^{500} states. Hence—with one fell swoop, one tick of the computer clock—a quantum operation could compute not just on one machine state, as serial computers do, but on 2^{500} machine states at once! Eventually, however, observing the system would cause it to collapse into a single quantum state corresponding to a single answer, a single list of 500 1's and 0's, as dictated by the measurement axiom of quantum mechanics. The reason this is an exciting result is because this answer, derived from the massive quantum parallelism achieved through superposition, is the equivalent of performing the same operation on a classical supercomputer with approximately 10^{150} separate processors (which is of course impossible)!

Early investigators in this field were naturally excited by the potential of such immense computing power, and soon the hunt was on to find something interesting for a quantum computer to do. Peter Shor, a research and computer scientist at AT&T Laboratories in New Jersey, provided such an application by devising the first quantum computer algorithm. Shor's algorithm harnesses the power of quantum superposition to rapidly factor very large numbers (on the order of 10^{200} digits and greater) in a matter of seconds. The premier application of a quantum computer capable of implementing this algorithm lies in the field of encryption, where one common (and best) encryption code, known as RSA, relies heavily on the difficulty of factoring very large composite numbers into their primes. A computer that could do this easily would naturally be of great interest to numerous government agencies that use RSA—previously considered to be "uncrackable"—and to anyone interested in electronic and financial privacy.

Encryption, however, is only one application of a quantum computer. In addition, Shor has



Above: Some atomic nuclei have a magnetic property that spins like a top. The spin axis prefers to align with an external magnetic field (green arrow), as shown at center. But a properly tuned radio pulse can tip the top—a 180-degree pulse (left) will flip it right over. And a 90-degree pulse (right) will knock it perpendicular to the field, causing it to precess like a gyroscope. This is the basis of nuclear magnetic resonance, or NMR. (After "Quantum Computing with Molecules," by Neil Gershenfeld and Isaac L. Chuang, Scientific American, June 1998.)



Above: A controlled-NOT gate inverts input A if and only if input B is 1. Gershenfeld and Chuang created a quantum controlled-NOT gate using chloroform molecules in an NMR machine. 1) The chloroform molecule contains a carbon-13 atom (input A) bound to a hydrogen atom (input B). 2) A 90-degree radio pulse tips both carbon nuclei perpendicular to the magnetic field (not shown). 3–5) The carbon nucleus precesses rapidly if the hydrogen nucleus is in state 1 (left), but more slowly if the hydrogen is in state 0 (right). 6) Applying another 90-degree pulse at just the right delay time inverts the carbon (left) or returns it to its original orientation (right).

put together a toolbox of mathematical operations that can only be performed on a quantum computer, many of which he used in his factorization algorithm. Furthermore, Feynman asserted that a quantum computer could function as a kind of simulator for quantum physics, potentially opening the doors to many discoveries in that field. Currently the power and capability of a quantum computer is primarily theoretical speculation; the advent of the first fully functional quantum computer will undoubtedly bring many new and exciting applications.

A Brief History of Quantum Computing

The idea of a computational device based on quantum mechanics was first explored in the 1970s and early 1980s by physicists and computer scientists such as Charles Bennett of the IBM Thomas J. Watson Research Center, Paul Benioff of Argonne National Laboratory in Illinois, David Deutsch of the University of Oxford, and Feynman. The idea emerged when scientists were pondering the fundamental limits of computation. They understood that if technology continues to abide by Moore's Law, then the continually shrinking size of circuitry packed onto silicon chips will eventually reach a point where individual elements will be no larger than a few atoms. Here a problem arises, because at the atomic scale the physical laws that govern the behavior and properties of the circuit are inherently quantum mechanical in nature, not classical. This then raised the question of whether a new kind of computer could be devised based on the principles of quantum physics.

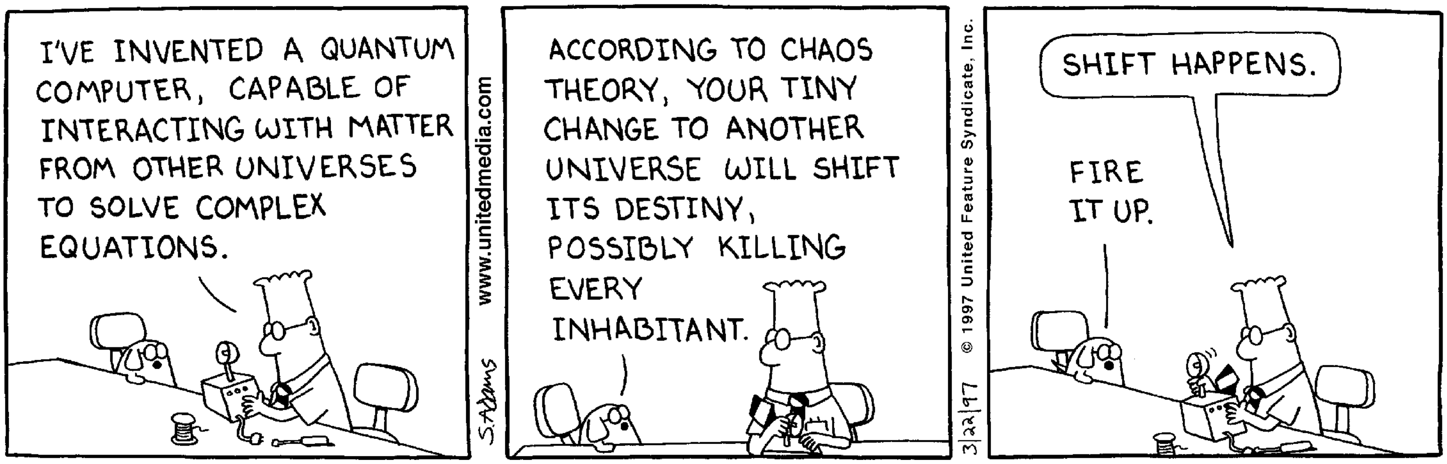
Feynman was among the first to attempt to provide an answer to this question by producing an abstract model in 1982 that showed how a quantum system could be used to do computations. He also explained how such a machine would be able to act as a simulator for quantum physics. In other words, a physicist would have the ability to carry out experiments in quantum physics inside a quantum-mechanical computer.

Later, in 1985, Deutsch realized that Feynman's assertion could eventually lead to a general-purpose quantum computer and published a crucial theoretical paper showing that any physical process, in principle, could be modeled perfectly by a quantum computer. Thus, a quantum computer would have capabilities far beyond those of any traditional classical computer. After Deutsch published this paper, the search began for interesting applications for such a machine.

Unfortunately, all that could be found were a few rather contrived mathematical problems, until Shor circulated in 1994 a preprint of a paper in which he set out a method for using quantum computers to crack an important problem in number theory, namely factorization. He showed how an ensemble of mathematical operations, designed specifically for a quantum computer, could be organized to enable such a machine to factor huge numbers extremely rapidly, much faster than is possible on conventional computers. With this breakthrough, quantum computing transformed from a mere academic curiosity directly into a national and world interest.

Obstacles and Research

The field of quantum information processing has made numerous promising advancements since its conception, including the building of two- and three-qubit quantum computers capable of some simple arithmetic and data sorting. However, a few potentially large obstacles still remain that prevent us from "just building one" or, more precisely, building a quantum computer that can rival today's modern digital computer. Among these difficulties, error correction, decoherence, and hardware architecture are probably the most formidable. Error correction is rather self-explanatory, but what errors need correction? The answer is primarily those errors that arise as a direct result of decoherence, or the tendency of a quantum computer to decay from a given quantum state into an incoherent state as it interacts, or entangles, with the state of the environment. These interactions between the environment and qubits are unavoidable, and induce the breakdown of information stored in the quantum computer, and thus errors in computation. Before any quantum computer will be capable of solving hard problems, research must devise a way to maintain decoherence and other potential sources of error at an acceptable level. Thanks to the theory (and now reality) of quantum error correction, first proposed in 1995 and continually developed since, small scale quantum computers have been built and the prospects of large quantum computers are looking up. Probably the most important idea in this field is the monitoring of phase coherence for error correction as a means to extract information and reduce error in a quantum system without actually measuring that system. In 1998, researchers at Los Alamos National Laboratory and MIT led by Raymond Laflamme managed to spread a single bit of quantum information (qubit) across three nuclear spins in each molecule of a liquid solution of molecules of alanine or trichloroethylene. They accomplished this using the techniques of nuclear magnetic resonance (NMR). This experiment is significant because spreading out the information actually made it harder to corrupt. Quantum mechanics tells us that directly measuring the state of a qubit invariably destroys the superposition of states in which it exists, forcing it to become either a 0 or 1. The technique of spreading out the information allows researchers to utilize the property of entanglement to study the interactions between states as an



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indirect method for analyzing the quantum information. Rather than a direct measurement, the group compared the spins to see if any new differences arose between them, without learning anything about the information itself. This technique gave them the ability to detect and fix errors in a qubit's phase coherence, and thus to maintain a higher level of coherence in the quantum system. This milestone has provided ammunition against skeptics and hope for believers. Currently, research in quantum error correction continues, with groups at Caltech (Preskill, Kimble), Microsoft, Los Alamos, and elsewhere.

At this point, only a few of the benefits of quantum computation and quantum computers are readily obvious, but before more possibilities are uncovered, theory must be put to the test. In order to do this, devices capable of quantum computation must be constructed. Quantum computing hardware is, however, still in its infancy. As a result of several significant experiments, NMR has become the most popular component in quantum hardware architecture. Only within the past year, a group from Los Alamos National Laboratory and MIT constructed the first experimental demonstrations of a quantum computer using NMR technology. Currently, research is under way to discover methods for battling the destructive effects of decoherence, to develop an optimal hardware architecture for designing and building a quantum computer, and to further uncover quantum algorithms to utilize the immense computing power available in these devices. Naturally this pursuit is intimately related to quantum error correction codes and quantum algorithms, so a number of groups are doing simultaneous research in a number of these fields. To date, designs have involved ion traps, cavity quantum electrodynamics (QED), and NMR. Though these devices have had mild success in performing interesting experiments, the technologies each have serious limitations. Ion-trap computers are limited in speed by the vibration frequency of the modes in the trap. NMR devices have an exponential attenuation of signal to noise as the number of qubits in a system increases. Cavity QED is slightly more promising; however, it still has only been demonstrated with a few qubits. Seth Lloyd of MIT is currently a prominent researcher in quantum hardware. The future of quantum computer hardware architecture is likely to be very different from what we know today; however, the current research has helped to provide insight as to what obstacles the future will hold for these devices.

