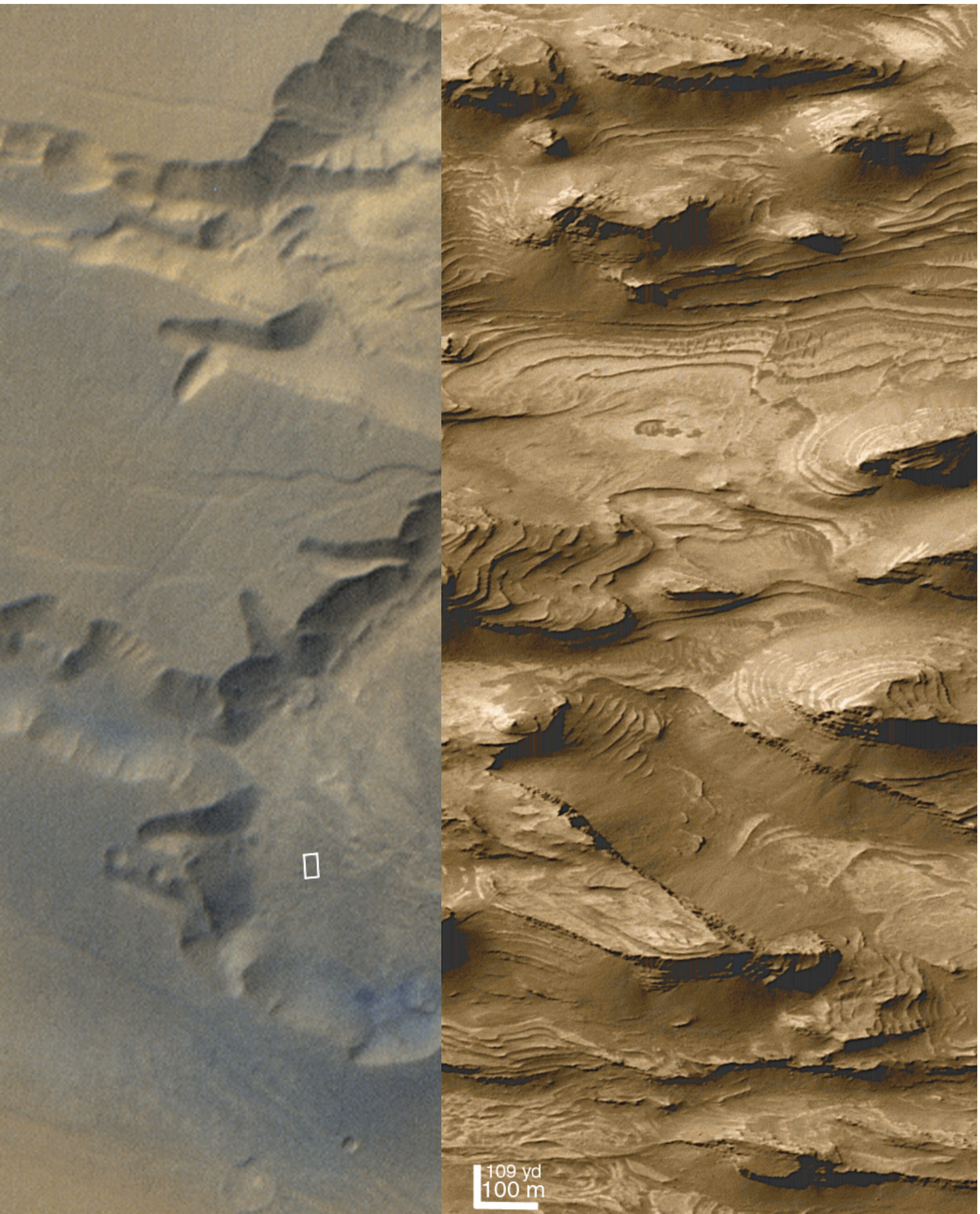
California Institute of Technology

E&S

ENGINEERING AND SCIENCE

Volume LXIV, Number 3/4, 2001

IN THIS ISSUE



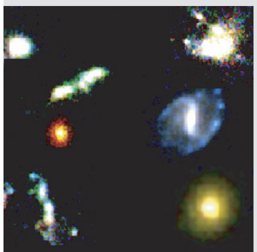
At left is a wide-angle Mars Global Surveyor (MGS) shot of the southwestern corner of Candor Chasma, which is part of the Valles Marineris system. The white box on the valley floor shows the field of view of the close-up at right. MGS images show that much of Mars is covered by thin layers of fine material—in this case, more than 100 layers, each about 10 meters thick—which erosion then sculpts into a remarkable variety of forms. For more on MGS's discoveries, see the story beginning on page 30.

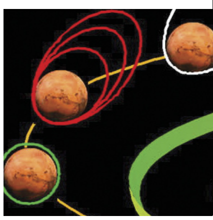
California Institute

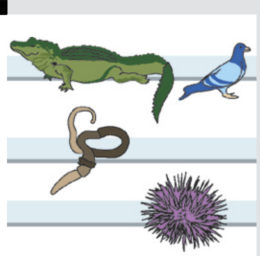
of Technology

ENGINEERING & SCIENCE

Volume LXIV, Number 3/4, 2001







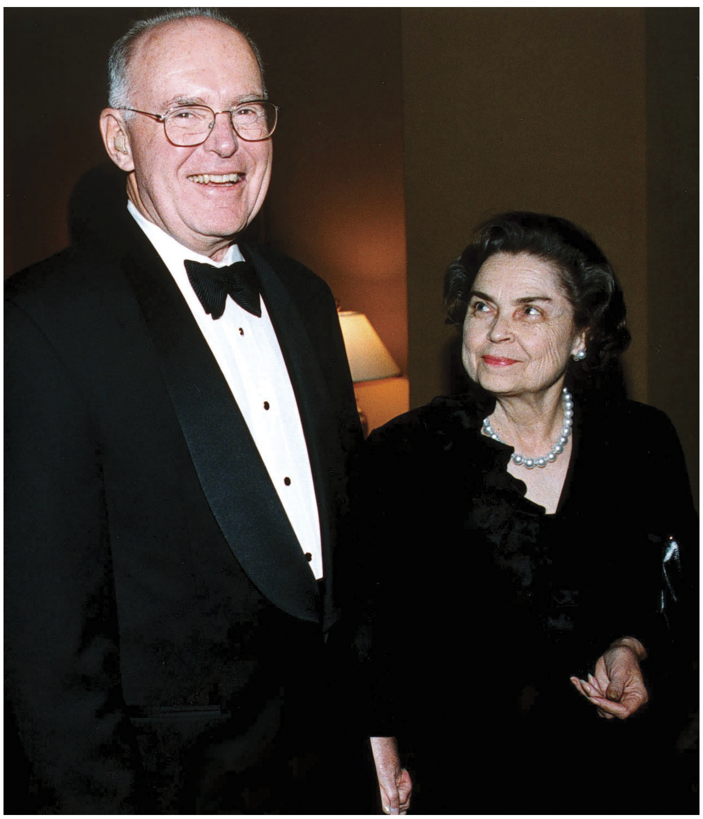
On the cover: The proposed California Extremely Large Telescope (CELT), if placed inside Pasadena's world-famous Rose Bowl, would fit quite neatly astride the 50-yard line. Actually, the telescope, with its 30-meter mirror, will more likely sit on a remote mountaintop in Hawaii or Chile, rather than in a stadium, cheered on to greater discoveries by 93,000 fans. How such a huge telescope could look back in time and show how galaxies evolved into the universe we see today is explained in an article beginning on page 12.

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. Published by Caltech and the Alumni Association. Telephone: 626-395-3630.

PICTURE CREDITS: Cover – Rose Bowl/Doug Cummings; inside front cover, 31, 35, 37, 38, 39, 40, 41 – NASA/JPL/MSSS; 2-4 – Bob Paz; 2 – CARA; 2, 53, 55, 56 – Caltech Archives; 4, 11, 42-43 – Doug Cummings; 4 – SNS; 6 – Doug Abernathy; 8, 9 – Herb Shoebridge; 9 – Luke Wang; 10 – NASA/University of Iowa; 10-11 – NASA/JPL/University of Arizona; 10, 30, 32, 33 – NASA/JPL; 30, 33, 34, 35 – NASA/GSFC; 36, 38, 41 – NASA/Arizona State University; 39, 41 – NASA; 52, 54 – Joan Marcus

Visit Caltech on the Web at **http://www.caltech.edu**

The Moores Step Up To the Plate



Gordon and Betty Moore.

Caltech has received two gifts totaling $600 million, half from Intel cofounder Gordon Moore (PhD '54) and his wife Betty and half from the Gordon and Betty Moore Foundation. Together they are the largest donation ever to an institution of higher learning. Moore said the gift is intended to allow Caltech to continue to do what it does best—collaborative work between disciplines—and to keep Caltech on the forefront of science and technology. "Caltech has a unique ability to do multidisciplinary work—partly because of its size and partly because of its history. It is described as being a national treasure and it certainly is. The education I received there has served me well. We are hoping this gift will position the institute well as it moves forward." Betty Moore, a graduate of San Jose State College in journalism, is very active in the couple's numerous philanthropic activities. She says Caltech has been an important part of her life during her 51-year marriage and she is pleased to be able to support it with this gift. "We've been very fortunate in our lives and we feel it's time to give back. We enjoy seeing the students and knowing that we're helping them."

The couple formed the Moore Foundation in November 2000 and set up offices in San Francisco. The foundation's main focus is the environment, scientific research, higher education, and the Bay Area. The foundation's grants of $300 million over a 10-year period and the Moore's $300 million gift over five years are for educational and scientific programs to be mutually agreed upon.

Moore has been a Caltech trustee for 18 years, and served as chairman of the board from 1993 to 2000. The couple's generosity to the Institute has included the establishment of the Gordon and Betty Moore Presidential Discovery Fund, which is intended to allow faculty to explore new and unique ideas. They also funded the G. E. Moore Electronic Materials and Structure Laboratory, the Gordon and Betty Moore Undergraduate Scholarships, and the Gordon and Betty Moore Laboratory of Engineering. □—*JP*

The Kerckhoff Marine Biological Laboratory, as seen from the end of its dock.

Misadventure on the High Seas

All the three Caltech marine chemists wanted as they set out on a small powerboat was to collect water samples—but before long, they found themselves in over their heads.

Jess Adkins, assistant professor of geochemistry and global environmental science; new staff member Diego Fernandez, an assistant professor of physical chemistry on leave from the University of Buenos Aires; and Jeff Mendez, a graduate student in environmental science and engineering, were on a routine outing from Caltech's Kerckhoff Marine Biological Laboratory in Corona del Mar on November 27 when strong gusts and five-foot waves capsized their craft.

"We had finished our first sample and turned around to go back, when a swell came at us and we realized we were in deeper than we thought," Adkins recounted. "We strapped everything down and put on life jackets, and then we took a wave that put us shin deep in water." He put out a radio SOS, noting their location with the boat's global positioning system (GPS), just minutes before another wave overturned the boat and plunged them into the frigid water.

Fortunately, the Mayday call was picked up right away. With the GPS information, an Orange County Sheriff's Department harbor patrol boat found the trio in about half an hour and took them to the harbor patrol base in Newport Beach. They suffered mild hypothermia but no other injuries. (The 24-foot boat, owned by Caltech's Division of Biology, was salvaged upside down, Adkins said. "There was no damage to the body, but the electronics and engine will probably have to be replaced.")

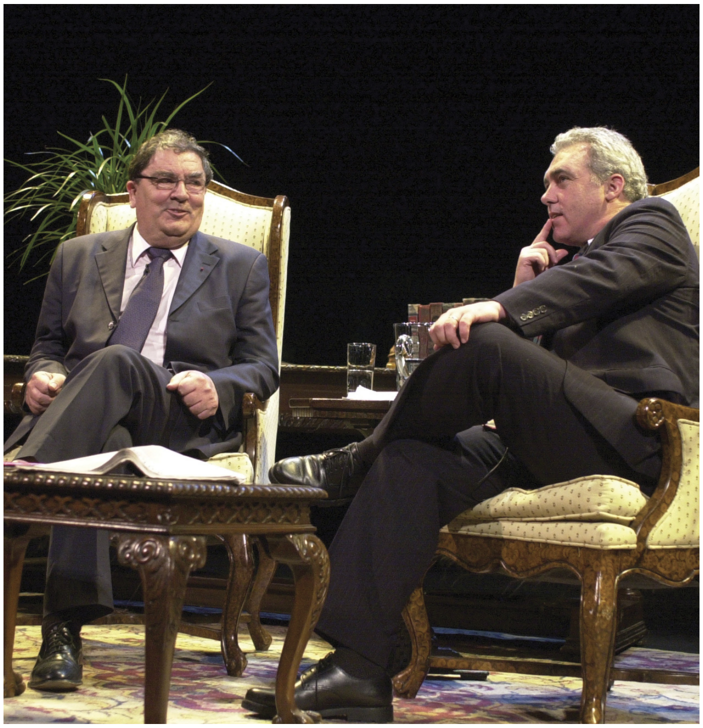
In retrospect, his perspective on the event has evolved, Adkins said. "As it was happening, I focused on what we had to do to stay afloat and stay warm. I always had the sense it would turn out fine. I didn't get scared until we actually got rescued." It wasn't that he hadn't realized the danger, but survival instincts kept him calm. "I knew it was a pretty bad situation, but we just had to do what we could. Whaling and thrashing about wouldn't have gotten us rescued any sooner."

Adkins also highly praised the officials who rescued them. "The harbor patrol and sheriff's department were fantastic. They deserve all the credit, getting out there so quickly."

The researchers' goal, which is also the basis for Mendez's doctoral thesis, was to collect samples weekly in order to study concentrations of metal in the water over time. "Once you know the variations over a few months, seasons, or years, the data let you do an 'event response' in cases such as an oil spill or storm-drain runoff," Adkins explained. "In particular, we're interested in Santa Ana winds and the dust they deposit on the ocean surface."

The trip was one of several the group had taken to determine the project's feasibility, he said, so the researchers will likely stay grounded for the next few weeks and rethink the logistics, possibly hooking up with oceanographers at USC and UCLA. In any case, he said, future excursions will definitely involve "a bigger boat."

Meanwhile, Adkins feels just about back to normal. He was in the classroom as scheduled for a guest lecture two days later. "It maybe wasn't my best lecture ever. I apologized that it was so disjointed—I hadn't had enough time to work on it." □—*DK*



Above: Nobel Peace Prize co-winner John Hume (left) was chatted up by Kevin Cullen (right), ***The Boston Globe***'s former bureau chief in Dublin and London, at the DuBridge Distinguished Lecture on November 20. Hume, a Roman Catholic and until recently the leader of the Social Democratic and Labour Party, shared the 1988 prize with protestant David Trimble, leader of the Ulster Unionist party, for their work toward peace in Northern Ireland. A streaming video of the event can be viewed at http://kkk\atcaltech.caltech.edu/theater/.

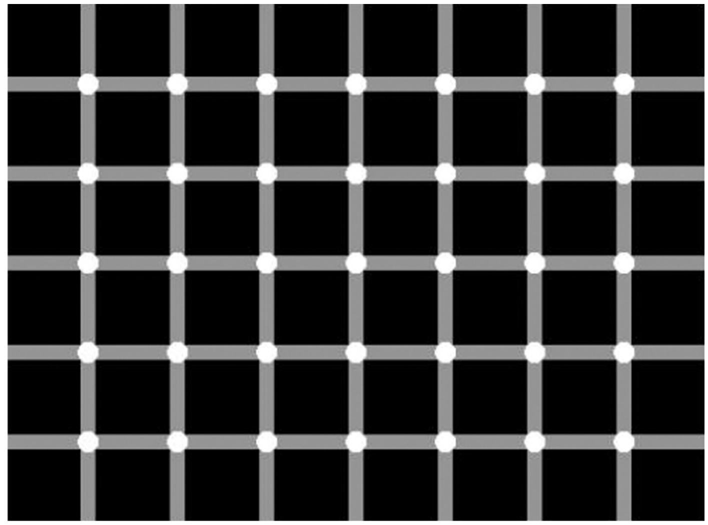
Hot and Cold Running Neutrons

It's really too bad that Superman has X-ray vision. Not that there's anything wrong with that, but if he'd had neutron vision, he'd be able to see a lot more. Neutrons, like X rays, can behave as waves. When you fire a beam of neutrons (or X rays) into a chunk of matter, some of them ripple off the atoms in the sample, and the angles which the waves are strongest tell you how those atoms are arranged. But X rays interact with electrons, so that the more electrons an atom has, the easier it is to see. Because neutrons interact with atomic nuclei, all kinds of atoms are visible, even hydrogen. Neutrons can even find out what the atoms are doing. If the wave sets up a vibration in the sample, the neutron's frequency will drop by the amount of energy lost and the neutron will slow down. Or the wave can cancel out an existing vibration, punting the neutron to a higher frequency and speeding it up. (These collisions are called "inelastic," as opposed to "elastic" ones in which no energy is exchanged. And they don't have to be single-atom collisions—some of the vibrations are ensemble affairs.) So you need a device that not only tells you where the neutron went but how long it took to get there. Such machines have been around for about 50 years, says Professor of Materials Science Brent Fultz, but the catch is that you need a lot of neutrons—a "bright source," in the lingo—to make them work well. Otherwise it's like trying to read the fine print in a phone book by flashlight. The Spallation Neutron Source (SNS), now under construction at the Department of Energy's Oak Ridge National Laboratory in Tennessee, will be the brightest neutron source in the world by a factor of 10, and Fultz is principal investigator of a team building an instrument to take full advantage of it.

This instrument, called

Right: The SNS's physical plant, drawn in on an aerial photo of the construction site. The hydrogen ions are made in the front-end building, and shoot down the linear accelerator, or linac, en route to the accumulator ring and eventually the mercury target.

How many black dots do you see in the white circles? In fact, there aren't any. In this optical illusion, the black dots appear and vanish in a manner correlated with their fellows in both space and time. The phenomenon spans about four unit cells (a unit cell is a crystal's basic repeating structure) and has a frequency of roughly four cycles per second. ARCS will measure correlated vibrations and spins on similar scales in real crystals.

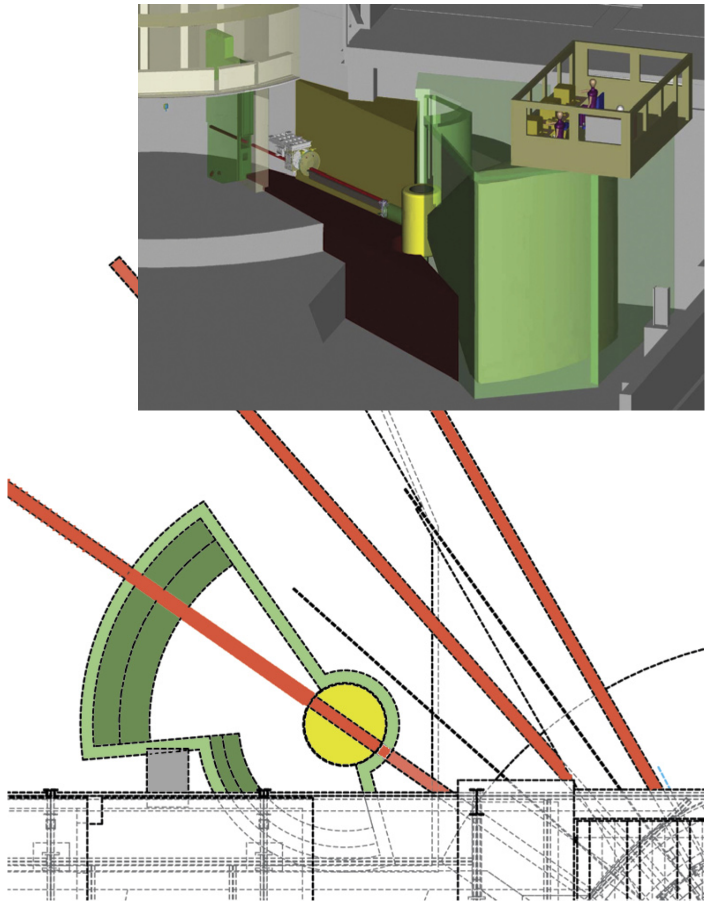


ARCS (short for **A** high-**R**esolution direct geometry **C**hopper **S**pectrometer, whose complete, vowel-impaired acronym would have been utterly unpronounceable) is one of five instruments slated to be on line when the SNS opens for business in 2006. The Department of Energy will spend $15 million on ARCS—a modest sum compared to the entire project's $1.4 billion price tag. As an instrument at a national facility, ARCS will be open for use by all comers, but Fultz and therefore Caltech in general will get a guaranteed time allotment. Eventually, the SNS will host 18 instruments to be built over a 10-year period, and will make the United States the world leader in neutron science—a distinction we'd lost to Europe over the past couple of decades.

The SNS will be a busy place indeed. Neutrons have no electric charge so they don't ionize the samples they penetrate, and because they can "see" hydrogen atoms, you can use them to study the structures of proteins, DNA, and whatnot. And each neutron is a tiny magnet, so it interacts with magnetizable materials. Thus everybody from basic biologists to drug designers to the folks who develop ever-smaller hard drives for your computer will be standing in line, not to mention the chemists looking to create better catalysts or develop new materials with made-to-order properties. And since the neutron's speed determines the frequency of its associated wave, you can tune the neutron beam to the energy range of your choice.

ARCS looks for inelastic collisions ranging in energy from a few millielectron volts (meV) to 500 meV, which are quite gentle and require very slow neutrons. They're called thermal neutrons in the trade, as room temperature is equivalent to about 25 meV. This range is particularly intriguing as it includes phonons, or quanta of vibrational energy that have been linked to high-temperature superconductivity; magnons, which are magnetic spin waves that move through a material like wind through a wheat field and may lead to a theory of quantum magnetism; and a host of other vibrational modes. These vibrations contribute a degree of randomness, or entropy, to a material, and that's what Fultz is interested in. The atoms in a crystal sit in preferred positions, like the marbles in their wells in a game of Chinese checkers. As the vibrational energy increases, the atoms stray farther and farther out of position. This disorder creates vibrational entropy. But entropy has many faces. As the "game" heats up, the red and blue balls intermingle and gaps open up between them, increasing the configurational entropy. At some point, the atoms have become so thoroughly rearranged that the crystal takes on a brand-new form—a so-called phase transition. Even the "board" itself can change—perhaps morphing from a triangular grid into a square one, as in Western checkers. But a few years ago, Fultz discovered that vibrational entropy alone could cause phase transitions, even if the crystal also had a lot of conformational entropy. "I'm pretty proud of that," says Fultz. "It's not every day that you find a new type of entropy that's important in thermodynamics." So Fultz and his grad students are using neutron scattering to find precisely where the entropy in various phase transitions comes from.

The SNS is Big Science. The system starts out with hydrogen atoms that have been given an extra electron each so that they have a negative charge. These get fired down a 300-meter-long particle accelerator that revs them up to energies of 1 billion electron-volts, the equivalent of 1 megawatt of electricity and six times Caltech's entire power consumption. At the far end of a quarter-mile of plumbing—the same length as a drag strip!—they shoot through a micron-thick carbon foil that strips off their electrons, leaving naked protons that are dumped into a storage ring the diameter of a Wal-Mart parking lot. Sixty times a second, or roughly once every 1,200 orbits, a kicker magnet flings the ring's entire contents out in a pulse less than a millionth of a second long. This slug of screaming-hot protons slams into 5.6 liters (76 kilograms) of mercury, banging some of its neutrons loose in a process called spallation. (In the outside world, "spallation" means to knock flakes or slabs off a larger body, such as when you chip concrete with a hammer.) Mercury was chosen because it has a bucketful of neutrons—120 per nucleus, on average—and because, being a liquid, it can be pumped through the hot zone. It takes 1,500 liters of mercury cycling continuously through a cooling system to handle the punishment. So



ARCS has been assigned beam line 18, the leftmost of the three shown in red in the plan view. The neutron detector fills a three-story, high-vacuum chamber (light green); for comparison, note the size of the control room in the 3-D view. The detector (olive), built in two sections to accommodate a concrete pillar (gray), wraps 60° vertically and 160° horizontally around the sample chamber (yellow).

you get a boatload of neutrons, which is good, but they're almost as hot as the protons, which is bad. In order to cool them a million- or billionfold, to the point where they're actually usable, they pass through a "moderator," which is a bath full of either water or liquid hydrogen, depending on how cold you want them, en route to the experimental stations.

The neutrons come flying out in all directions, so the 18 experimental stations are arranged around the mercury target like the spokes of a wagon wheel. Each experiment therefore has a pie-slice-shaped piece of real estate in which to set up shop, which leads to some design challenges, says Fultz. You can either build a small detector close to the source, or a big one farther away. The ARCS team opted for the close-in approach for maximum neutron intensity. Once the neutrons hit the sample, they again scatter to all points of the compass; thus the detector has to surround the sample as completely as possible. Wedging a big detector into the pointy end of the space is further complicated by an unhandily placed concrete pillar that supports an overhead crane and, incidentally, the roof. The details of the design are still being worked out, Fultz says, as some things depend on what the neighbors on the adjoining beam line decide to do—the exact boundaries between the instrument spaces are negotiable—and on what other chopper spectrometers wind up being built. "If they build another one that's optimized for magnetic studies, we'll optimize for vibrational studies, for example, and this governs where we put our detectors."

Even after passing through the moderator, the neutrons still have an assortment of speeds, which is where the Fermi chopper comes in. The chopper is a rapidly spinning cylinder pierced by a slit through which the incoming neutrons pass. The rate at which the cylinder rotates governs the speed of the neutrons that make it through, and the moment when the slit is in alignment (i.e., open) sets the reference time that allows you to measure whether the inelastic collision has sped the neutron up or slowed it down. The chopper, the helium-3-filled detector tubes (which can tell where the neutron has hit to within a few square centimeters), and the rest of the hardware are not too far beyond off-the-shelf technology.

Argonne National Laboratory's Doug Abernathy, the instrument scientist and project manager, is responsible for putting it all together and will be on-site to supervise construction.

Meanwhile, Fultz will be overseeing the design of the software that runs the hardware, collects the time-of-flight and position data from the detectors, and calculates each neutron's momentum in order to measure the sample's vibrational and magnetic energies. In typical Caltech fashion, this means assembling a multidisciplinary team—for example, Oscar Bruno, professor of applied and computational mathematics, has been working on more efficient methods for tracing scattered neutrons through the sample. "Software development has historically been neglected in the neutron-spectroscopy community, which means that people haven't been able to extract all the science that's available in the data," says Fultz. "Each run gives about half a gigabyte of data—not big by high-energy physics standards, but still modestly large. And this is where Caltech can really make a contribution, by developing not only a software package for this instrument but also standards and procedures the entire community can use." Caltech's Center for Advanced Computing Research (CACR) has considerable expertise in this area, so Fultz is collaborating with software integrator Michael Aivazis, a member of the professional staff at CACR.