FUTURE OUTLOOK

At present, quantum computers and quantum information technology remain in their pioneering stage. At this very moment obstacles are being surmounted that will provide the knowledge needed to thrust quantum computers up to their rightful position as the fastest computational machines in existence. Error correction has made promising progress to date, nearing a point now where we may have the tools required to build a computer robust enough to adequately withstand the effects of decoherence. Quantum hardware, on the other hand, remains an emerging field, but the work done thus far suggests that it will only be a matter of time before we have devices large enough to test Shor's and other quantum algorithms. Thereby, quantum computers will emerge as the superior computational devices at the very least, and perhaps one day make today's computers obsolete. Quantum computation has its origins in highly specialized fields of theoretical physics, but its future undoubtedly lies in the profound effects it will have on the lives of all humankind. □

While Gershenfeld and Chuang are tinkering with magnets, some folks at Caltech are playing with light. In this approach, photons carry information and atoms store it. All you need to do is design a gate that allows them to interact.

QUANTUM COMPUTING AT CALTECH

Valentine Professor and Professor of Physics Jeff Kimble has taken the first step in that direction. Kimble has been in the quantum-optics biz for over 20 years—see *E&S* Summer '93. This past February, his lab and collaborators in New Zealand successfully trapped a cesium atom, suspending it in a weak laser field in an "optical resonator"—a pair of mirrors, 10 microns apart, that are so highly reflective that a photon will bounce back and forth hundreds of thousands of times before escaping. The atom and the resonator share a quantum of excitation and could act as a gate.

Meanwhile, Professor of Theoretical Physics John Preskill has been thinking about error correction. In 1996, his grad student Daniel Gottesman (PhD '97) developed a systematic method for deriving quantum codes that could be used for fault-tolerant computation. Now Preskill is trying to design quantum fault-tolerance into the hardware. After all, that's what your hard disk does—the data is encoded in puddles of magnetic field that either point straight up or straight down. Oh, sure, an individual atom in the puddle might get zapped by a stray cosmic ray and flip its field the wrong way, but peer pressure from the surrounding atoms soon pushes it back into alignment. But qubits can "point" in any direction, and their errors are just wobbles of a degree or two. Fortunately, if you share the encoded information among many qubits, you only have to worry about errors that jiggle *all* of the qubits in exactly the same way.

One scheme Preskill is exploring exploits the Aharonov-Bohm effect, which is seen in an electron orbiting around a donut-shaped magnetic coil. As the electron moves, its wave function acquires a phase that depends only on the number of times per orbit that its path goes through the donut's hole. "It can take any path," Preskill explains. "As long as the number of windings is the same, the way the wave function changes is the same. So you use the particle's trajectory to store information that will be well protected." And unlike most things quantum, the bigger the system gets, the less likely it is to decohere. "You can pound on it with a hammer—bang! bang! bang!—and inflict a lot of local damage, but you can't damage nonlocal information unless many hammers conspire together. And the environment isn't smart enough to do that." An analogous optical system could be developed, he says.

How many qubits can happily coexist in one gate is not yet clear, but a real quantum computer will probably need an array of gates that will have to share information. Kimble's current setup consists of a forest of prisms, mirrors, beam splitters, and what have you that takes up about 50 square feet of benchtop. (And standard lab-model NMRs use powerful magnets that are bigger than washing machines and weigh over half a ton—not the sort of thing you'd want near your credit cards—and about another 1,000 pounds of radio-field generators and sundry electronic gear. Then there's that vial of funky liquid that they won't let you take on an airplane.) If quantum computing is ever going to go commercial, the apparatus clearly needs to become a lot more manageable.

So Assistant Professor of Physics Hideo Mabuchi (PhD '98), a former grad student of Kimble's, is beginning a collaboration with Professor of Physics Michael Roukes and Professor of Electrical Engineering, Applied Physics, and Physics Axel Scherer to build miniaturized solid-state optical systems. Roukes and Scherer are nanofabrication experts—makers of teeny-tiny machinery on computer chips. One of Roukes's specialties is micromagnets, and last year Scherer's lab, in collaboration with Summerfield Professor of Applied Physics Amnon Yariv and a group at USC, created a chip with an array of the world's smallest lasers, using quantum wells as light sources. The light is confined to an optical resonator that consists of a hexagonal array of tiny, carefully spaced holes drilled through a layer of atoms half a wavelength thick. The beam eventually emerges perpendicularly to the chip's surface, allowing optical communication with other components. But the lasing atom is embedded within the crystal, so any quantum entanglements would quickly decohere via the neighboring atoms. So the collaboration plans to drill a cavity in the center of Scherer's resonator. Then Roukes will lay down a couple of loops of nanowire that will electromagnetically trap a cesium atom in the cavity. It's Mabuchi's job to figure out how to entice the atom into the trap, and then verify that it's in there. Says Scherer, "Of all the approaches people are taking to create entangled states, this one, as ludicrous as it may seem, is probably the sanest. At least all the pieces work." Says Mabuchi, "One of the nice things about working with Axel and Mike is it gives us an understanding of how these devices were meant to be miniaturized and manufactured in the real world."

Kimble, Mabuchi, Preskill, Roukes, and Scherer have just launched a three- to five-year project funded by the Department of Defense's Multidisciplinary Component of the University Research Initiative (MURI). Their goal is to demonstrate quantum error-corrected communication over a 100-kilometer distance, incidentally developing technology that could later be used for quantum computing. We're still a long way from running Peter Shor's algorithm—just factoring 15 into 3 × 5 would require about 4,000 operations on four qubits, and it's anybody's guess how much effort it will take to get the system to hang together that long. But hey—it's a start. ☐—*DS*

Speed Dependence and Crack Addiction

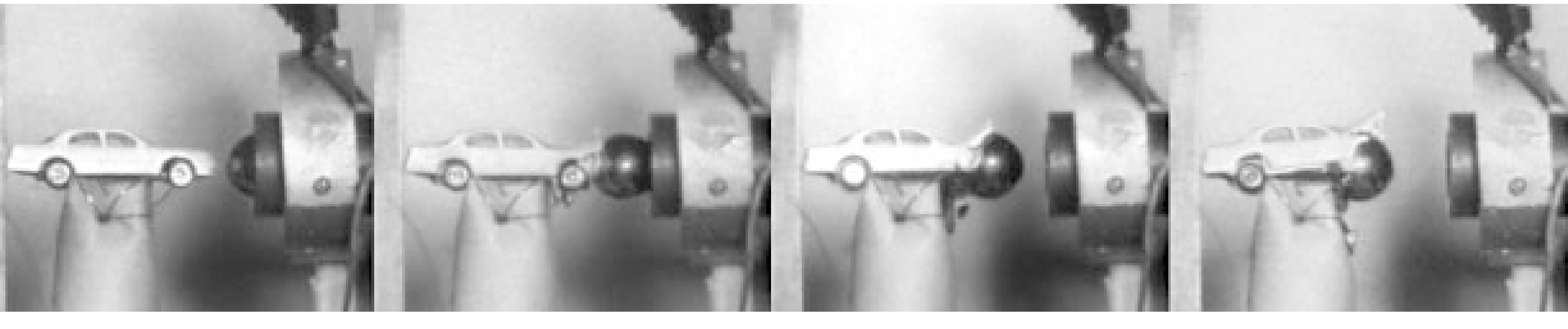
by Ares J. Rosakis

Kids, don't try this at home. In a set of high-speed photos (below) shot by Owen and grad student David Anderson, a toy car suffers a head-on collision with a one-inch ball bearing shot from an air gun. The car's body was one piece of die-cast metal, so the hood only became a moving part once the impact tore it loose. And in a famous Edgerton photo (right), a bullet piercing Plexiglas makes a cornucopia of Mach cones.

Image not licensed for Web use

I'm a fracture mechanician, which means that I spend my time breaking things in the laboratory. My wife, Ioanna, who is a psychologist, says this shows there must be something wrong with me. My retort is that at least my specimens, unlike her patients, do not cry when they're subjected to stress. In my labs at the Graduate Aeronautical Laboratories at Caltech (GALCIT) we subject materials to very high rates of stress in a controlled manner by dropping weights on them or shooting air guns at them—we have a variety of whacking machines—and then we photograph them as they break. We're watching how cracks grow over very short time scales, a few millionths of a second, to try to find out how material bonds break and whether there's a speed limit for crack propagation. Can cracks travel supersonically, for example? In this article, I'll share with you nearly a decade's worth of work by my graduate students, postdocs, and collaborators, and I extend a special thanks to David Owen, senior research scientist and director of our experimental facilities for dynamic solid mechanics. Without these talented people nothing would have been done, and their hard work has recently culminated in some exciting discoveries.