Compatibility issues run rampant, says Aivazis. The package will contain many disparate pieces of code contributed "typically by scientists whose main focus

Tech Today Debuts

What Nobel Laureate is speaking on campus today? Is there a basketball game this week? And what was the latest on business mileage reimbursement from Human Resources? You'll find it all at *Tech Today* (http://atcaltech.caltech.edu/tech-today/), a Web site brought to you by *At Caltech* and *Caltech 336*. Each weekday, *Tech Today* provides you with current campus news and events at a glance in a single, convenient, user-friendly page. The site includes a wealth of links to Caltech and JPL divisions, resources, and calendars; international and local news sites such as the BBC, CNN, *New York Times*, and *Los Angeles Times*; science magazines and journals; search engines; and even the daily menus for Chandler and Avery dining halls. Check it out . . . today! □—*DK*

is to solve a particular problem. They generally produce code that contains the right science done very well but that is very hard to extract from its context." Aivazis has created a software framework, or environment, in which the assorted bits of code can coexist. Called Pyre for PYthon Research Environment (Python being the language it was written in), it "grabs pieces of code written in Fortran, C, C++, and what have you, and produces a veneer, if you will, that gives you access to how they do physics without your having to be a software engineer. You don't need the specialized knowledge that went into producing the code in order to use it successfully in your application." Pyre also reduces the risk that innocent changes in one person's code may produce astonishing results in the other's. Aivazis will be in charge of setting standards for how data is handled and exchanged between the codes, and making sure that all the pieces play well with one another.

But in the long run, says Fultz, Caltech's biggest contribution may be in opening new avenues of research. "In the past, these instruments have been treated as a piece of hardware—you come in with your sample and you get a result. We're trying to make a deeper connection with theory in order to design better experiments. There's a lot of science involved in figuring out how to write the software, so we'll be doing extensive prototyping work on other machines before ARCS is running. ARCS won't miss many neutrons, and we want to be sure we take full advantage of our capabilities. That's what I find most rewarding—the voyage of discovery to learn what the machine can do." □—*DS*

There's Air Out There (Sort Of)

Astronomers using NASA's Hubble Space Telescope have made the first direct detection of the atmosphere of a planet orbiting a star outside our solar system and have obtained the first information about its chemical composition. Their observations demonstrate that it is possible to measure the chemical makeup of the atmospheres of extrasolar planets and perhaps search for the chemical markers of life beyond Earth.

The planet orbits a yellow, sunlike star called HD 209458, a seventh-magnitude star (visible through an amateur telescope) lying 150 light-years away in the constellation Pegasus. Its atmospheric composition was probed when the planet passed in front of its parent star, allowing astronomers to see light from the star filtered through the planet's atmosphere.

Lead investigator David Charbonneau of Caltech and the Harvard-Smithsonian Center for Astrophysics, Timothy Brown of the National Center for Atmospheric Research, and colleagues used a spectrometer called the Space Telescope Imaging Spectrograph (STIS) to detect the presence of sodium in the planet's atmosphere. "This opens up an exciting new phase of extrasolar planet exploration, where we can begin to compare and contrast the atmospheres of planets around other stars," says Charbonneau. The astronomers actually saw less sodium than predicted for the Jupiter-class planet, leading to one interpretation that high-altitude clouds in the alien atmosphere may have blocked some of the light. The findings will be published in the *Astrophysical Journal*.

The Hubble observation wasn't tuned to look for gases expected in a life-sustaining atmosphere, which in any case is improbable for a planet as hot as this one. Nevertheless, such observations could potentially provide the first direct evidence for life beyond Earth by measuring unusual abundances of atmospheric gases caused by the presence of living organisms.

The planet orbiting HD 209458 was discovered in 1999 through its slight gravitational tug on the star. Based on that observation the planet is estimated to be 70 percent the mass of the giant planet Jupiter, or 220 times more massive than Earth. Subsequently, astronomers discovered the planet passes in front of the star, causing the star to dim very slightly for the transit's duration. This is the only example of a transit among all the extrasolar planets discovered to date.

The planet is an ideal target for repeat observations because it transits the star every 3.5 days—the extremely short amount of time it takes to whirl around the star at a distance of merely 4 million miles from the star's searing surface. This precarious proximity heats the planet's atmosphere to a torrid 1,100° C.

Previous transit observations by Hubble and ground-based telescopes confirmed that the planet is primarily gaseous, rather than liquid or solid, because it has a density less than that of water. (Earth, a rocky planet, has an average density five times that of water.) These earlier observations thus established that the planet is a gas giant, like Jupiter and Saturn.

The planet's swift orbit allowed for observations of four separate transits to be made by Hubble in search of direct evidence of an atmosphere. During each transit a small fraction of the star's light passed through the planet's atmosphere on its way to Earth. When the color of the light was analyzed by a spectrograph, the telltale "fingerprint" of sodium was detected. Though the star also has sodium in its outer layers, the STIS precisely measured the added influence of sodium in the planet's atmosphere.

The team—including Robert Noyes of the Harvard-Smithsonian Center for Astrophysics and Ronald Gilliland of the Space Telescope Science Institute in Baltimore, Maryland—next plans to look at other colors of the star's spectrum in hopes of detecting methane, water vapor, potassium, and other chemicals in the planet's atmosphere.

As other transiting giants are found in the next few years, the team expects to characterize the chemical differences among their atmospheres, helping astronomers better understand a bizarre class of extrasolar planets dubbed "hot Jupiters." These planets are the size of Jupiter but orbit closer to their stars than does Mercury in our solar system. While Mercury is a scorched rock, hot Jupiters have enough gravity to hold onto their atmospheres, though some are hot enough to melt copper.

Conventional theory is that these giant planets could not have been born so close to their stars. Gravitational interactions with other planetary bodies or gravitational forces in the circumstellar disk must have carried these giants via spiraling orbits precariously close to their stars from their birthplace farther out, where they bulked up on gas and dust as they formed.

Proposed moderate-sized U.S. and European space telescopes could allow for the detection of many much smaller Earth-like planets by transit techniques within the next decade. This will be very challenging, since finding a planet orbiting at an Earth-like distance will mean a much tighter orbital alignment is needed for a transit. And the transits would be much less frequent for planets with an orbital period of a year, rather than days. Eventually, study of the atmosphere of these Earth-like planets will require meticulous measurements by future larger space telescopes.

The Space Telescope Science Institute is operated by the Association of Universities for Research in Astronomy for NASA under contract with the Goddard Space Flight Center, Greenbelt, Maryland. The Hubble Space Telescope is a project of international cooperation between NASA and the European Space Agency. The National Center for Atmospheric Research's primary sponsor is the National Science Foundation. □

SIRTF Science Center Dedicated

With the snip of a ribbon, the top three floors of the Keith Spaulding Building of Business Services became the Space Infrared Telescope Facility (SIRTF) Science Center. SIRTF, to launch in late 2002, will join the Hubble Space Telescope, the Compton Gamma-Ray Observatory, and the Chandra X-Ray Observatory as NASA's fourth "Great Observatory," each looking at a different portion of the electromagnetic spectrum. SIRTF sees the "thermal" infrared from 3 to 180 microns, which is absorbed by Earth's atmosphere, and will be looking for objects like brown dwarfs and newborn planetary systems. The Science Center will schedule SIRTF's observations, and process and distribute its data. Before wielding the scissors, Caltech president David Baltimore remarked, "I love the symbolism of turning an administrative building into a science center—sort of swords-into-plowshares." He then praised Provost Steven Koonin (BS '72) for organizing the "heroic" process of relocating the multitudinous folk of Business Services in order to create the space.

Among the invited guests was Gerry Neugebauer (PhD '60), Millikan Professor of

Some 30 years ago, George Housner (MS '34, PhD '41), Braun Professor of Engineering, Emeritus, noticed that this branch had moved from its cutout in the parapet of the arcade by Parsons–Gates. He realized that the tree was tilting, which is why heavy steel columns now brace it. However, he's not standing next to Millikan Pond. Several views of campus are included in a set of murals depicting Pasadena landmarks that have been painted on hoardings at the newly opened Paseo Colorado in downtown Pasadena.

Physics, Emeritus, one of the founding fathers of infrared astronomy. At the dawn of his career, he worked with a strip-chart recorder wired to a single-element sensor. By the time he retired in 1998, detector arrays of a million pixels had become commonplace (see *E&S*, 2001, No. 1).

SIRTF continues in that tradition, having, as JPL director Charles Elachi (MS '69, PhD '71) put it, "orders of magnitude improvement in resolution and spectral coverage" over its predecessor, IRAS.

NASA Associate Administrator for Space Science Edward Weiler noted that the original 1994 design weighed 5,700 kilograms and cost $2 billion. The launch version weighs 950 kilograms and costs only half a billion, thanks to a revolutionary mission plan in which the telescope trails Earth rather than orbiting it, safely away from its heat. In the deep freeze of deep space, SIRTF needs only 60 percent of IRAS's coolant for a mission projected to last six times as long. □—*DS*

The SIRTF Science Center was dedicated on October 22. At left, from left: Charles Elachi; B. Thomas Soifer (BS '68), professor of physics and director of the new center; David Baltimore; and Edward Weiler. At right, Marcia and Gerry Neugebauer.

A New International Power Grid

Today's powerful science projects require equally powerful computers. Complex experiments in such fields as physics, biology, and astronomy will depend on the ability to access and manipulate hugely complex quantities of data. Now a new computing "grid" will provide researchers with the computational power of an entire scientific community. The National Science Foundation has awarded $13.65 million over five years to establish the International Virtual Data Grid Laboratory. The iVDGL will bring together 15 universities and four national laboratories to connect an international network of powerful computers at 40 locations worldwide, notes Caltech professor of physics Harvey Newman, one of iVDGL's coleaders.

The grid, which is expected to come on-line next year, is similar to an electric utility grid in that it can tap into power—in this case, computing power—at multiple locations, creating one ultra-powerful computer that will be available to scientists around the world. The iVDGL grid will reach into Europe and Asia through partners in England, Italy, Japan, and other countries.

Among other large-scale experiments, the grid will serve the Laser Interferometer Gravitational-Wave Observatory, or LIGO, a joint project of Caltech and MIT. (Gravitational waves are distortions of space and time caused by accelerating masses such as exploding stars or vibrating black holes.)

The computing power generated through the grid will be staggering. The grid will be capable of handling quantities of data measured in petabytes. One petabyte is equivalent to one million gigabytes, which is roughly the amount of data contained in 100,000 personal computer hard drives. Its computational speed will be staggering too, eventually measured in petaflops. One petaflop equals one thousand trillion calculations per second. The grid will be powerful enough for hundreds of users worldwide to run jobs simultaneously, although exceptionally large processing jobs will be able to use the entire grid.

Besides Caltech, several universities are member institutions of the LIGO Scientific Collaboration. They include Pennsylvania State University, the University of Texas at Brownsville, and the University of Wisconsin at Milwaukee (UWM). Funds from iVDGL will be used by the group to build a data analysis center for LIGO at Penn State, and also provide for the upkeep and operation of an existing facility at the UWM.

"The iVDGL represents an important first step in the establishment of a computational grid that can be accessed by both the LIGO Laboratory and the LIGO Scientific Collaboration," says Caltech member of the professional staff Albert Lazzarinito, the group leader of LIGO's data analysis team. "This will enable us to perform computationally intensive data manipulations and astrophysical searches using other NSF-funded national resources that exist outside our laboratory." □—*MW*

POLEWARD, HO!

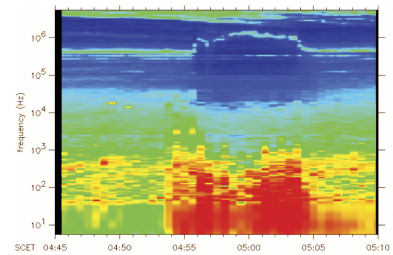
Galileo skimmed over Io's north pole on August 6 and under the south pole on October 16, collecting a host of close-up pictures and other data on the solar system's most volcanic family member.

The polar course was charted to determine whether Io has an internally generated magnetic field, the way Earth does. Io is bathed in Jupiter's powerful field, and Galileo crossed the field lines that actually pass through Io. Previous equatorial flybys had shown that Jupiter's field changes in Io's vicinity, but the field strengths and orientations picked up by Galileo's magnetometer at the poles showed that these changes are caused by electric currents flowing through the sea of charged particles, or plasma, in Io's surroundings rather than by currents flowing in Io's interior. This means that Io's molten iron core does not churn convectively, as Earth's does, probably because the core is heated from without as Io's outer layers flex like a stress-busting squeeze ball in Jupiter's crushing gravitational grip. Earth's core, by contrast, is heated from within as the liquid outer core slowly gives up its heat and condenses onto the solid inner core.

The magnetometer also discovered very localized currents flowing along field lines above two active volcanic regions. Mapping these currents may reveal more volcanic plumes, which are hard to find photographically unless the camera catches them edge-on.

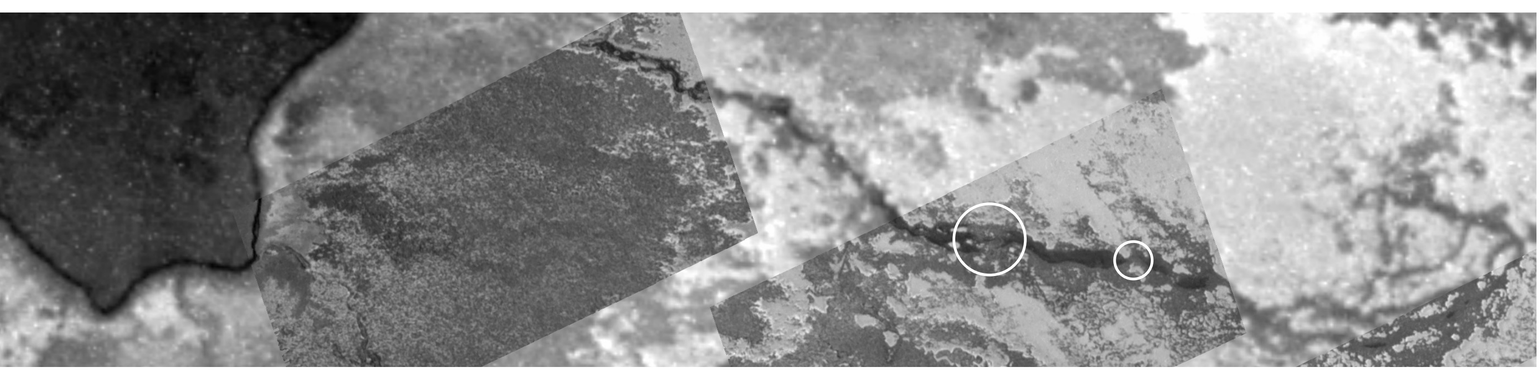
Meanwhile, the plasma-wave spectrometer went nuts over each pole, recording a powerful burst as the spacecraft passed through the "flux tube" where the plasma rides the magnetic field lines connecting Jupiter and Io. (The plasma, incidentally, comes from the sulfur and other guck spewed from Io's volcanoes, which gets ionized once aloft.)

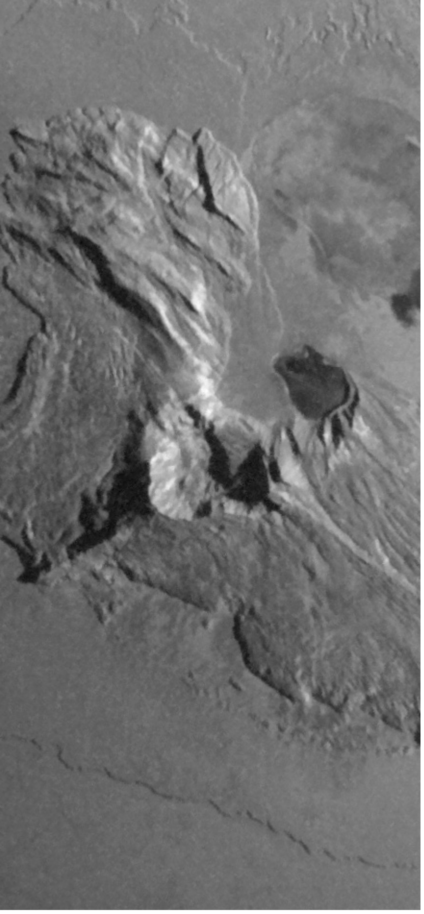
It was hoped that Galileo would fly through the plume of Tvashtar, a volcano that had been erupting furiously seven months earlier. Tvashtar, alas, had gone dormant, but the spacecraft caught a whiff from a previously unknown volcano some 600 kilometers farther south. The particles detected by the plasma-science package were no more than a few minutes old, and appeared to be "snowflakes" of sulfur-dioxide molecules containing up to about 20 molecules each. Analysis of the temperature and impact speed of the particles could say a lot about what's going on down in the volcanic vent. □—*DS*



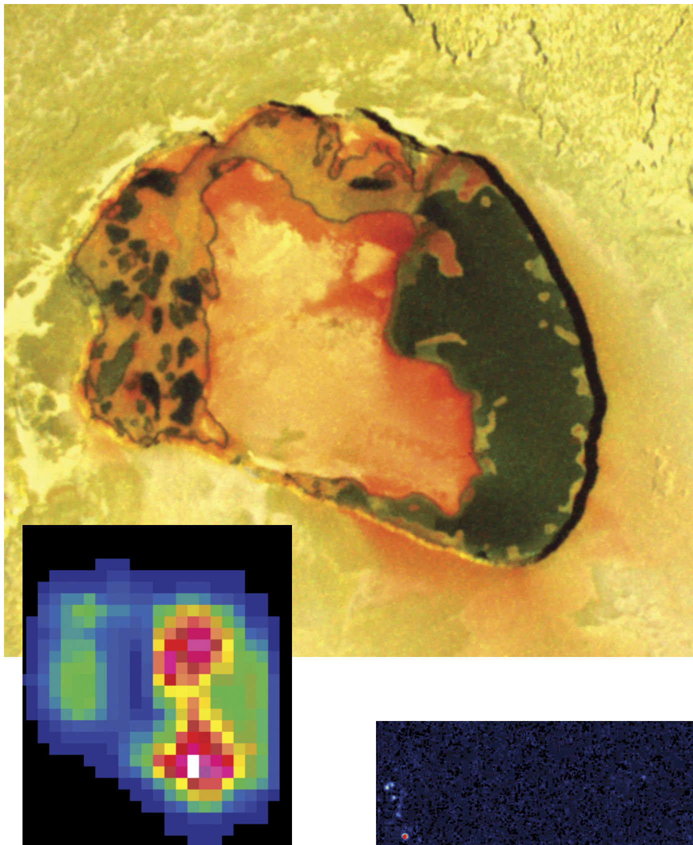
Above: The plasma-wave spectrometer's output during the 25 minutes of closest approach over the north pole. Time runs from left to right; the vertical axis is the frequency of the waves; and the colors represent each wave's intensity at that frequency, with red being the most intense. The plasma density inside the flux tube is more than 10 times higher than the plasma outside.

Below: This dark river is a lava channel draining Emakong Patera, the dark region at left, near Io's equator. The channel fed the surrounding bright lava flow, which runs for hundreds of kilometers. How the lava could stay molten for so long on Io's frigid surface was a mystery, but images taken on October 15 at a resolution of 30 meters per pixel show two places (circled) where the surrounding flow roofed the channel over for about 1,500 and 450 meters, respectively, insulating the lava. The background image has a resolution of 150 meters per pixel.



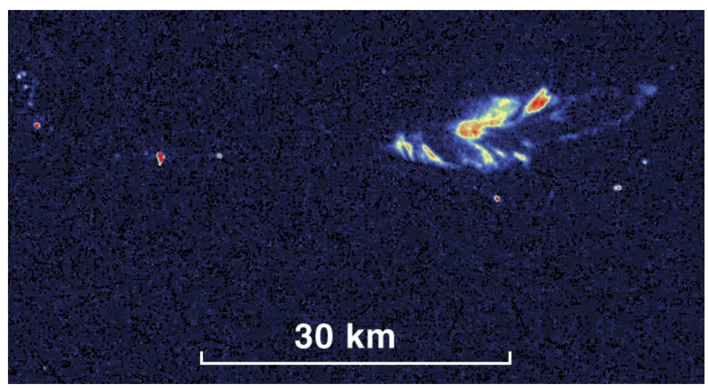


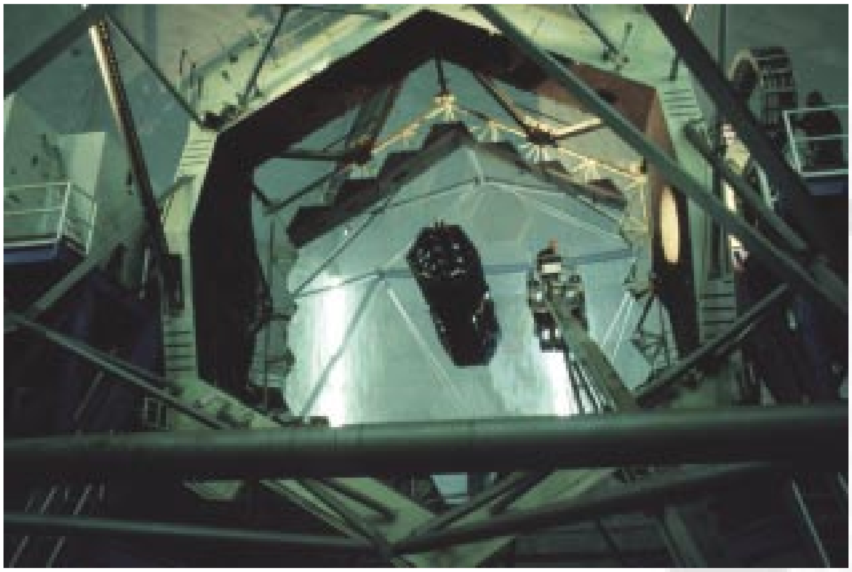
Above: Tohil Mons rises 5.4 kilometers—not quite as tall as Alaska's Mount McKinley (6.2 km), but dwarfing anything in the Lower 48. This view was taken with the sun low in the sky, so that shadows would throw features like the 500- to 800-meter-high cliffs to the upper left into sharp relief.



Above: Tupan Patera, named for a Brazilian thunder god, displays a dazzling range of colors in this only slightly enhanced image. The dark regions to the left and right are still-warm lava, which glows in the infrared (inset—white is hottest). The central area is relatively cool and may be an island. There, gaseous sulfur from the volcanic vents has condensed into various red and yellow materials; the green regions appear to indicate a chemical reaction between molten red sulfur and molten lava—the best evidence yet for such a reaction.

Below: This high-resolution infrared image of Pele at night (top) shows details 60 meters in length. Pele is believed to be a lava lake, and the string of bright spots may be where the lake's crust is breaking up against the caldera's wall, revealing hot lava beneath. Such linear features have been seen before in low-resolution images. The large, bright regions at right are new and may mark where the lava is sloshing violently and overturning large chunks of crust. Both types of activity are shown in the bottom picture of the Puu Oo caldera in Hawaii. Pele's lava is about 1,400 Kelvins, comparable to lavas erupted by Kilauea in Hawaii.





Since 1917, Caltech has been a partner in each of the world's largest telescopes (whose primary mirrors are shown here very roughly to scale): the 100-inch Hooker Telescope on Mount Wilson (top left), the 200-inch Hale Telescope on Palomar Mountain (top right), and one of the twin 10-meter Keck Telescopes on Mauna Kea, Hawaii (above). Joining this eminent group in the future may be the 30-meter CELT (California Extremely Large Telescope), now on the drawing boards.

Unraveling Cosmic History with Giant Ground-Based Telescopes

by Richard Ellis

Galaxies like our own Milky Way formed and evolved over billions of years. One of the most lively topics in astronomy today is the question of how this happened, and the route to answering it comes primarily from large telescopes. Big telescopes have the ability to look back in time and can chart cosmic history to before a billion years after the beginning of the universe. The challenge is to connect the objects we see at different times and to assemble a physical picture of the processes that lead to the rich variety of galaxies we see around us today.

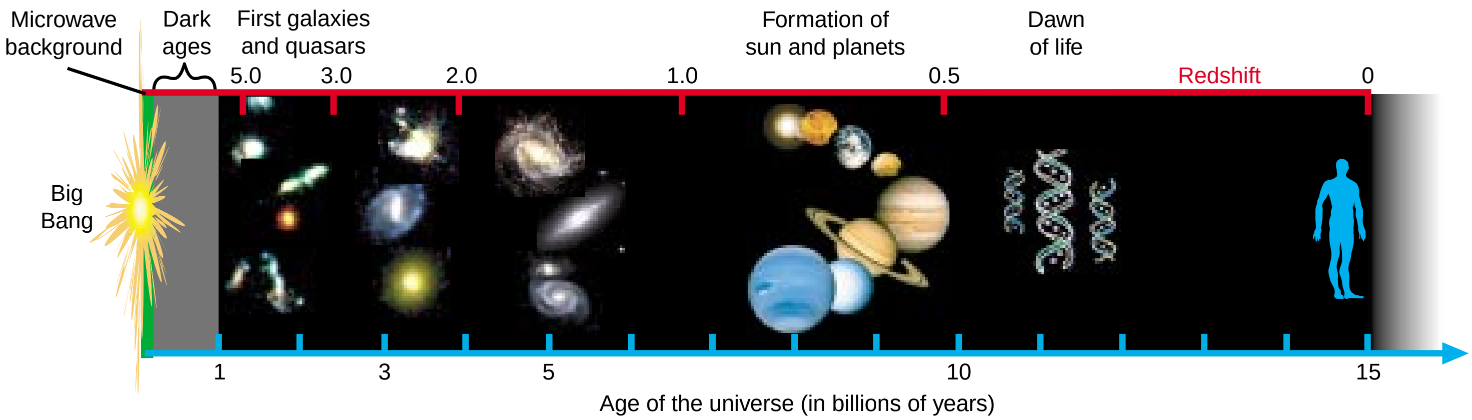
Unlike some experimental facilities, astronomical telescopes are not single-mission instruments destined to produce one major result; they produce a series of lasting discoveries. Pasadena has been, without question, at the center of large-telescope science for almost a hundred years. Just up the hill behind Caltech is the famous 100-inch Hooker Telescope on Mount Wilson, which was the largest in the world from 1917 until 1948. At the 100-inch, Edwin Hubble demonstrated that galaxies such as the Andromeda spiral lie beyond the confines of our own Milky Way, and it was with that instrument that he also discovered the now-familiar expansion of the universe.

Caltech's 200-inch Hale Telescope, which succeeded the Hooker as the world's largest in 1948, is still a frontline research facility on Palomar Mountain, 130 miles to the south of Pasadena. Here, too, a number of landmark discoveries have been made, and I confidently expect more. A remarkable technical achievement at its time and still in fine shape, this telescope discovered quasars—luminous energetic objects that we see to great distances—and also inferred the presence of nebulous hydrogen clouds in intergalactic space from their effect on the light passing through them. The 200-inch quantified our physical picture of how stars evolve, and their statistical properties were used to place an important lower limit on the age of the universe.