I'll try to relate this work to your everyday experience, which, here in Los Angeles, may include bullets. In the 1930s, Harold Edgerton

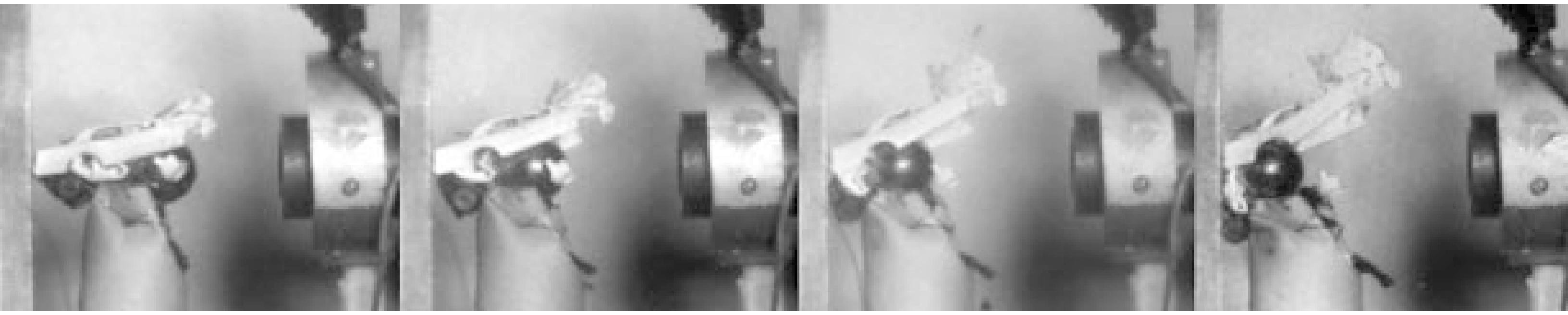


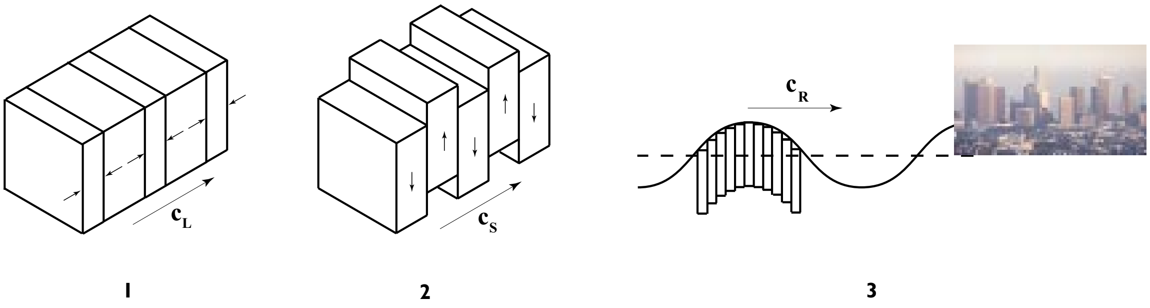
This is heady stuff. We are using experimental methods to explore territory out where the theory doesn't run. We're looking at a whole new set of phenomena.

at MIT took some of the first photographs of a speeding bullet in flight. The photo on the opposite page, shot in 1962, shows a bullet going through a piece of Plexiglas. The bullet's speed is about 800 meters per second, which is about average as bullets go. However, it is much faster than the speed of sound in air, which is about 340 meters per second. As a result, this is a supersonic bullet, so there is a pressure shock wave front, seen as a set of V-shaped lines attached to the tip of the bullet. That shock wave, also called a Mach cone, represents the envelope within which information regarding the disturbance caused by the bullet's passage can travel. A particle of air very close to the bullet but outside the shock wave has no clue at all that the bullet is approaching. You can also see other waves propagating, as well as debris from the Plexiglas, and even some little Mach cones associated with Plexiglas fragments that are moving supersonically as well.

Supersonic aircraft are another part of our everyday experience—some of you may even have traveled in the Concorde. And everyone has their own personal Mach-cone detectors—when you hear a sonic boom, that's a Mach cone sweeping by you.

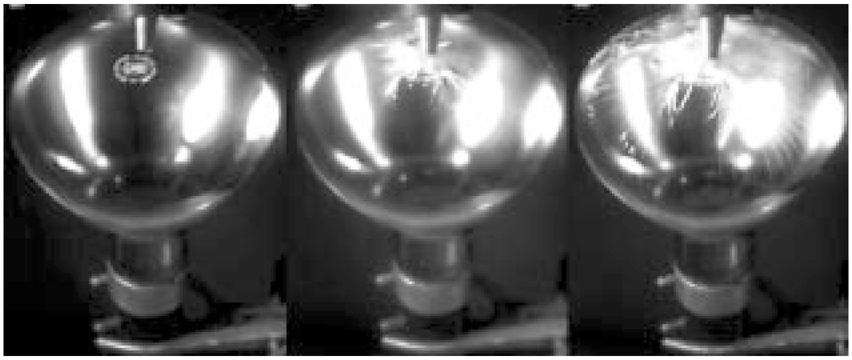
Now how does this relate to cracks? Well, cracks are disturbances that propagate in a solid instead of air, so in order to see whether a crack is supersonic, intersonic (I'll get to that in a minute), or subsonic, we have to compare its speed to the speed of sound in that solid. However, solids are more complicated materials than air, and they feature a larger collection of wave speeds than air does. There are basically three major types of waves that solids can sustain. First are the dilatational waves, also called pressure or *p* waves, equivalent to sound waves in air. Pressure waves vibrate along the direction of their travel, creating alternating regions of compression and expansion, and they propagate at speed c_L. Next come the shear or *s* waves that propagate at a slower speed, c_S, which is usually less than half of the pressure-wave speed. Shear waves vibrate perpendicularly to their direction of travel. Those of you with an interest in seismology or geology will recognize *p* and *s* waves as being associated with earthquakes—seismologists measure the difference in the waves' arrival times in order to calculate how far away the earthquake was, like counting the seconds between the lightning bolt and the thunderclap to see how far away the storm is. Both of these waves are called body waves, because they propagate through the solid's interior. And finally, we have the Rayleigh waves, which are surface waves, which you may also recognize in their earthquake context. Rayleigh waves have a rolling motion, and are equivalent to ripples in water.





Right: Three classes of waves in solids. 1) A dilatational wave stretches and squeezes the solid as it passes through—the segments were originally of equal volume. 2) A shear wave distorts the solid sideways. 3) A Rayleigh wave ripples the solid's surface, in this case while advancing on downtown Los Angeles.

They usually move at about 95 percent of the shear-wave speed, and they are responsible for most of the damage to cities. So when we compare our cracks to these three wave speeds, a supersonic crack is obviously faster than any of them. But if the crack is slower than the dilatational-wave speed and faster than the shear-wave speed, it is called intersonic. For a Mach cone to be visible, the crack must be at least intersonic. (If the crack is supersonic, two Mach cones will exist—one for each wave speed that has been exceeded.) And, of course, if the crack is slower than the body-wave speeds, it is subsonic.

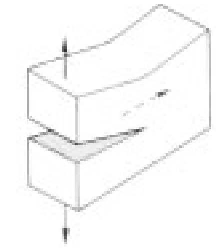


But because solids are much "stiffer" than air, sound propagates much faster, and even subsonic cracks in solids can be moving faster than the speed of sound in air. Above is a series of high-speed photographs that Dave Owen and grad student David Anderson made of a bullet being shot through a light bulb. In the first photo, the bullet has not quite reached the light bulb. In the second photo, shot 30 microseconds (30 millionths of a second) later, the bullet has just touched the glass. Notice that cracks have already propagated from the point of impact, while the bullet has barely moved. This means that the crack tips are moving faster than the bullet. In the third photo, another 30 microseconds have elapsed, and the cracks have run all the way across the face of the bulb. A small calculation shows that these cracks are propagating with speeds on the order of 2,300 meters per second. (Remember, the speed of sound in air is a mere 340 meters per second.) However, these cracks are still subsonic with respect to the glass, because the shear-wave speed of glass is about 3,000 meters per second. You can also see that the cracks are branching as they go, and the branches are starting to connect with one another to create fragments. (This is also what happens when you break a window. You start with a single crack, which branches. The branches branch, and then they connect into fragments.)

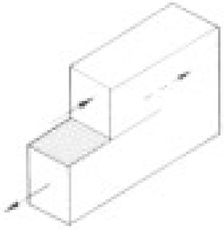
I should mention at this point that there are three different types of cracks. Those in the light bulb and the windowpane are known as Mode I, or "opening," cracks because they pull apart to create an opening between two halves of the material. Mode II, or "shearing," cracks are created by sliding one side of the material with respect to the other. These are beloved of geologists—the San Andreas fault, where two crustal plates are sliding against each other along a plane of weakness, ruptures by the creation of Mode II cracks. And Mode III cracks, called "tearing" cracks, are somewhat like the ripping of a piece of paper or cloth. We'll focus on the first two modes.

Engineers have traditionally dealt with Mode I cracks. That's the way homogeneous solids—hunks of metal, plastic, or ceramic—usually break. If you have been reading *the* book on dynamic

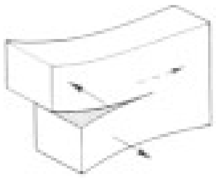
Well, of course, geophysicists will tell you—naturally shear cracks are important. We've been studying them for years. Earthquake ruptures are just basically big old shear cracks that propagate from here to there on a prescribed path.



Mode I cracks open a material perpendicularly to their direction of travel.



Mode II cracks shear a material along their direction of travel.



Mode III cracks tear a material by shearing it perpendicularly to their direction of travel.