Now Caltech's largest telescopes are the twin 10-meter Keck Telescopes on the summit of Mauna Kea on the big island of Hawaii. The Kecks are used for a wide variety of research (including many projects unforeseen at the time their construction was proposed): locating the enigmatic gamma-ray bursts and proving these are at great distances; using supernovae to determine that the universe is probably not just expanding but accelerating (an exciting project with profound consequences that I'm involved in myself but won't have room to discuss here); and weighing the black hole at the center of the Milky Way. But I want to concentrate on the role of large telescopes in understanding how galaxies evolved to their present forms.

Ground-based telescopes suffer to differing extents from the fact that they are forced to view celestial objects through the earth's atmosphere. Even from Mauna Kea, where we are about half way to space in terms of the column of air above sea level, light rays are distorted by turbulent layers high in the atmosphere. Light pollution from San Diego and Los Angeles significantly affects many kinds of observations from Palomar and Mount Wilson, respectively. At infrared wavelengths, from even the darkest sites, the night sky and telescope structure generate a strong thermal background that plagues us. For these reasons, telescopes placed above the earth's atmosphere, such as the Hubble Space Telescope (HST), can produce stunning images at high resolution and, if kept cold and equipped with infrared sensors such as the upcoming Space Infrared Telescope Facility (SIRTF), can be particularly effective for certain studies. Because of the high cost of launching telescopes into space, however, HST and SIRTF are not large-aperture telescopes; both have primary mirrors smaller than the 200-inch constructed in 1948. The modest aperture of space telescopes does therefore restrict their applications. But large ground-based

This article was adapted from a Seminar Day talk last May.



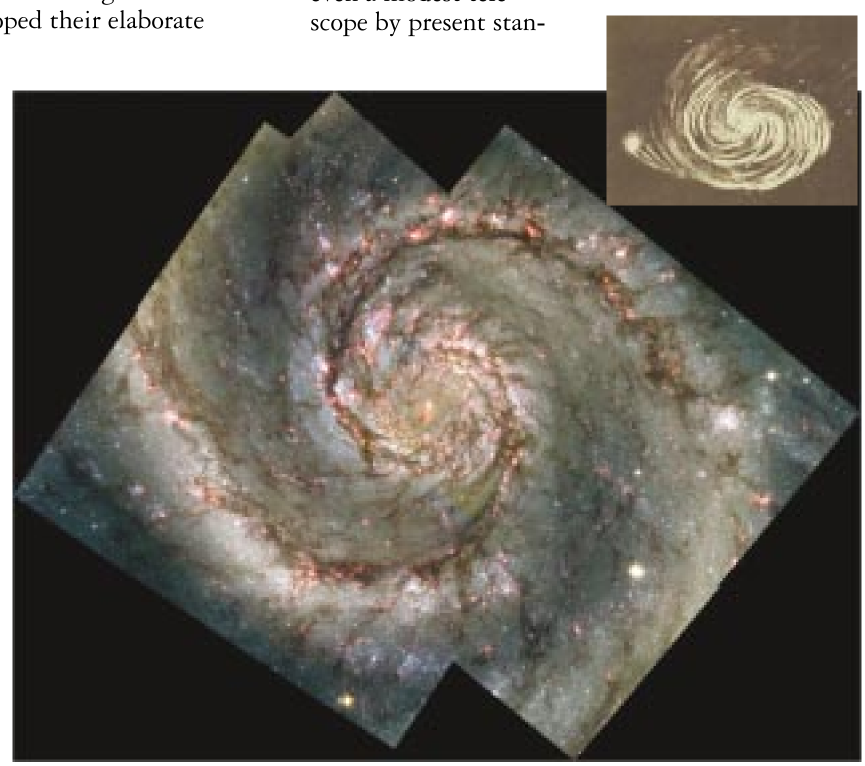
Above: The history of the universe. The Big Bang 15 billion years ago and the resulting microwave background are mere fractions of cosmic history at one end, with the age of man an insignificant segment at the other. The first galaxies began to form when the universe was about a billion years old, evolving over the next 10–12 billion years into the mix of spiral and elliptical galaxies we see today.

telescopes such as the twin Kecks are working together with the Hubble Space Telescope in a complementary partnership, as I shall explain.

We think the universe is about 15 billion years old. We can deduce this from the age of the oldest stars in our locality as well as from the rate at which the universe is expanding—extrapolating backward to that moment when the cosmic density would reach an infinite value. (Actually, it's something of a relief that these two estimates now agree; this wasn't always the case.) The drawing above shows roughly where we are today in cosmic history. From the Big Bang to the first directly observable era, when the microwave background was produced, was just a sliver of time compared to the long subsequent period during which galaxies formed and developed their elaborate structures. Similarly, life in the solar system began only 4 billion years ago, and modern civilization is only a minuscule chapter at the end of the cosmic tale.

My own research covers the very large time interval between the production of the microwave background and the modern day (so naturally I tend to think it's pretty important!). But astronomers don't generally deal in units of time; rather we prefer to think in terms of the *redshift,* denoted conventionally by the letter z. This is inferred by the displacement of a distant object's spectral lines toward longer wavelengths. Redshift is related to the distance (via the cosmic expansion which "stretches" light) and the "look-back" time to a source, but more fundamentally it indicates the scale of the universe at the time the light from that redshifted source left on its long journey to our telescope.

It takes some mental agility to deal with this concept, but, just as an archaeologist can slice below the streets of Rome or London and probe different eras, so astronomers can slice the observable universe into different time shells. The finite speed of light means that we're looking back in time as we look deep into space and, remarkably, even a modest telescope by present stan-



Right: The "grand design" spiral galaxy, Messier 51, was the first in which the spiral structure was observed visually (by Lord Rosse, who also sketched it, inset). The recent Hubble Space Telescope image (observed by Scoville and Polletta) of the central regions of Messier 51 shows the blue light that arises from the continued production of young stars in this class of galaxy.

Messier 87 is a giant elliptical galaxy in the constellation of Virgo. This color image demonstrates the remarkably homogeneous color of the constituent stars. Orange stars generally indicate an older population, and the uniformity suggests that such galaxies are devoid of young stars, having exhausted their hydrogen supply many billions of years ago. (Courtesy Anglo-Australian Observatory)

dards, such as the 100-inch Hooker Telescope, is capable of looking back to galaxies 5 billion years ago, corresponding to $z = 0.5$. The physical significance is that $1+z$ (i.e. 1.5) is the factor by which the universe was smaller in linear terms at the time such a source is being observed. Redshift is thus an important yardstick and has the distinct benefit, unlike distance, of being directly observable once a spectrum of a distant source is obtained.

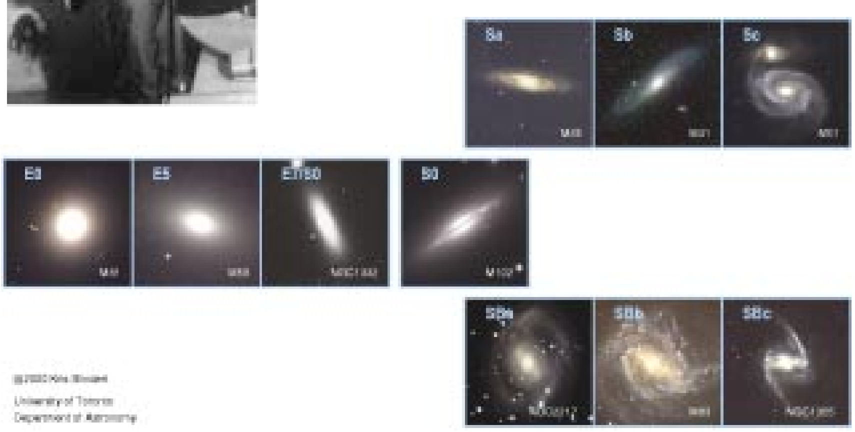
Seeing a particularly distant object is obviously exciting, since we are directly witnessing the past. This excitement has driven the construction of larger and larger telescopes over the past century, but to understand the significance of what we are seeing, it is first helpful to conduct an inventory of what's around us today. Anyone who has casually examined a picture book of galaxies will be aware that there is quite a variety of types. The stunning Hubble Space Telescope image on the opposite page, observed by Moseley Professor of Astronomy Nick Scoville and Maria Polletta at JPL, is the Whirlpool Galaxy, Messier 51—a famous spiral. Inset is a wide-field view of the same galaxy, as sketched by the third Earl of Rosse in the middle of the 19th century using his 72-inch Leviathan telescope, which was the world's largest at the time. If you think it's tough to observe galaxies nowadays in Los Angeles, I suggest you go to the peat bogs of Ireland, as my wife and I did a couple of years ago, to visit Lord Rosse's telescope, which rarely sees a clear night. That amazing telescope has, through great efforts, been recently refurbished. The telescope is unusual in being on a fixed azimuthal mount so an object of interest can be observed only for a short period, which oftentimes would coincide with cloud or rain. One has to admire Rosse's perseverance; he discovered spiral structure—by eye of course, without any recording medium. He was, by all accounts, somewhat eccentric. (Indeed, most astronomers are eccentric, Caltech having its fair share!)

Besides spirals, we also see elliptical galaxies, such as Messier 87, which are simply balls of stars. You'll notice that most of the stars in this galaxy (left) have a uniform orange-red color, and this is quite an important distinction between these systems and the spirals discussed above (which have many blue stars). The color of a star is a fairly reliable guide to its age—the redder stars are older. Uniformity of color is thus an indication that the galaxy had a simple history, with all its stars being the same age. Bluer stars such as those seen in the beautiful spiral arms of Messier 51 formed *after* the bulk of the galaxy assembled.

In 1926, Edwin Hubble classified the galaxies he photographed by their visual color. His famous diagram resembles a tuning fork. He ordered spirals in terms of the degree to which their arms are tightly wound. He further divided spirals into normal examples and those with nuclear "bars." Hubble's student, Allan Sandage, PhD '53, who is still working actively at the Carnegie Observatories, summed up Hubble's achievement when he said that this diagram, which was a purely visual classification system, describes a true order among the galaxies. In other words, it's a lasting classification that has a good physical basis. It is a tribute to Hubble's intuition that this classification system is still the one in use today.

In Hubble's tuning-fork diagram, two key physical facts should be noted. First: as we go

Edwin Hubble at Palomar.



Hubble's "tuning fork" classification system for normal galaxies is arranged here with photographs of typical examples. He classified galaxies according to the dominance of their central bulge, which is largest for ellipticals (E) and minimal for spirals of type Sc. Note also how the integrated color becomes redder as the bulge becomes more dominant. The intermediate lenticular galaxies (SO) appear as spirals with red colors similar to ellipticals. Hubble also separated spirals into barred (SB) and non-barred versions. (Courtesy Kris Blindert, U. of Toronto)

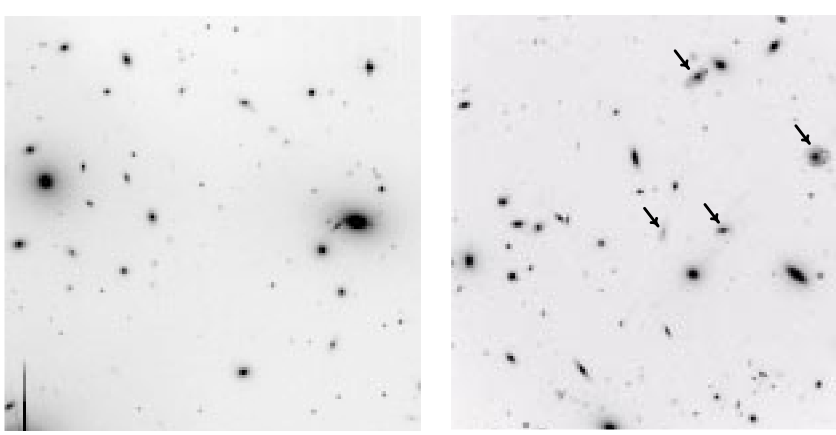
Ellipticals are particularly numerous in dense clusters. The left panel (courtesy Anglo-Australian Observatory) shows that such systems in the nearby Virgo cluster have remarkably similar colors, powerful evidence that they completed their star formation billions of years earlier. Similar analysis of the HST image (right) at a redshift of 0.54 (6 billion years ago) implies that earlier examples share similar properties, strengthening further the conclusion that these galaxies contain very old stars.

from spirals toward elliptical galaxies, the central region, which we call the *bulge* of the galaxy, becomes more prominent. When we reach the ellipticals, the bulge effectively becomes the whole galaxy. So one way to characterize the sequence physically is in terms of the fraction of the galaxy's total light contained in this bulge. This gives a structural explanation of Hubble's sequence.

Second: as we go along the sequence in the opposite direction, the galaxies become bluer in color. As we discussed, the ellipticals are uniformly orange-red, but by the end of the sequence on the right, the spiral galaxies are much bluer except in their bulge regions. Elliptical galaxies are thought by many to be very old, perhaps the first systems that formed, whereas the spiral galaxies appear to have continued to form stars, as is evidenced by their blue, younger stars. Note that spirals need not be actually younger than ellipticals; it could be that they are just as old but simply continued to form stars to more recent times. In this respect, Hubble's sequence is thus telling us about the *rate at which stars form to make a galaxy*. A simple explanation would be that ellipticals are those galaxies that formed their stars fairly quickly at some point in the past, whereas spirals continue to form stars over their entire lifetimes. Now as stars form from cold clouds of hydrogen gas, this distinction would be telling us about how quickly the reservoir of gas was exhausted—fairly quickly in the case of the ellipticals but very slowly for the spirals.

This speculation, from the "fossil record," about how the local population of galaxies came to be is all well and good, but the great advantage of looking at great depths into the universe is that we can trace the evolution of these objects directly—we can look for elliptical galaxies and spirals at earlier times. Because objects appear smaller when viewed at a great distance, it was not until the Hubble Space Telescope was launched that it was possible to accurately distinguish between, for example, spirals and ellipticals at significantly earlier cosmic epochs.

If we look at distant clusters of galaxies, where galaxies congregate together under a common gravitational field, even 6 billion years ago we find that elliptical galaxies are still present with approximately their present properties (above). Importantly, there's still a striking uniformity in their colors, both internally and when we compare one galaxy with another at the same redshift in a different cluster. Either these galaxies all had star-formation histories that were somehow synchronized across the population (which seems a bit far-fetched), or whatever differences occurred in their histories happened so long ago that by the time we are now viewing them, those differences are inconsequential. This result, which we



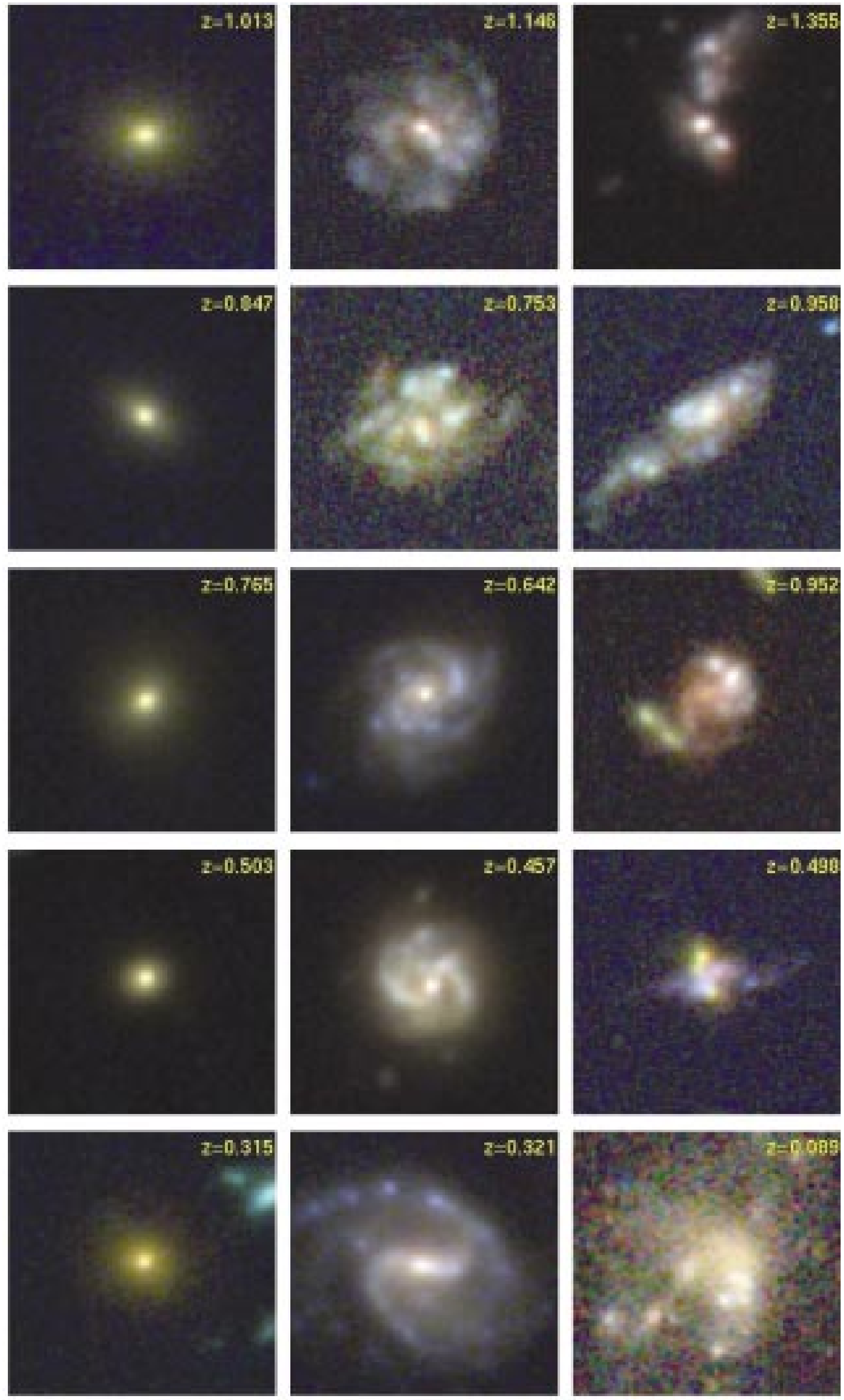
A comparison of galaxy populations in their dense cores shows mostly old ellipticals and lenticulars in the nearby cluster (left). But in the distant cluster (right), at a redshift of 0.4 or 4.5 billion years ago, the HST reveals, along with the ellipticals, a different population: spirals (see arrows). These spirals must have suffered some fate in the intervening time that transformed them into the later abundant lenticulars.

deduced fairly soon after the Hubble Space Telescope was launched, is consistent with the view that the stars that make up elliptical galaxies in clusters formed a very long time ago, perhaps 12 billion years, corresponding to a redshift greater than 3. So, for these galaxies at least, we are confident that their stars formed fairly soon after the Big Bang.

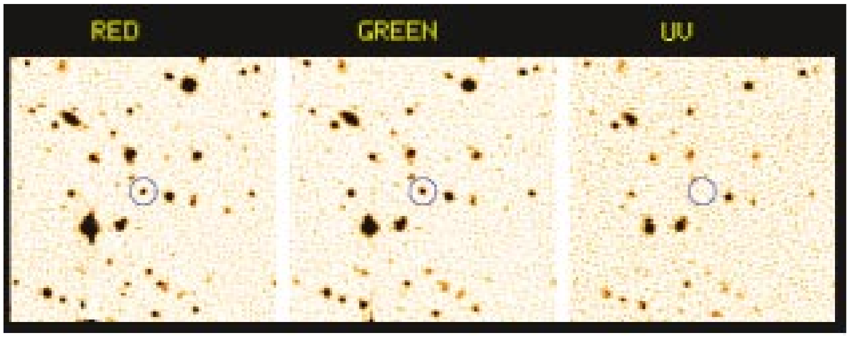
Unfortunately, as so often happens, as we learn more we find that things may not be so simple. Galaxies don't evolve in isolation. We have already seen that they cluster together, and, as we wind the clock back, the universe gets smaller, so galaxies get closer to one another. It seems reasonable to suppose one galaxy can be influenced by its neighbor. Take the nearby cluster (the left panel) at the bottom of the opposite page: the galaxies in the dense central regions look fairly uniform and featureless; many of them are indeed ellipticals. But if we look back to only 4.5 billion years ago (a redshift z=0.4) in the same kind of environment, we see spiral galaxies (right-hand panel).

Let me now introduce a classic problem of evolutionary deduction; we cannot be absolutely sure that a particular cluster seen 5 billion years ago evolves into a particular one we see today. The only way around this is to appeal to a statistical comparison of many such systems. When we do this, we get the revelation that some galaxies must be transforming from one class to the other. It seems there are environmental processes that change a spiral galaxy, removing its gas supply, curtailing the production of young stars so as to make them end up as a galaxy of a different Hubble type. Clearly, if galaxies can change from one class to the other, we are going to have to be cleverer in figuring out how to trace their evolution.

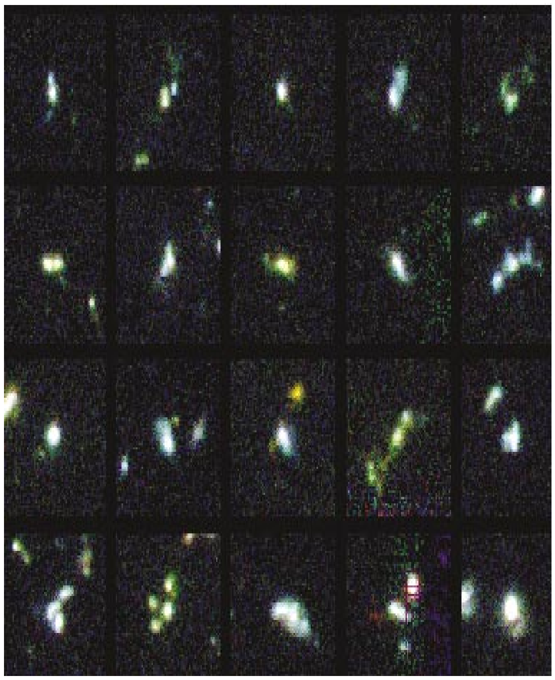
So, how far back can we see regular spirals and ellipticals? The Hubble Space Telescope can just about identify recognizable spirals and ellipticals at a redshift of 1, corresponding to about 8 billion years ago. Beyond that, more examples may exist,



The redshifts of these HST images of faint galaxies are drawn from a comprehensive survey undertaken by Ellis and his colleagues, using ground-based telescopes. Galaxies of various types have been studied to a redshift of 1, corresponding to about 8 billion years ago. Such systematic surveys of random patches of sky are essential to understanding how normal "field" galaxies (those outside dense clusters) evolve. The left-hand column shows ellipticals, spirals are in the center column, with irregulars on the right. A much higher fraction of irregulars is seen in the past, and Ellis's group is trying to understand what happened to them.



Left: The most distant galaxies can be picked out from the myriad of other systems in the foreground by using a technique based on the ultraviolet-absorbing effects of hydrogen gas. This absorption produces a characteristic drop in the light received from the most distant galaxies. In these images of the same field with different color filters, the central source disappears in the ultraviolet, indicating that it's sufficiently redshifted for hydrogen absorption to have occurred. (Courtesy Chuck Steidel)



Right: HST images for an array of distant galaxies found via the above technique. At these redshifts (z=2–3, corresponding to 10–12 billion years ago), few look like familiar spirals and ellipticals. Many have irregular forms and multiple components, and these are young systems in the process of assembling.

but we start losing resolution with the HST's current camera, and we also find it hard to measure accurate redshifts from which to deduce distances, except in restricted cases. My recent work has involved taking a census of galaxies of different types looking back 4 to 8 billion years. Using large ground-based telescopes, in partnership with the HST, I've been categorizing galaxies according to their morphologies. Lest I overemphasize the Hubble Space Telescope, let me point out that a crucial ingredient in this project is the galaxy redshift, available only from ground-based telescopes; this tells me how far back I'm looking. I have also measured their infrared brightnesses with the Keck, which determines how many stars are in each one. Infrared light is a better guide to the underlying stellar composition of a galaxy than blue light, which highlights only the transient young stars.

One of the most interesting results from this census of galaxies back to redshifts of 1 is the preponderance of faint galaxies that are neither ellipticals nor spirals; these are irregular in form and frequently seen to be blue and to be interacting with other systems. Although we can find local irregulars, they appear to have been much more common in the past. What led to their demise?

The infrared brightness provides us with an important accounting tool of how many stars there are in each category (spiral, elliptical, and irregular) at each epoch. By tracking the fraction of the total stellar mass in each type at each redshift we can determine whether galaxies are changing from one type to another. We find that the stellar mass in ellipticals and spirals is slowly growing as the universe expands, at the expense of a substantial decline in the stellar mass in irregulars. We deduce that there must be some process for "converting" irregulars into these more regular forms.

The most likely explanation for these transforms is that the merger of galaxies plays a key role in their evolution. We can find examples of galaxies interacting with one another today, and computer simulations suggest that if we throw two self-respecting spirals at each other, they produce, perhaps surprisingly, not a mess, but a galaxy that is further to the left in Hubble's tuning-fork diagram. Because the universe was denser in the past and galaxies were closer together, merging was surely more prevalent then.

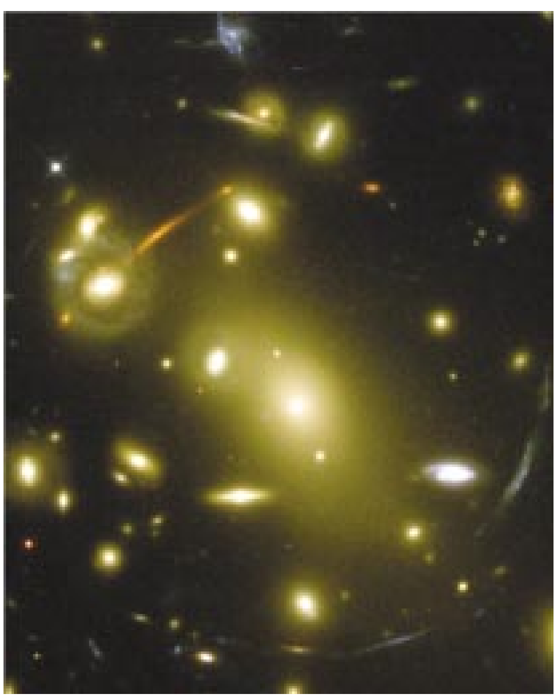
Let us now consider what galaxies look like even before 7 billion years ago. Professor of Astronomy Chuck Steidel and his colleagues have been locating and studying such early examples. One of the key techniques that Steidel has pioneered is based on the energy spectrum of a galaxy, utilizing the expected drop in ultraviolet light caused by the absorbing effects of hydrogen gas, both in the galaxy and along the line of sight to it. This absorption edge occurs in the far ultraviolet but, for a source beyond redshift 3, the wavelength at which it occurs is shifted into the optical, where it can be detected with sensitive cameras at Palomar. A galaxy at redshift 3 or more is visible in red and green filters but is extinguished in the ultraviolet

(UV) filter. This "drop" is the telltale sign that it is an extraordinarily distant object. The project is an excellent example of the partnership between Palomar and Keck. Palomar searches for these signatures with its panoramic cameras, and Keck, with its superior light grasp, verifies via the spectrum that this is indeed a very distant object.

What do the earliest galaxies look like? Interestingly, they don't look anything like Edwin Hubble's galaxy sequence. Many of them are lumpy with multiple components; they're physically very small, and the spectra tell us they are forming stars at a prodigious rate. So it seems that these may well be primeval galaxies, the ancestors of the bigger systems that we see at later times.