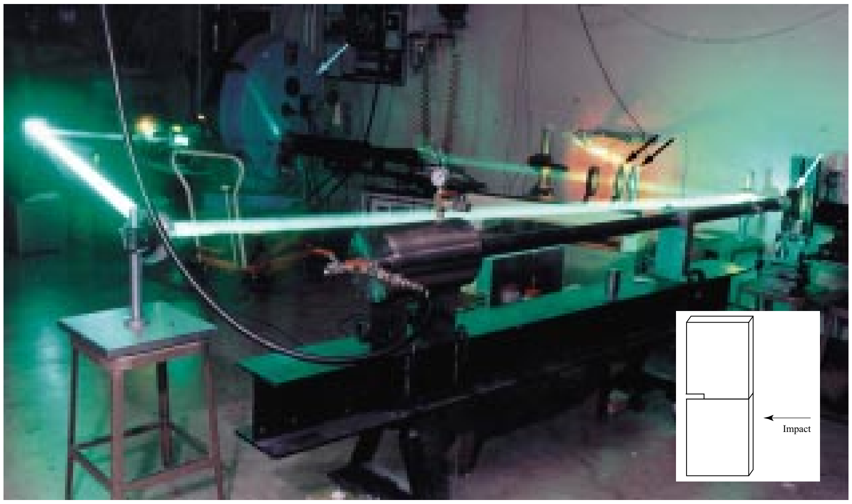
fracture mechanics, by my PhD advisor at Brown University, Ben Freund (who, incidentally, was a JPL distinguished visiting scientist here last year), you will know that in homogeneous elastic solids, the theoretical limiting speed for crack growth in Mode I is the Rayleigh-wave speed of the material. (Remember, the Rayleigh waves are the rolling waves that are heading toward L.A. in the figure.) In practice, the speed of Mode I cracks is even more restricted. Unless there's a weakness for the crack to follow, branching instability sets in at about 40 percent of the Rayleigh-wave speed. In other words, as the crack takes off and starts propagating faster and faster, it prefers to branch in two or more directions rather than continue as a single, faster crack. Then the branches accelerate and branch again, and so on. If there is a weak path—if you scribe a piece of glass with a glass cutter, for example—then you can reach the Rayleigh-wave speed, as Professor of Aeronautics and Applied Mechanics Wolfgang Knauss (BS '58, MS '59, PhD '63) and grad student Peter Washabaugh (MS '84, PhD '90) first demonstrated. But you cannot go faster than that.

Mode II cracks, the shear cracks, have so far been irrelevant to engineers because if you try to shear a solid block of high-strength steel or a brittle plastic, the crack immediately kinks and follows a curved path that creates Mode I conditions locally at the crack tip. The crack has a mind of its own—you load the specimen in a complex way, and the crack will turn so that its tip is opening, rather than shearing, the material. As a result, Mode II crack growth simply couldn't happen in a homogeneous material.

However, engineers are now looking at shear cracks more closely. Take the case of a proposed lightweight design for the Tomahawk cruise missile. The current version is all steel, but you could save weight and increase the range by making the cylindrical body out of a type of fiberglass called S-glass, and then bonding that to the metal nose. The first few times prototypes were test fired, the launch vibrations caused some cracking at the fiberglass-metal joint, and I suspect that the nose was in danger of falling off. The cracks were trapped in the interface, and they followed that path all the way around the circle. They could not turn, following their natural inclination to accommodate local opening, and as a result these interfacial cracks were shear-dominated. Such cases involving jointed or layered structures have caused engineers to reevaluate composite structures of all sorts in terms of the reliability of their joints under even moderately dynamic loading.

Well, of course, geophysicists will tell you—naturally shear cracks are important. We've been studying them for years. Earthquake ruptures are just basically big old shear cracks that propagate from here to there on a prescribed path. However, nobody knew conclusively how fast they could travel, or how much stress was needed to start them, because growing shear cracks were never observed in the lab. Back in the 1970s, R. Burridge of Schlumberger Cambridge Research Ltd., Freund, Bertram Broberg of the Lund Institute of Technology in Sweden (who was a Sherman Fairchild Distinguished Scholar here at Caltech in 1976–77), Dudley Andrews of the U.S. Geological Survey in Menlo Park, Shamita Das of Oxford, and Keiiti Aki of USC had prophesied that intersonic shear speeds were possible. And there had been hints, first reported by Ralph Archuleta at UC Santa Barbara, that some shallow earthquakes had ruptured faults that fast. But nobody had ever actually seen it happen, and without controlled experimental observations from the laboratory, no theory ever gains a firm footing.

So we set out to create shear cracks in the laboratory. We started by making a composite specimen, like the Tomahawk body-nose structure. We bonded a transparent polymeric panel—we used a plastic called Homalite 100, but it could have been Plexiglas or whatever—to a metal plate,



Above: The basic experimental setup for CGS interferometry. A two-inch-diameter laser beam comes from the rear through a system of mirrors to the specimen (white arrow and inset), which butts up against the gas gun—the long pipe and the cylinder connected to the hose in the foreground. The beam is reflected off the highly polished, mirror-smooth specimen through a pair of gratings (black arrows) to create a series of diffraction spots, one of which is trained on the high-speed camera (blue arrow).

edge-to-edge like two cigarette packs stood on end and placed one on top of the other. We sandblasted the metal surface to roughen it, and glued the two pieces together with a mixture of the liquid monomer from which the polymer is made, and the catalyst that starts the polymerization reaction. Thus the bond was made of the same material as the polymer side of the composite so that we weren't adding a layer of adhesive that might alter the system's behavior, and we could control the bond strength by changing how much we roughened the metal or how long we allowed the polymer to cure. At one end of the joint we left an unbonded area, a notch, which concentrated the stresses and initiated the crack, ensuring that it passed through the field of view of a high-speed camera. Then we fired a slug of steel or aluminum at the thin edge of the metal plate opposite to the notch, creating an instantaneous shear stress. In microseconds, a crack had propagated from the notch all the way along the bond to the composite's far end.

This was much faster than any possible movie camera could advance its film, so the film in our camera didn't move. Instead, it was mounted along the inside surface of a drum, and a rotating mirror in the center of the drum swept the images across it. For a light source, we used a laser that pulsed like a strobe in sync with the camera. Of course, the number of frames in our movie was limited by the size of the drum, but we could shoot 80 frames at rates of up to 2 million frames per second. Recently we got a high-resolution digital camera that can shoot 16 frames at up to 100 million frames per second—one of the fastest cameras in the world. The digital-camera system is really made up of 16 individual CCD arrays that all look at the same thing, but are programmed to turn on and off in rapid succession.

In order to see the Mach cones and to measure stresses in the breaking material, we need to record what's going on in the material around

Owen holds a typical gas-gun projectile.

The ammunition in the gas gun doesn't even have to be metal. In preparation for JPL's Mars Sample Return project, which is a series of missions that may begin launching by the end of this decade, our lab in collaboration with Mark Adams at JPL is shooting granite slugs at Kevlar-based composite plates. The Sample Return project, as its name implies, proposes to return Mars rocks to Earth in a sealed capsule. In order to save launch weight, the capsule will not have a parachute but will instead plummet into the Utah desert at a terminal velocity of about 100 miles per hour, or roughly 50 meters per second. After all, the contents are just rocks—it's not like they'll be hurt by a hard landing. However, the question has arisen as to whether the impact could hurt the container. In the microsecond when it's hitting the rocky ground at Autobahn speeds, could it be breached and the samples contaminated with boring old earthly bacteria?

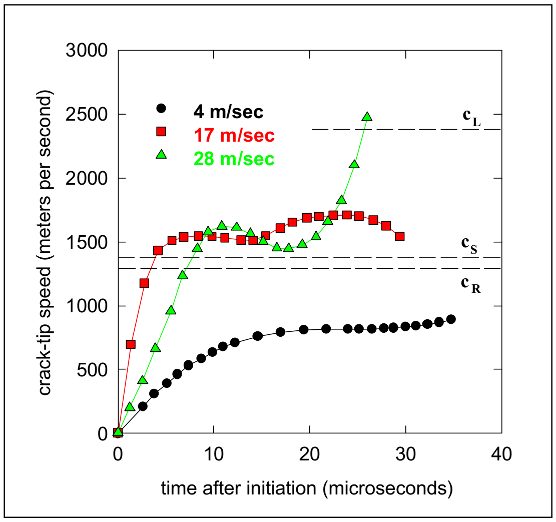
Above: Rosakis and a high-vacuum target chamber being modified for use with the digital camera (the blue-sided box at upper left). Built for plasma-jet studies in 1963 for the late Professor of Aeronautics Lester Lees, and later used by von Kármán Professor of Aeronautics, Emeritus, Anatol Roshko (MS '47, PhD '52), the chamber wouldn't look out of place on a battleship—just the ticket for confining hypervelocity shrapnel.

Above: A peek inside the 2-million-frame-per-second camera, which—believe it or not—uses ordinary 35-millimeter film. The arrow points to the rotating three-sided mirror, which bounces the light off a nest of other mirrors before it finally reaches the film at the periphery—you can see the laser's green dot there. Both cameras were manufactured by the Cordin Company of Salt Lake City, Utah.

And speaking of spacecraft, coherent gradient sensing has found its way up to JPL as well. The Lab, through the System on a Chip project directed by Elizabeth Kolawa, is funding a development project on campus that has led to us patenting CGS for use in measuring the curvatures inherent in microelectronic components. Stresses build up in semiconductor wafers as a result of the thin films of dissimilar materials laid down one upon another. These stresses are exacerbated by the endless cycle of thermal expansion and contraction between, say, day and night on Mars. You sure don't want the top layers of your silicon circuitry to snap apart, so this method may become a vital preflight test to ensure that they won't.

the crack as well as to track the movement of the crack itself. Traditionally, people have studied fractures in transparent materials, because if you shine polarized light through them, you can see interference fringes by looking through a second polarized filter. These fringes are actually maximum shear-stress contours, and the method, called photoelasticity, has been around since the early 1920s. But confining yourself to transparent materials has certain obvious limitations, so about 12 years ago then-postdoc Hareesh Tippur (now a professor at Auburn), grad student Sridhar Krishnaswamy (MS '84, PhD '89, now a professor at Northwestern), and I invented a new method. We called it coherent gradient sensing (CGS), and it works on any smoothly polished, reflective material. The crack distorts the surface ahead of and around itself, and these ripples or slopes in turn distort the reflected light. We pass this light through a pair of gratings to create an interference pattern that we can photograph. Thus, we're actually measuring the slopes on the surface of the specimen in the direction perpendicular to the grating lines, from which we can calculate the stresses.

Back in the early '90s, Tippur and John Lambros (MS '89, PhD '94, now a professor at the University of Illinois) began shooting at our metal-Homalite composite with an impact speed of four meters per second—basically as fast as you can swing your fist—which is nothing. It's far from being ballistic. Yet we found that the crack started at zero speed and rapidly accelerated to about 800 meters per second, very close to the Rayleigh-wave speed of the softer material, i.e., the Homalite. And it did so in only 20 microseconds—a fantastic acceleration on the order of 10 million *g*s. To give you an idea of what that means, the Tomahawk missile achieves only about 10 *g*s when it's fired. The crack's acceleration was impressive, but the top speed was still in line with Mode I theory. However, when the impact speed

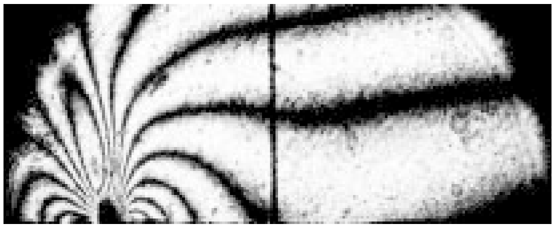


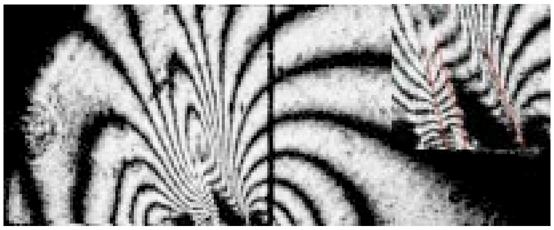
Left: A plot of crack speed as a function of time for a Homalite-steel bimaterial composite at three different impact speeds. The dashed lines are the c_L, c_S, and c_R speeds for Homalite.

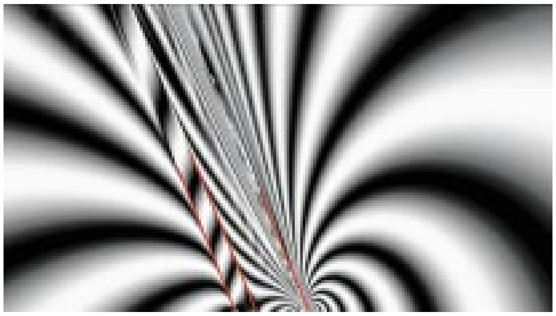
was increased to 17 meters per second, the crack started propagating faster than the Rayleigh-wave speed—and even faster than the shear-wave speed—within 10 microseconds. The crack had become intersonic; it was traveling between c_L and c_S. Ultimately, when the bullet speed was increased to 28 meters per second, the crack even exceeded the dilatational wave speed of the polymer, becoming, for a short time, supersonic with respect to the Homalite.

What you see in the images at left is a concentration of photoelastic fringes that show the location of the crack tip, which travels across the field of view as the pictures progress. But the most stunning part of all this—the most stunning to me, at least—is that the nature of these fringes, even to the untrained eye, changes with time as the crack becomes faster and faster. In the beginning, the fringes all converge on the crack tip, and at the end they have actually formed as many as three distinct sets of inclined lines, which are shear shock waves (jumps in shear stress) equivalent to the shocks made by bullets and airplanes. This shows us, without even making a measurement, that we have exceeded the shear-wave speed.

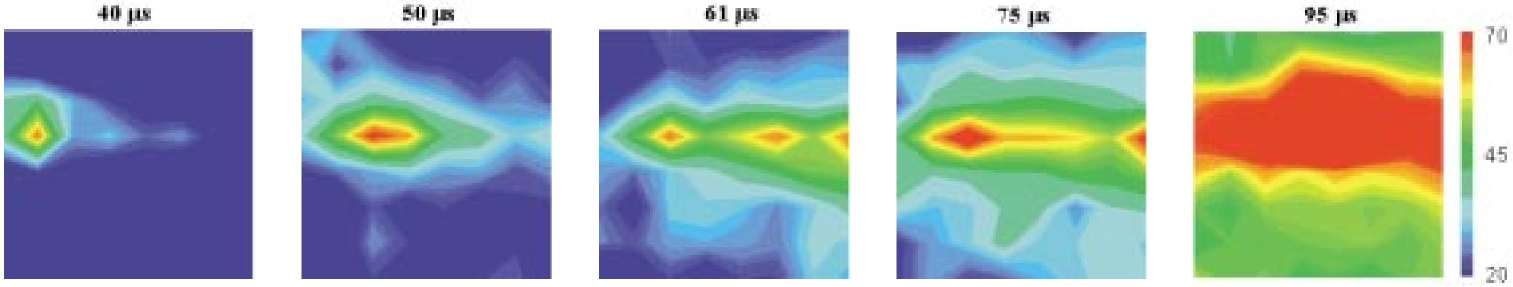
But the bullet only made one set of lines, so what's going on here? Going back to your everyday experience, have you ever tried to move a big carpet? You have it all unrolled on the floor, and discover that it's two feet too close to the wall. But if you just try to pull it, it's very difficult to shift. The easiest way is to hump up a little ripple in it, and then push the ripple across the room. And that's similar, I think, to what's happening here. The Homalite is the carpet, the metal is the floor, and the shear fracture is a ripple







In these dynamic photoelasticity pictures of a Homalite-metal composite, the crack is traveling from left to right along the bottom edge of the image. In the top image, the crack is subsonic and the fringes converge on the crack tip. But less than 20 microseconds later, the crack has gone intersonic and three wave fronts, highlighted in red in the inset, are visible. At far right is the model's prediction of how intersonic fringes should look.



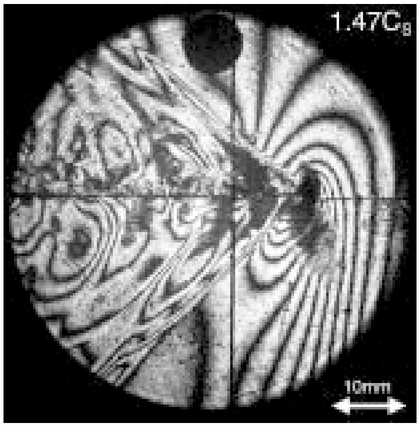
Above: This sequence of thermal maps shows the temperature rise, in centigrade, generated in the wake of a passing intersonic shear crack. As the crack moves by, its faces rub together in frictional contact, causing local hot spots and dissipating heat. (Again, the crack tip is moving from left to right.) These millimeter-square images were made by an infrared camera built at GALCIT by grad student Pradeep Guduru, Rosakis, Professor of Aeronautics G. "Ravi" Ravichandran, and Rosakis's first grad student, Alan Zehnder (MS '83, PhD '87, now a professor at Cornell), who came back on sabbatical for the project. The camera is capable of obtaining 1,000 micro-images at a rate of a million frames per second.

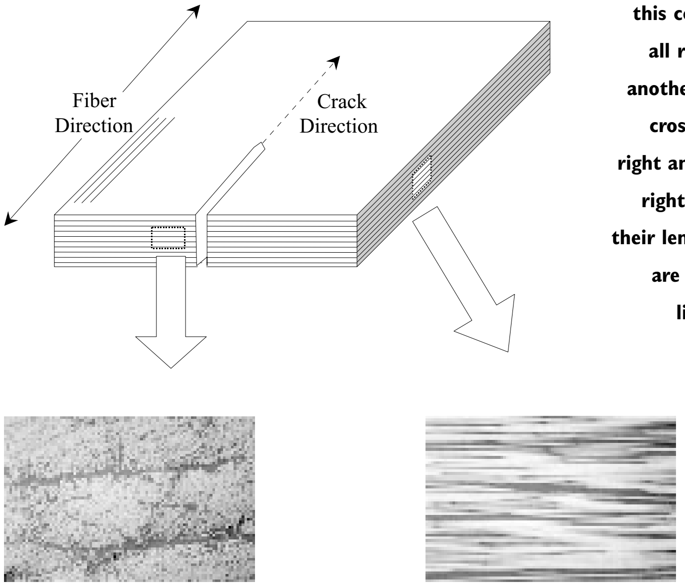
propagating in the interface between the two. The ripple has a distinct tip where it initially separates from the floor. Then the carpet comes down again to touch the floor in frictional contact before the crack is finally pulled apart some distance behind. (As a side note, this friction can generate a lot of heat, as shown in the infrared images above.) I won't go into details of the proposed mechanism worked out by my grad student Omprakash Samudrala; my colleague Young Huang of the University of Illinois, Urbana-Champaign; and me in 1998. Suffice it to say, it allows us to find the stresses and singularities mathematically, and it predicts three shock waves—at the crack tip, at the point where frictional contact resumes, and at the point of final separation—which in special cases become one or two sets of lines.

This carpet-ripple model is very reminiscent of seismology's self-healing pulse model of how earthquake ruptures propagate. During an earthquake, a fault does not slip all at once, but moves in a shear pulse that starts at the hypocenter—the earthquake's underground point of origin; the epicenter is the corresponding point on the earth's surface—and travels along the fault. As a matter of fact, the self-healing pulse concept was first introduced by Professor of Engineering Seismology Thomas Heaton (PhD '78) and has been extensively modeled by Harvard's James Rice (who was a Sherman Fairchild Distinguished Scholar here at Caltech in 1988–89), Northeastern's George Adams, and USC's Yehuda Ben Zion. So our results provided a physical, laboratory demonstration that such things as rupture pulses may exist.

When I started showing these results around to the scientific community, some of my colleagues said, "Well, it's expectable to have intersonic shear-crack growth between two very different materials, because their wave speeds are very different. Stress information travels very fast in the metal, and loads the interface, 'pulling' the crack intersonically with respect to the plastic. This is no big deal." The big deal, they said, would be to have the same material on both sides of a weak plane (which incidentally is a more realistic representation of a "young" earthquake fault) and still propagate intersonic pulses in shear. But my notion was that it didn't matter whether the material was the same or different—it was the existence of the weak plane that allowed cracks to propagate in shear that gave us this result.