So, now we've used a succession of telescopes to explore the depths of the universe, and we have some kind of census at each epoch. We have Steidel's early star-forming galaxies at redshifts of 3 to 4; we have my inventory of all massive galaxies at redshifts up to 1; and we have the present-day Hubble sequence. How do we join these data together into a single coherent story?

Many astronomers believe the answer to this question lies in understanding the role of dark matter. It has been clear for more than 10 years that the universe contains a large amount of dark matter. We think it is present at the earliest stages in the expansion of the universe and that it acts as a seed for the infall of hydrogen gas, which leads to the formation of stars and subsequently galaxies. In the same way that a dust particle can accelerate the growth of a raindrop, so a dark-matter particle can act as the gravitational focus to lure hydrogen gas into that region. Without dark matter, it seems impossible to explain the structures we see around us today.



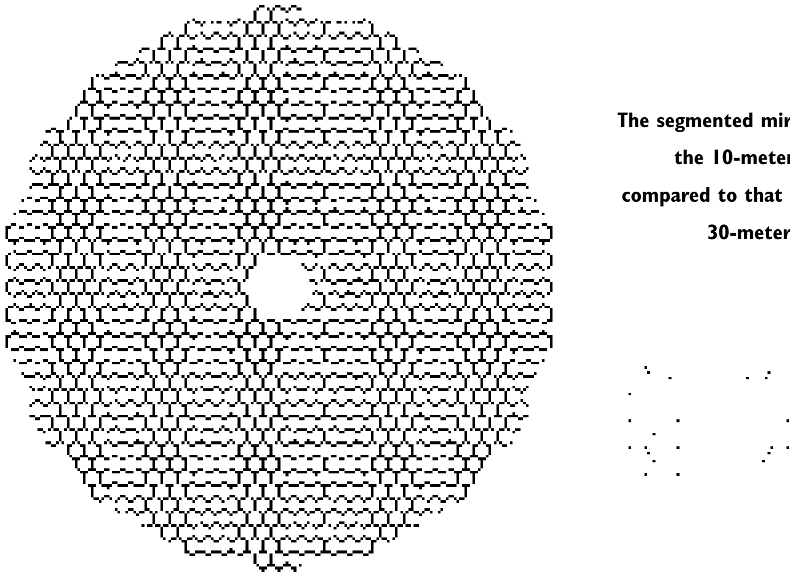
Einstein at work: Light signals from distant galaxies are distorted by foreground masses, as can be seen in this HST image of the rich cluster Abell 2218 (z=0.18). The orange/red objects are cluster ellipticals, but the blue and red distorted arcs represent faint background galaxies stretched and magnified by the gravity of Abell 2218—a phenomenon called gravitational lensing predicted by general relativity. The degree of distortion can be used to determine the mass of the cluster, which exceeds by 50 times the mass of the visible orange galaxies. This is a simple but powerful proof that dark matter exists.

Without dark matter, it seems impossible to explain the structures we see around us today.

You might ask how we are so sure dark matter is there if we can't see it. Well, we can detect its effect in a number of ways. The most elegant in my opinion follows from Einstein's prediction that light rays can be deflected by massive objects. And just as objects seen through an optical lens can be distorted, so a sheet of distant galaxies appears distorted by lumps of matter in the foreground *even if that matter is not shining*. In the illustration at left of a cluster of galaxies, the arc-like objects are much more distant galaxies whose light is being gravitationally deflected and stretched by matter in the foreground cluster. The amount of distortion seen reveals there is 50 times as much mass in this cluster as that estimated from the stars that make up the cluster galaxies. Very recently my collaborators and I detected the same distortions statistically in random fields on the sky, providing valuable confirmation that dark matter is not just sitting in special locations like the cluster shown.

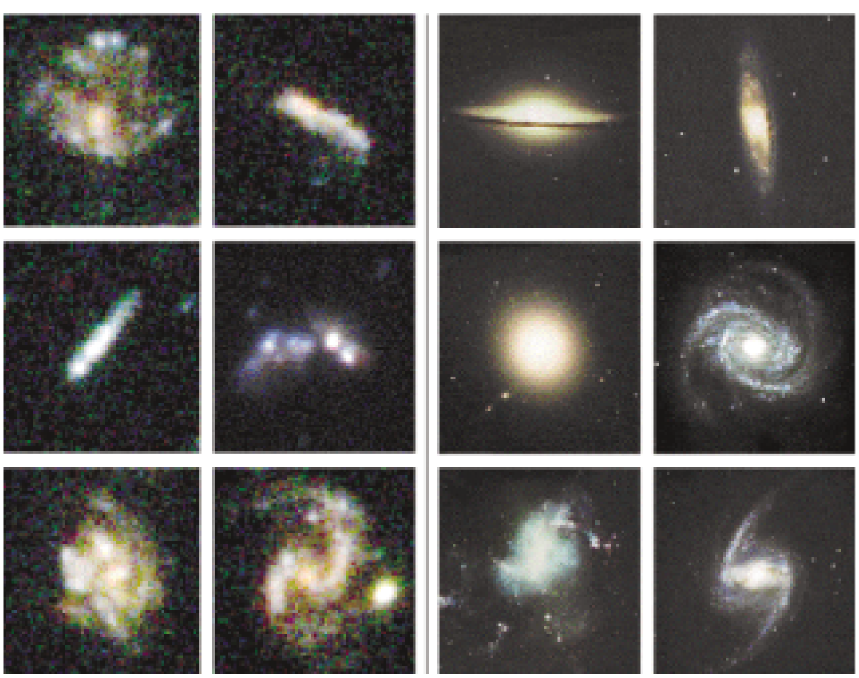
It really would be helpful to know what this dark matter *is*, but that's another story. (Let me confess, at least, that nobody is really sure!) For our purposes, it's enough to know that it obeys the laws of gravity, and because it does, we can predict quite easily how it congregates and assists in forming the structures that seed galaxy formation. This theory of hierarchical assembly is remarkably simple and powerful. It can explain the fluctuations in the microwave background seen shortly after the Big Bang, and also the large-scale distribution of galaxies that we see today. It is ultimately capable of predicting the origin of Hubble's sequence, and indeed several theorists are already very confident they are on the right track. Our job as observers is to keep them under control and make sure they don't become overconfident in their assertions.

The challenge we now face is how this assembly history, which we can sketch in outline, leads to the detailed structures that we see inside galax-



The segmented mirror of the 10-meter Keck compared to that of the 30-meter CELT.

Below: How do we establish the "big picture"? Astronomers have now developed various techniques to select sources at different epochs in the history of cosmic expansion. What are the processes that transform the ancient galaxies on the left (seen in HST images) into the mature regular systems on the right that we see today?



ies—for example, the bulges and bars in spirals and the physical processes that occur when irregulars merge with larger systems and lose their identity. Bars and bulges are just examples of the kind of internal details we would like to study at high redshift; they are important diagnostics for the dynamical state and evolution of spiral galaxies.

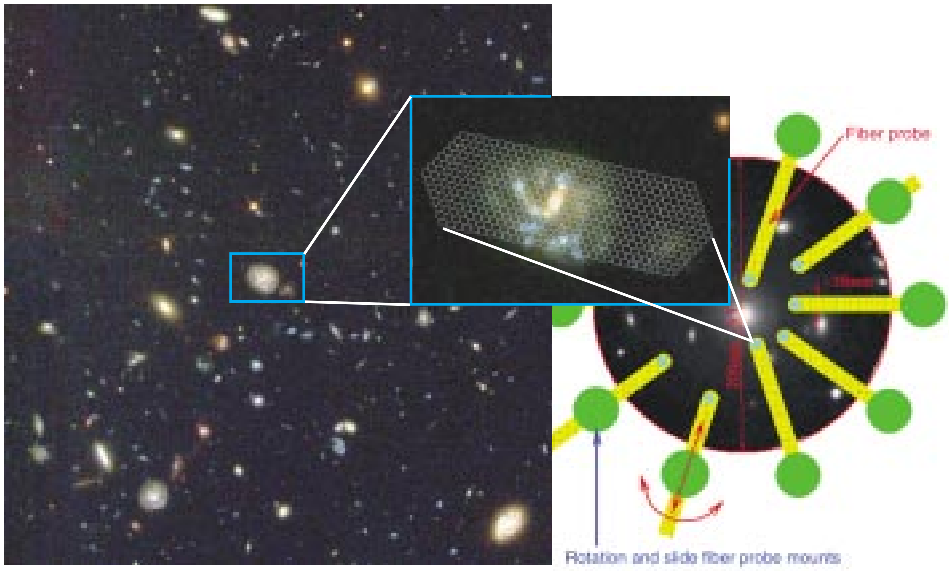
The Keck Telescopes have truly revolutionized our view of the distant universe, but, to be frank, even those giants will be unable to study precisely the *internal properties of distant galaxies*. To analyze the spectroscopic signal from individual subcomponents of a faint galaxy demands the exquisite angular resolution of the Hubble Space Telescope *and* about 10 times the light grasp of the Keck Telescope. A larger aperture is essential to dissect galaxies into their subcomponents because each subunit will be correspondingly fainter and more challenging to observe.

The Keck's 10-meter-diameter primary mirror, the world's largest, is composed of 36 hexagonal segments, each with an edge length of 0.9 meters. Keck was a very ambitious experiment at the time it was conceived, because it was the first telescope to be made of many individual segments. Can one contemplate making a larger primary mirror from more segments and hence a more powerful telescope?

This brings me to the proposed CELT project, the California Extremely Large Telescope (a name I'm particularly fond of since I *am* a Celt). Modeled on the segmented-mirror technology of Keck, the 30-meter CELT mirror requires a thousand segments, each with an edge length of 0.5 meters. It may sound like a formidable task, but the transition from the 200-inch telescope at Palomar to the Keck could, in some sense, be viewed as a more imaginative leap and a bigger technical challenge than replicating the Keck's technology on a larger scale.

With triple the diameter, CELT will have 3^2, or 9 times, the light-gathering power of the Keck. The current design has a fast focal ratio (or f/number), which means that the dome that contains it will be as small as possible. A unique feature is its wide field of view, bringing many objects at once within the range of observation. And my colleagues are confident they can achieve the resolution of the Hubble Space Telescope, if not better, over a limited field—which is very exciting. In the last decade, there's been a revolution in our ability to correct the blurring that's caused by the earth's atmosphere, a technique we call adaptive optics.

So where are we with this undertaking? As with the Keck Observatory, this is a 50–50 partnership with the University of California, led by Jerry Nelson, BS '65, the former project scientist for Keck. We've been working on the



Catching faint, early galaxies in the act of assembling themselves is a major motivation for building CELT. An array of fiber probes trained on a sample of irregular galaxies (above, center) can analyze the spectroscopic data of the galaxy's subcomponents and answer questions about their physical state. Keith Taylor, member of the professional staff, is designing robotic fiber probes (one example is shown above, right) that will dissect the images of many faint galaxies simultaneously.

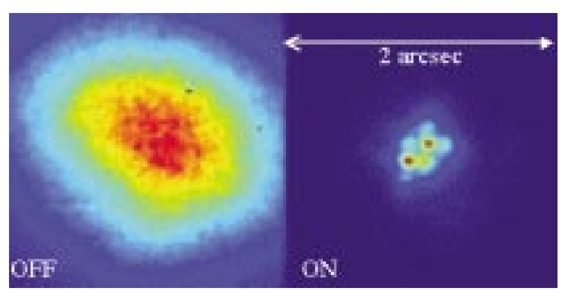
design of the telescope for over a year, and working groups composed of astronomers and instrumental scientists have been looking into various concepts. We have developed a scientific case that acts as a target of what we want to achieve. We've also been studying the instruments. And we've been looking at where to put the telescope.

The biggest challenge is not necessarily the size of the mirror and the manufacture of the segments. Nelson believes the mirror segments can be made much more efficiently than they were for the Keck, and he has been investigating novel techniques for polishing many simultaneously. Segmented-mirror technology is a relatively new development in world astronomy, and Caltech and UC are well ahead of the competition in the only practical way to make larger primary mirrors.

Adaptive optics will help enormously. This technique allows us to correct for the distortion of Earth's turbulent atmosphere, thereby gaining the same resolution in a large, ground-based telescope that we get from spaced-based ones, like the HST, above the atmosphere. We have already demonstrated this technique at an elementary level at both Palomar and Keck Observatories. Here's how it works: A light wave coming through the atmosphere gets distorted. When the signal from that wavefront hits a mirror with several hundred deformable components, the mirror adjusts the position of each of the components to create an opposite deformation that cancels out that of the incoming wavefront. In the demonstration at Palomar, in fairly typical conditions, my colleagues were able to correct the blurred image of a binary star and see it at considerably improved resolution. It's exciting for me personally that Palomar can play a key role in developing this technology, further integrating our various observatories.

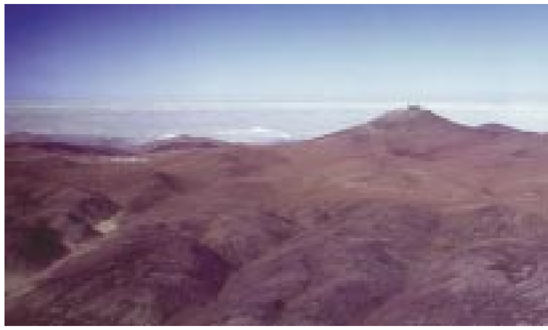
A telescope is, of course, just the light-gathering collector; we need big instruments—detectors, spectrographs, cameras—to analyze the light collected with our big mirror. Typical Keck instruments weigh four tons. Scaling this up to a 30-meter telescope, we could be talking about instruments the size of a tennis court—unless we're very clever. Innovation will be vital in keeping the cost down. The largest detector at Palomar, the panoramic imager that's used for finding Steidel's remote galaxies that I mentioned earlier, contains six charge-coupled devices (CCDs), each 4,000 by 2,000 pixels. CELT will need much larger detectors, including huge ones operating at near-infrared wavelengths, where the technology is not yet so far advanced. And, in order to dissect a distant galaxy and measure the signal from each subcomponent, we're going to need robots that position little units on top of the galaxies we want to study.