So in 1998 Samudrala and grad student Demirkan Coker took two pieces of Homalite and glued them weakly together with the monomer. During the first week of experiments, when the impact speed was only 11 meters per second, the crack turned and followed the direction of local Mode I, the direction of local opening. It thought it was in a homogeneous material—it didn't recognize the fault, and it propagated subsonically. For weeks we gradually increased the impact speed, but the crack still kept turning away from the intended path and I was starting to get worried. I had made a bet with my grad students, you see, and my ego was on the line. But we pressed on, and as we ratcheted up the speed, the crack grew along the interface and we began to see our familiar Mach cones (below). And again we measured crack speeds that approached the





Top: The carbon fibers in this composite material all run parallel to one another. Bottom left: A cross section taken at right angles to the fibers; right: one taken along their length. Both images are 350 microns (millionths of a meter) vertically.

dilatational-wave speed of Homalite. The work was published in *Science* in May 1999.

Now let's look at a different kind of composite material that's widely used in the real world. Above is a pair of photomicrographs of a commercially available carbon-fiber laminate. This stuff is made of small fibers all running in one direction through an epoxy binder. Usually it's built up in layers, like plywood, with the fibers in each layer running at an angle to the fibers in the previous layer. This makes the material very strong, and it's used in everything from jet-engine intake-fan blades to tennis rackets. We knew that the wave speeds along the fibers are much higher than the wave speeds across the fibers. The *p*-wave speed along the fibers is seven and a half kilometers per second. That's fast. So when we drove shear cracks along the fibers, they also accelerated very quickly to this speed—imagine sprinting from Caltech to the Rose Bowl and back again in a second. Our original camera had a very hard time following them, even at 2 million frames per second, which is why we bought the digital camera. This composite is opaque, so we had to use the CGS technique, but the high-speed images still revealed our familiar Mach cones and frictional contact structure. The work will appear in the *Philosophical Magazine, Part A* in August.

The bullet-like crack in this CGS image is moving at the fantastic speed of 7.5 kilometers per second.

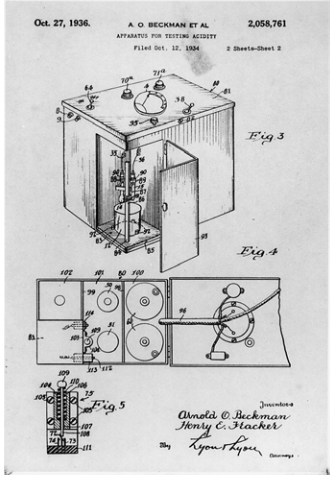
Returning to the question I asked at the beginning—is there a speed limit to crack propagation? All I can give at this point is a partial answer. The Rayleigh-wave speed is not the limit to crack growth. We have reached the dilatational-wave speed, and I believe we've exceeded it, but that wasn't unambiguously beyond experimental error. It's hard to theoretically justify going faster than the dilatational-wave speed, except under very specialized conditions.

This is heady stuff. We are using experimental methods to explore territory out where the theory doesn't run. We're looking at a whole new set of phenomena. And on the practical side, almost everything in the built environment is made of materials bonded to other materials. I'm not just talking about carbon-fiber composites and layered microelectronic structures, but such mundane things as the joints between your chimney bricks, for example. We can get very fast Mode II cracks in materials that were only thought to be able to sustain the much slower Mode I cracks, and we can get very fast Mode II crack growth from very low-speed loadings. So it's possible to have near-instantaneous catastrophic failures in situations where they would not previously have been expected. We can use this knowledge to try to design bonds that resist cracking, or that crack in very predictable ways for specific purposes—layered body armor that disintegrates in a controlled way while protecting the wearer, for example, analogously to the way crumple zones in cars channel the force of an impact away from the occupants. But the biggest immediate advances may be in seismology, where one of the basic tools of the trade is "inverting" measurements from a network of seismometers to determine the source mechanism of an earthquake. The current techniques assume the rupture is subsonic, but the realization that some ruptures occasionally propagate intersonically means we can make more accurate models, thus improving our understanding of earthquakes and their consequences. □

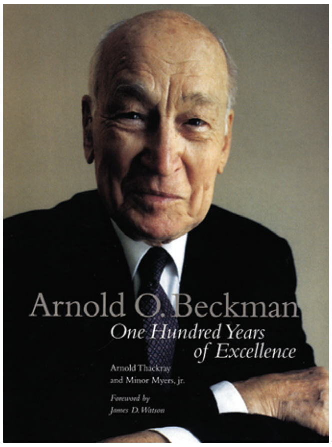
PICTURE CREDITS:
32, 34, 35 — Bob Paz;
32 — Dave Owen, Dave Anderson; 34, 35 — Doug Smith; 36 — Omprakash Samudrala;
37, 38 — Demir Coker;
37 — Coker/Samudrala

Professor of Aeronautics and Applied Mechanics Ares Rosakis obtained his BSc from Oxford in engineering science and his ScM and PhD in solid mechanics from Brown, where he first got hooked on cracks. Upon graduation in 1982, he came to Caltech as an assistant professor, becoming a full professor in '93. A Fellow of the American Society of Mechanical Engineers, he has also been named a Presidential Young Investigator by the National Science Foundation, has received the B. L. Lazan and Heyenyii awards from the Society of Experimental Mechanics, the Rudolph Kingslake medal and prize from the Society of Photooptical Instrumentation Engineers, and an Excellence in Teaching Award from Caltech's Graduate Student Council. This article is adapted from a Seminar Day talk.

The pH meter, which was born in 1934, was, in fact, a marriage of electronics and chemistry in a single, simple, portable instrument.



ARNOLD O. BECKMAN
ONE HUNDRED YEARS OF EXCELLENCE



by Arnold Thackray and Minor Myers, jr.
Forward by James D. Watson
Chemical Heritage Foundation
379 pages
$65.00

The legend of Arnold Beckman has been oft retold (twice in *E&S* alone). Histories of Beckman Instuments have chronicled the huge success of the firm, sprung from modest beginnings—perhaps the first start-up company in a garage. Was there anything left to say?

Yes, it turns out—as *Arnold O. Beckman: One Hundred Years of Excellence,* by Arnold Thackray and Minor Myers, jr., makes clear. Published by the Chemical Heritage Foundation in a series that "records, analyzes, and makes known the human story of chemical achievement," the book offers a picture of Beckman's inventive genius and the significant role he played in bringing about a revolution in instrumentation.

The Horatio Alger story is here, of course, retold with much new detail—growing up a blacksmith's son in Cullom, Illinois, where his interest and ability in chemistry was apparent by the age of nine; working his way through the University of Illinois playing the piano; meeting and marrying Mabel Meinzer, his wife and partner in all things for 64 years, and then traveling across the country to Pasadena in a Model T that suffered 19 flat tires in one day in the Badlands; joining the Caltech faculty after receiving his PhD in 1928; and inventing (for a friend in the citrus business) the pH meter, out of which grew Beckman Instruments and a personal fortune for its founder.

Everyone at Caltech knows the latter chapters. You only have to look around at Beckman Auditorium, Beckman Institute, the Mabel and Arnold Beckman Laboratories of Behavioral Biology, and the Arnold and Mabel Beckman Laboratory of Chemical Synthesis to see how generous the Beckmans have been with their fortune. (And Caltech has not been the only recipient.)

But what this book does particularly well is detail the middle of the story: Beckman's instruments themselves, especially the ones he invented and built with his own hands. It might not make as good a movie as the rest of the legend, but it's fascinating all the same. Not only was Arnold Beckman an enormously talented, hands-on scientist, he also had the vision to sense "the sweet spot of opportunity" in all the right places.

For example, when Beckman temporarily abandoned his Caltech chemistry studies in 1924 to return to the East Coast for a couple of years to court and marry Mabel, he happened to walk in the door of what was to become Bell Labs and joined the founding research group. There, at the forefront of electronics, he learned lessons that would serve him well later on.

The pH meter, which was born in 1934, was, in fact, a marriage of electronics and chemistry in a single, simple, portable instrument. With its vacuum-tube amplifier, it was, say the authors, the "first chemical instrument with electronic technology at its heart."

Beckman soon realized that the amplifier in his pH meter could strengthen all sorts of weak electrical signals, a recognition that turned him toward optics and a new class of analytical instruments. The most famous of these was the DU spectrophotometer, still hallowed in chemical labs countrywide (they were produced until 1964). It enabled chemists to determine composition by analyzing a substance's absorption spectrum. "A key ingredient in what historians have called the 'second chemical revolution' (the first was that of Antoine Lavoisier in the late eighteenth century), through its speed, precision, accuracy, and affordability, the DU

Arnold and Mabel Beckman were deeply involved with all their philanthropic ventures. Here, in what would become the subbasement of Caltech's Beckman Institute, they toast the laying of the cornerstone in September 1988.

increased the pace of chemical research," say the authors.

In 1942, when the DU came into being, the United States was going to war; the DU played a significant role in the production of penicillin and synthetic rubber. Beckman dove deeper into the war effort and the electronics business with a potentiometer (he called it the helipot, also derived from the pH meter) that he developed for radar research at MIT's Radiation Lab, as well as the micro-microammeter for measuring radiation. Several decades later he noted that, although electronics manufacturing might seem "a far cry from a pH meter, yet along the way each step was a logical extension of something we were already doing. As someone said about sin, 'One thing leads to another!'"

The Pauling oxygen analyzer, designed by Linus Pauling and built by Arnold Beckman, was a war project to measure the oxygen in a mixture of gases in submarines and high-flying aircraft. Because of the instrument's secrecy, Beckman couldn't tell the board of directors of his company, National Technical Laboratories, about it, and so formed another—Arnold O. Beckman, Inc., the first bearing his name. (Beckman Instruments, Inc. was founded in 1950.) The oxygen analyzer was also the first of the medical and biological instruments for which the Beckman name became known: after the war it was used to protect premature babies from too much oxygen, which caused blindness. Caltech, because of Pauling, held the patent, and for many years the royalties on it were Caltech's largest single source of patent income.

Besides being in the vanguard of biotechnology, Beckman was present at the creation of the silicon chip industry—Silicon Valley came within a hair of locating in Orange County. But this time his sense of the sweet spot deserted him; he backed the wrong horse: William Shockley. Beckman had indeed sensed the significance of the silicon chip, but failed to see in time that Shockley had dropped the ball and that others were about to score the goal.

The Shockley/Fairchild/Intel story is recounted with a level of candor and a richness of anecdote that you don't often come across in business histories. But it's characteristic of the detailed chronicle of Beckman's own companies as well as the book as a whole, which is chock full of all sorts of things you may never have known about Arnold Beckman and his influence.

Like smog. When Arie Haagen-Smit began to lose interest in studying Los Angeles pollution, it was Beckman who spurred him on—and then Beckman, of course, who built the instruments to detect the smog components that Haagen-Smit discovered.

Beckman had a lifelong passion for photography, which has contributed a wealth of previously unpublished family pictures to this handsome, large-format volume. There are detailed diagrams of Beckman's instruments and sidebars on all sorts of extraneous information—on such things as smog, radar, Bell Labs, and Steele's *Fourteen Weeks in Chemistry*, which inspired a nine-year-old boy in Illinois. The book also comes with a CD-ROM video portrait of Beckman, narrated by his son.

James Watson says in his introduction: "Arnold Beckman's contribution to science and to society came, in part, from his rare talent for creating these new instruments and his decision to make them available to industry and science alike. It has been amplified by his unique philanthropic support of the same forward-looking research that his innovations furthered."

Beckman himself, in characteristic modesty, claimed in his 90s that he had been given far more credit as a scientist than he deserved. "As an instrument maker, a toolmaker, fine. I get credit as a businessman, and I don't consider myself a businessman. . . . I still think I was a damn good teacher." ☐ *—JD*

This book may be ordered from the Caltech Bookstore, Mail Code 1-51, Pasadena, CA 91125;
fax: (626) 795-3156; or
e-mail: citbook@caltech.edu

Please add $5 to the $65 price of the book for postage and handling. California residents add 8.25% sales tax.

HERSCHEL KENWORTHY MITCHELL
1913 — 2000

Herschel Mitchell in 1988, photographed by his wife, Annamarie.

by Norman Horowitz, Professor of Biology, Emeritus

Emeritus Professor of Biology Herschel K. Mitchell died on April 1, following a stroke, his second in a period of 10 years. The first stroke confined him to a wheelchair, but he retained the ability to speak and was frequently seen on campus with his attendant, Douglas Ross.

Mitch, as he was known to his friends, played an important role in the advances that revolutionized the science of biology in the 20th century. Born on November 27, 1913, in Los Nietos, California, near Los Angeles, he attended Pomona College and graduated in 1936 with honors in chemistry. This was followed in 1938 by a master's degree in chemistry from Oregon State College and, in 1941, a PhD in chemistry from the University of Texas.

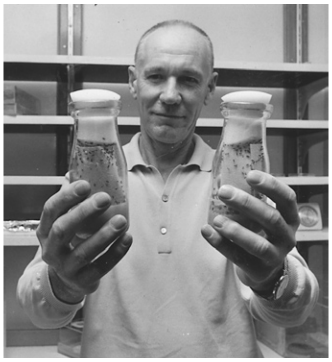
At Oregon State, Mitchell worked with biochemists R. J. Williams and E. E. Snell, and he accompanied them when they moved to the University of Texas in 1940. His most significant research in those years dealt with the B vitamins folic and pantothenic acid. He was the discoverer of folic acid and was primarily responsible for its initial isolation from four tons of spinach.

From Texas, Mitchell moved, in 1943, to Stanford University as a research associate in the laboratory of George Beadle. The Beadle lab was investigating the role of genes in metabolism—work that had been made possible by Beadle and Tatum's discovery of mutations in the mold Neurospora that blocked the synthesis of specific vitamins, amino acids, and nucleic acid bases. At the time, Neurospora was the only genetically well-understood microorganism. Its genetic organization and metabolic properties made it ideal for the revolutionary program initiated by Beadle and Tatum that succeeded in uniting genetics and biochemistry. Mitchell occupied a unique position in the Beadle group. He was a genuine glassblowing chemist with little knowledge of genetics, whereas the others were geneticists, largely self-trained in chemical procedures. Mitch, for his part, had to learn basic genetics, which he soon did.

When Beadle left Stanford in 1946 to become chairman of the Division of Biology at Caltech, he took Mitch with him, along with other senior members of his research group. In 1949, Mitchell became associate professor of biology at Caltech, and in 1953 full professor. He retired in 1984 as professor emeritus.

Over the years, Mitch and the excellent students and postdocs he attracted to his laboratory made important contributions to the developing field of biochemical genetics. Among the most consequential of these was the first demonstration of an enzyme missing from a Neurospora mutant. Such a demonstration was one of the early goals of the Beadle lab. Up to that point, the evidence had established that specific gene mutations cause blockage of specific biosynthetic reactions, and it was assumed that loss of the enzyme catalyzing the reaction was responsible. The demonstration by Mitchell and Lein that the enzyme

In 1995 Mitchell attended Ed Lewis's Nobel Prize celebration. From left: biologists Norman Horowitz, Lewis, Seymour Benzer, Mitchell, Norman Davidson, and Ray Owen, all professors emeriti.



Mitchell appeared in the January 1972 *E&S* with some of his Drosophila—in this case miniflies he had produced by injecting two-day-old larvae with a polypeptide derived from bee venom.

(tryptophan synthetase in this case) was absent from the mutant but present in the wild type from which the mutant arose was an essential step in the argument that eventually established that genes control metabolism by producing (in a manner not then understood) the enzymes required for specific chemical reactions, the rule being that one gene governed the synthesis of one particular enzyme. Beadle called this the "one-gene-one-enzyme" hypothesis. It later was refined to become "one-gene-one-protein" and, finally, since some proteins are composed of more than a single polypeptide, each with its own gene, "one-gene-one-polypeptide." Other refinements are now recognized, but all are reducible to the idea of a simple relation between genes and proteins.

Mitch's interests were wide ranging. His published works include papers dealing with the biosynthesis in neurospora of adenine, pyrimidine nucleosides, nicotinic acid, lysine, histidine, and tryptophan; and they include studies on topics as diverse as maternal inheritance and temperature-sensitive mutants in this organism.

In the early '50s, Mitchell became interested in the problem of development in higher organisms and turned his attention to the genetically important insect Drosophila. Development can be described, at one level, as the programmed synthesis of specific proteins through time. Since the structure of every protein of an organism is encoded in the organism's genes, development involves the activation of specific genes at the time and place the proteins they encode become needed for production of the organism.

The problem that came to occupy Mitch's attention starting in the 1970s and to which he made important contributions was the phenomenon of heat-shock. Heat-shock refers to the effect of brief exposure to heat on the biochemistry of cells and tissues. It had been known since the early '60s that heat-shock causes "puffing" of specific regions of the giant salivary chromosomes of Drosophila, and it had been suggested that puffing was an indicator of gene activity. In 1973 Mitchell, together with Swiss biochemist Alfred Tissières, began to work on heat-shock. They made the basic discovery that heat-shock induces the production of a small number of proteins and inhibits the production of most others. This was the first chemical work ever done on heat-shock, and it gave rise to a large amount of research on its mechanism and biological role. It has recently been found that the proteins induced by heat-shock are principally "chaperones" that function in the refolding of proteins damaged by heat stress. The phenomenon is not restricted to Drosophila, but has been found in all species examined, from bacteria to man—indicating that it is very ancient and also very important. Since 1973, the study of heat-shock has become a new area of biological research, one for which Mitchell was a founding father. □

MEYEROWITZ NEW CHAIR

Elliot Meyerowitz, a specialist in the genetics of flowering plants, has been named chair of the Division of Biology at the California Institute of Technology. Meyerowitz replaces Mel Simon, who is returning to full-time faculty and research duties after serving five years in the office.

A member of the Caltech faculty since he arrived as an assistant professor in 1980, Meyerowiz has been professor of biology since 1989 and was executive officer from 1995 to 2000. His primary research interest is the genes that control the formation of flowers, and how altering these genes will affect flower development. He has identified mutations that cause petal cells to develop into stamens instead, and another mutation that causes these same embryonic petals to become sepals (see *E&S*, 1997, No. 4).

Meyerowitz earned his bachelor's degree in biology, summa cum laude, at Columbia University in 1973, and his doctorate at Yale University in 1977. He received the John S. Nicholas Award for Outstanding Biology Dissertation from Yale for his doctoral reserach. He came to Caltech following a postdoctoral appointment at Stanford.

OF BIOLOGY

He was corecipient of the 1996 *Science pour l'Art* Science Prize, presented by the firm LVMH—Moët Hennessy• Louis Vuitton to researchers whose science is of aesthetic and artistic merit. His other honors include the 1996 Genetics Society of America Medal, the 1995 Gibbs Medal from the American Society of Plant Physiologists, and the 1994 Pelton Award from the Botanical Society of America and the Conservation Research Foundation.

Meyerowitz is a member of the National Academy of Sciences, the American Academy of Arts and Sciences, and the American Philosophical Society. □—*RT*

TEACHING AWARDS

This year ASCIT (Associated Students of the California Institute of Technology) honored five with its teaching awards: Juan De Castro, lecturer in Spanish; Dennis Dougherty, professor of chemistry; Bradley Filippone, professor of physics; Joseph Kirschvink, professor of geobiology; and Kip Thorne, the Feynman Professor of Theoretical Physics.

Honorable mention went to John Allman, the Hixon Professor of Psychobiology and professor of biology; Gregory Smedley, instructor in mechanical engineering; Douglas Smith, instructor in history; and Katherine Stevenson, Taussky-Todd Instructor in Mathematics.

ASCIT also recognized William Bridges, the Carl F Braun Professor of Engineering, and Steven Frautschi, professor of theoretical physics, with lifetime achievement awards.

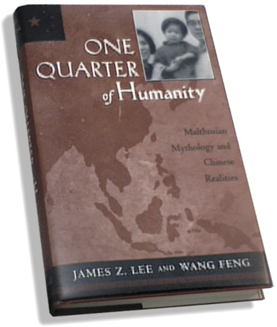
The Graduate Student Council gave its teaching awards for 2000 to Markus Keel, Taussky-Todd Instructor in Mathematics; Hideo Mabuchi, assistant professor of physics; and Anthony Leonard, the von Kármán Professor of Aeronautics. □

BOOK PRIZES

Books written by faculty members in the Division of the Humanities and Social Sciences continue to rake in recognition.

Morgan Kousser, professor of history and social science, was selected as a cowinner of the American Political Science Association's 2000 Ralph J. Bunche Award for his book *Colorblind Injustice: Minority Voting Rights and the Undoing of the Second Reconstruction*.

James Lee, associate professor of history, received the Otis Dudley Duncan Award for his book *One Quarter of Humanity*: *Malthusian Mythology and Chinese Realities*. This award is made annually by the American Sociological Association for distinguished scholarship in social demography.



For her book *Mesmerized: Powers of Mind in Victorian Britain,* Alison Winter, associate professor of history, was given the 1999 Arthur Shapiro Award by the Society for Clinical and Experimental Hypnosis for the best book on hypnosis.

Articles, too, are winning prizes. The Program in Early American Economy and Society has selected Lance Davis, the Harkness Professor of Social Science, to receive a cash award "for one of the best journal articles" in the field of American economic history. He and his coauthor, Stanley Engerman, are being recognized for their article "The Economy of British North America: Miles Traveled, Miles Still to Go." □

AND OTHER HONORS

Giuseppe Attardi, the Steele Professor of Molecular Biology, was corecipient of the 2000 Passano Award for "ground-breaking accomplishments in human mitochondrial DNA research."

Of the 14 new Foreign Associates of France's Académie des Sciences, five were American, and three of the five were from Caltech: President David Baltimore, Nobel laureate and professor of biology; Seymour Benzer, Crafoord laureate and the Boswell Professor of Neuroscience; and Peter Dervan, the Bren Professor of Chemistry.

Professor of Astronomy Richard Ellis has received the title of Honorary Professor of Observational Astrophysics, conferred on him by Cambridge University in recognition of his "significant contributions to the development of astronomy at Cambridge." He will hold the title for a period of three years.

Caroline Fohlin, assistant professor of eonomics, has been awarded a Berlin Prize Fellowship by the American Academy in Berlin, an institute for the advanced study of arts, culture, and public affairs, where scholars can engage in independent study for an academic year or semester. Fohlin's project for her fellowship period of spring 2001 will be "Financial System Design and Industrial Growth: Lessons from the German Experience."

Harry Gray, the Beckman Professor of Chemistry, was named cowinner of the $50,000 Harvey Prize, presented annually by the Israel

Institute of Technology to a scholar or scientist who has worked toward promoting good will between Israel and the nations of the world. Also, Gray and Maarten Schmidt, the Moseley Professor of Astronomy, Emeritus, have been elected members of the American Philosophical Society. The society is the oldest learned society in the United States devoted to the advancement of scientific and scholarly inquiry.

Professor of Biology Paul Patterson has received a $100,000 grant from the Charles A. Dana Foundation for his work on stress, cytokines, and melanoma.

Niles Pierce, assistant professor of applied mathematics, has won the 1999 Leslie Fox Prize in Numerical Analysis, a competition for scientists under the age of 30.

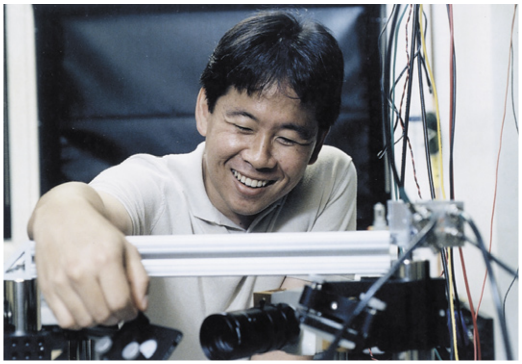
Douglas Smith, instructor in history, has been awarded a National Academy of Education/Spencer Foundation Postdoctoral Fellowship for 2000–2001. As a Spencer Postdoctoral Fellow, he will continue his work on the politics and policies of racial segregation in the 20th-century South.

Armand Tanguay, Jr., visiting associate in electrical engineering, has been elected a fellow of the American Association for the Advancement of Science "for distinguished contributions to physical optics, optical materials, and devices, and optical information processing and computing, including the invention of stratified-volume holographic optical elements."

Alexander Varshavsky, the Smits Professor of Cell Biology, has received a $450,000 Medical Investigator Award from the Steven and Michele Kirsch Foundation. ☐

NO-STRINGS MACARTHUR GRANTS GO TO TWO YOUNG FACULTY MEMBERS


Erik Winfree


Hideo Mabuchi

Two members of the California Institute of Technology faculty have been awarded $500,000 grants from the John D. and Catherine T. MacArthur Foundation.

Erik Winfree, assistant professor of computer science and computation and neural systems, and Hideo Mabuchi, assistant professor of physics, were among the 25 new MacArthur Fellows announced in June. The awards are presented each year to individuals chosen for their exceptional creativity, accomplishments, and potential—no strings attached.

Winfree and Mabuchi, along with the other 23 winners this year, were nominated by an anonymous panel and then selected by a 13-member committee, also serving anonymously. The Fellows are required neither to submit specific projects to the foundation, nor to report on how the money is used.

An important underpinning of the program is the foundation's confidence that the Fellows are best able to decide how to use the money in furthering their work. Mabuchi, a specialist in quantum optics, says he is not yet sure exactly what he'll do with the money.

"I may try to incorporate creativity into the type of science education we normally do at Caltech," he said. "Physics usually builds technical skills, so I would like to see if something could be done to encourage creative skills."

Mabuchi's research primarily explores the details of how microscopic quantum systems interact with macroscopic measurement and control devices used in the lab (see page 29). This is an important avenue of work for future electronic devices, because, as those devices become increasingly smaller, designers will find it more necessary to take quantum effects into consideration.

"Microelectronic devices are coming down to the size where you have to understand the physics very carefully," he said.

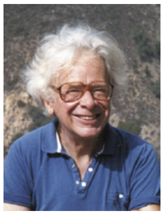
Winfree said he felt a "sense of freedom" when he received word of the award. Winfree's research emphasis is the emerging field of biomolecular computing, and he has been especially interested in DNA computing.

"I might, if I am lucky, be able to augment our understanding and imagination of computation in the molecular world," he said of his goals as a scientist. "The understanding of algorithms will serve as a key to understanding the behavior of complex systems such as the biological cell. The question is how to make this transfer of concepts concrete and useful.

"Thus, if my brief moment in the limelight is good for anything, I would like to champion—as others have before me—the notion that computer science is not just about computers. It is the study of processes that generate organization, wherever you find them: algorithms are a fundamental part of nature."

Both Mabuchi and Winfree earned their PhD degrees from Caltech in 1998. ☐
—*RT*

PHYSICS + PHILANTHROPY



With an eye to philanthropy as well as their own personal finances, Caltech physicist Felix Boehm and his wife, Ruth, have turned the sale of a piece of Colorado real estate into both an investment and a legacy.

Early in the 1970s, the mountains of Aspen, Colorado, became a favorite vacation spot for the Boehm family. Not only did the picturesque 9,000-foot mountain region remind them of their native Switzerland, but they were drawn to both the Aspen Center for Physics, for which Boehm served as trustee from 1976 to 1979, and the Aspen Music Festival. It was also a refreshing place to escape Pasadena's summer smog and heat, and their sons liked the skiing and mountaineering.

But after many seasons in the home they built at Red Mountain Ranch in Aspen, the Boehms found their enthusiasm for the annual Aspen trek had waned, and the family came to a joint decision to dispose of the Aspen residence. Having built the home in 1973, however, their cost basis was quite low; they realized that a huge capital gain would result in substantial taxes upon sale of the property.

After considering their options, Felix and Ruth decided to establish a charitable remainder unitrust funded with a gift of their Aspen home. By doing so, they received a sizable tax deduction, and there were no capital gains taxes owed on the subsequent sale of the property by the trust for $1.6 million. The trust will provide them with an additional source of income for the rest of their lives. All assets that remain in the trust after the death of the survivor will go to Caltech.

Boehm, now the William L. Valentine Professor of Physics. Emeritus, feels grateful to Caltech for enabling him to spend his time at the Institute and to be part of its faculty. "Caltech is a small place," he explained. "It's like a family. Besides my own family, Caltech is the natural entity that I would like to support."

The Boehms designated their gift to support postdoctoral fellowships in physics and astronomy. Noting that there are already a number of endowed chairs in these two disciplines at Caltech, Felix emphasized that "young people not yet known should also be supported." It is very difficult for postdoctoral students to have the opportunity to work and do research without the added pressure of teaching or other duties. According to Boehm, such a fellowship offers support during the "most productive time in life to be creative and do things."

Felix Boehm knows firsthand the benefits to be derived from a postdoctoral fellowship. After receiving his PhD from the Federal Institute of Technology in Zurich in 1951, he was invited to Columbia University in New York as a Boese Fellow, where his work focused on beta decay and atomic excitations. In 1953, Caltech was able to convince him to accept a postdoctoral research fellowship at the Institute, rather than take the instructor position offered by Stanford.

Boehm was among a group of scientists who, in 1957, discovered a breakdown of the space symmetry, referred to as parity, in beta-decay. His current work on the Palo Verde Neutrino Detector project is descibed in the 1999, No. 3, issue of *Engineering & Science* ("The Secret Life of Neutrinos").

Since his youth, Boehm has been "strongly attracted to the mysteries and powers of science." This lifelong interest has prompted the Boehms to leave an enduring legacy at Caltech. By sharing the details of their gift, Felix and Ruth Boehm hope to "encourage others to follow suit."

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