Where can we put this giant telescope? We have two basic options, one in the northern and one in the southern hemisphere (believe me, there are no other hemispheres, we've looked). The first is located on the summit of Mauna Kea. That's where the two Keck Telescopes are, as well as



An adaptive optics technique developed at Palomar by Rich Dekany, BS '89, member of the professional staff, and colleagues at JPL uses a sensor tuned to real-time measurement of the distorted incoming wavefront to restore the smeared image of a binary star (left) to the resolution typical of an HST image (right).

Two possible sites for CELT are Mauna Kea (right) in Hawaii and the Atacama Desert (below) in Chile. Professor of Astronomy George Djorgovsky leads the site review team.



several others. As you can see (above) it's getting kind of crowded up there. Fortunately a plan has been developed for replacing the smaller telescopes with larger ones over the years; we are hopeful that CELT will be a high-priority replacement in the next decade.

The other alternative is in the southern hemisphere, in Chile's Atacama Desert. This is where the Europeans have their VLT (Very Large Telescope), which consists of four 8-meter telescopes that, when linked as an interferometer, will effectively operate as a 16-meter mirror. There are a number of excellent sites in the Atacama Desert, but their characteristics are not as well known as those of Mauna Kea. We have drawn up a list of criteria, including how stable the atmosphere is, how the weather varies with seasons, and whether the nights are uniform in temperature. An international program, involving ourselves as well as other U.S. and international teams, is currently gathering site information for many of the Chilean locations. In view of economic and political considerations, it's most important to have at least two viable sites.

The challenge we now face is to understand how gravity built up the structures we see. We have a theory based on the presence of dark matter, but we need to understand the detailed physics of how it led to galaxies assembling.

To sum up: With our existing telescopes we have already explored the universe over a wide range in its cosmic history, back to barely a billion years after the Big Bang. But the exploring is over. The challenge we now face is to understand how gravity built up the structures we see. We have a theory based on the presence of dark matter, but we need to understand the detailed physics of how it led to galaxies assembling. We are confident that we can develop the technology to examine the internal workings of distant galaxies, but for this we need a much larger telescope and investment in detectors, adaptive optics, and, of course, the manufacture of hundreds of mirror segments. Even though the 30-meter telescope is a very ambitious experiment, I consider it no more ambitious than the 200-inch Hale was in the 1930s and the 10-meter Keck in the 1980s. In the case of adaptive optics we have the great advantage that we can experiment with our existing telescopes, such as the venerable Palomar Observatory, which will be given a new lease on life as a valuable base from which to make these key innovations for the future. □

Professor of Astronomy Richard Ellis claims no responsibility for naming the California Extremely Large Telescope, although he is a genuine Welsh-born Celt himself. He earned his B.Sc. from University College London in 1971 and his D.Phil. in astrophysics (1974) from Oxford University. From 1974 to 1993 he was a member of the faculty at the University of Durham, and in 1993 was appointed the Plumian Professor of Astronomy and Experimental Philosophy (a chair formerly held by the late Sir Fred Hoyle) and director of the Institute of Astronomy at the University of Cambridge. Although he had been a visiting professor at Caltech in 1991 and 1997, the lure of large telescopes finally brought him here on a more permanent basis in 1999 to continue to pursue a number of aspects of observational cosmology—and even larger telescopes. He is also director of Palomar Observatory and retains a joint appointment as professor of observational astrophysics at Cambridge.

Celtic influence? The 30-meter California Extremely Large Telescope happens to be about the same diameter as a somewhat older astronomical observatory.

Biodefense: Scenarios, Science, and Security

by Steven E. Koonin

On November 7, Caltech sponsored a forum on biodefense, free and open to the public in Beckman Auditorium. Moderated by veteran Southern California news broadcaster Jess Marlow (now with KCET's "Life and Times"), the panel included Dr. Alan P. Zelicoff, chief scientist of Sandia National Laboratories' National Security and Policy Planning Division, who developed the Rapid Syndromic Validation Project (RSVP), a medical database designed to report and contain outbreaks of disease; Dr. Jonathan E. Fielding, director of public health of Los Angeles County and professor of health services and pediatrics at UCLA; and Steven E. Koonin, professor of theoretical physics and Caltech provost. Koonin has advised the government for more than a decade on the technical aspects of national security and in 1998–99 led a large study on civilian biodefense for the Department of Defense. His remarks at the forum are adapted here. The entire forum can be viewed on line at http://atcaltech.caltech.edu/theater/.

My involvement in the biodefense business started about two and a half years ago, when I led a study by some 20 academics looking at the defense of the civilian population against biological terrorism. We submitted our report in the fall of 1999. Over the past few weeks, it has been an eerie feeling for me to go back and read that report in the context of recent events.

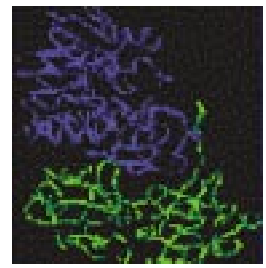
I'd like to share with you some of the contents of that report. First I'll describe some of the "what if . . . ?" situations that we used to get our minds around the problem. No one expected events to play out exactly as described, but they give a good idea of what the general aspects are. Then I'll go through some of the technical recommendations that we made, to give you some sense that there *are* things that we can be doing to better defend ourselves against bioterrorism. And finally, I'll make a few remarks about organization.

We came up with four scenarios. The first involves anthrax, which we are all too familiar with these days. What we hypothesized two and a half years ago was the spreading of anthrax spores from the platforms of the New York City subway. It turns out that the trains in tunnels are very effective at spreading the spores around. In our scenario, this is done without any prior notice, no tipoff that it's going to happen. But then on the following Saturday comes a tip that a terrorist group has attempted to carry out such an attack.

What would happen if this were to take place today? First, we don't have validated dispersal models; it would be very difficult for us to say, a priori, where the spores would go and, hence, who would be affected. Second, about 4 million people ride the New York subways every day, and even if only one percent of them contracted the disease, that's still 40,000 people.

If an attack is overt—that is, if we have warning ahead of time—then we can try to reduce casualties by distributing the appropriate antibiotics. The names are familiar these days: Cipro, doxycycline, penicillin, and so on. But if the event is covert—that is, if we don't know about it—then there is no "event." There are no first responders to distribute medication. A few days later, people start checking into hospital emergency rooms with severe distress, and by that time, most of the people who exhibit symptoms will be lost. Or at least that's the rule from previous experience; I think the rule is being updated as we deal with the cases of inhalation anthrax that have taken place recently. In any case, there will be a panic rush on medical facilities as soon as it becomes known that there has been a wide-scale dispersal of spores.

Scenario number two involves smallpox: a terrorist cell plants smallpox in the air ducts of a flight from Europe to the United States with 265 people aboard. The first sign of a problem is when the whole air crew reports in sick two weeks later (the smallpox incubation time is about 12 days). At the same time, some group takes credit for "infecting the Great Satan" with smallpox. This disease, as we have all heard lately, is highly contagious. To give you a sense of how serious it can be, let me offer a historical digression: on March 1, 1947, a man arrived in New York City by bus from Mexico. Four days later he was hospitalized with a fever and died five days after that. Because he had a variant of the disease called hemorrhagic smallpox, which is not as obvious to identify, it took about a month before this was diagnosed correctly. He induced three secondary and twelve tertiary infections, mostly among the health-care workers who were caring for him. Three of them died. Among unvaccinated populations, the fatality rate is about 30 percent for smallpox, so this number is consistent. As a result of that one case and those secondary and tertiary infections, New York City immunized more than 6 million people, essentially depleting the whole U.S. vaccine supply on just one case.



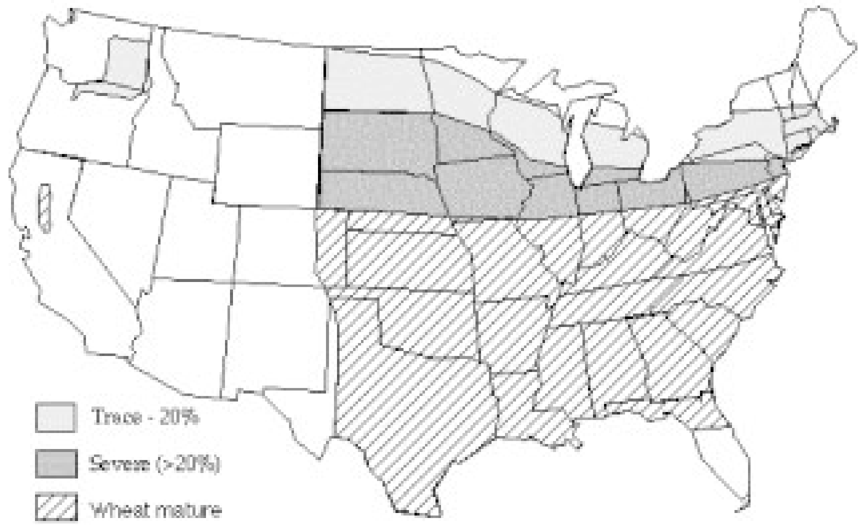
The lethal ricin protein (right) is derived from castor beans (center), the seed of the castor oil plant (*Ricinus communis*, left).

So, what would happen today if this event were to occur? Again, there's no actual "event" and no responders. Nothing happens for two weeks. Eventually we would realize what's going on and would quarantine and vaccinate. Right now we have 15 million full-strength doses on hand. Medical experts think that this can be diluted to about 75 million, and, as you've probably read in the newspapers recently, drug companies have already started cranking up vaccine production.

Returning to our smallpox scenario, the effects spread continentwide, because all of these passengers would be catching their connecting flights and dispersing across North America before anything was noticed. There's certainly the possibility of an epidemic, and, as I mentioned, 30 percent of unvaccinated people typically die. While vaccinations stopped in 1975, some of us may still have some immunity from the vaccinations we received as children, but it is thought that the efficacy of the vaccine decays on a five- to 10-year timescale. As in the previous scenario, as soon as the cases start showing up, a panic rush on medical facilities will ensue. The fact that smallpox is communicable and so virulent make this probably the most devastating possibility, and you can understand why the public health officials are so worried about it.

Scenario number three is not quite a biological attack, but it's an attack using a chemical agent derived from a biological system. The agent in this case is ricin. You can imagine this scenario in terms of the Oklahoma City bombing attack, but with the bomb wrapped with ricin.

Ricin is a chemical produced from castor beans, which contain this biologically very interesting protein. This protein manages to get into cells and gum up the ribosomes, which are the little machines that make proteins in your body, and so are essential for you to keep on living. A lethal dose of ricin is as small as 10 micrograms when inhaled; that's a very small droplet. The symptoms occur within a few hours: fever, cough, nausea, and death within three days at most. There is no known treatment; once you've been exposed to ricin, you die.



Wheat rust exists naturally in the United States, as shown in this map tracing its occurrance in the first week of July 1999. But deliberate infection would still have economic and psychological effects.

What would happen today? The local first responders, the people who show up to deal with the explosion, would be unlikely to consider a biological agent. Eventually it would be recognized as a hazardous-material incident, but because the effects would be very rapid, the likely casualty figures would be in the thousands rather than the hundreds you would have expected from the explosion by itself.

The last scenario is an agricultural one: a wheat-rust attack in the Great Plains by an enemy state. Remember, this was two and a half years ago, and at the time it was President Milosevic whom we were concerned about. In our scenario, Milosevic announces that if NATO doesn't stop bombing, he's going to infect the American wheat crop with wheat rust in several counties in the Great Plains.

How would that play out now? Wheat rust is an ongoing problem in the United States, even without somebody releasing it deliberately. You can see on the map of wheat rust, above, for the

But you just need to remember what happened with foot and mouth disease in Great Britain this past year to get some sense of how disruptive an agricultural attack could be to the economy.

first week of July 1999 when we did our study, that it ranges from "trace" through "severe" in a band across the country. So there would be only a modest economic impact. In fact, in some years, 10 to 12 percent of the California wheat crop is lost to this fungus. But there would be an unknown psychological impact, because we would see the ability of a foreign country to reach into our homeland. Wheat rust does come in a variety of strains local to a given area, and so you might be able to distinguish a deliberate introduction of a strain by its difference from the naturally occurring local ones.

You don't hear much about agriculture as a bioterrorist target. But agriculture accounts for 13 percent of the U.S. gross domestic product and 17 percent of employment, most of it in the food-processing and distribution chain. A number of agents, such as foot and mouth disease, African swine fever, wheat rust, and rinderpest, don't harm humans but can severely disrupt the economy, which is the purpose of attacks like this. It's not about the food supply; the food supply is much more robust than could be taken out with a single agent. But you just need to remember what happened with foot and mouth disease in Great Britain this past year to get some sense of how disruptive an agricultural attack could be to the economy.

What lessons can we draw from these four scenarios? There are several. The first is that good intelligence is the best defense. Knowing our opponents' goals, capabilities, and intentions and trying to stop a release before it happens is obviously the best way to go about things, *if* we can manage to do that.

The second lesson is that there is often no "event." The revelation of an attack can be either delayed because of incubation times or hidden in the natural background. The third is that people are currently the "canaries" for biodefense. We wait until people show up sick in the emergency room before realizing that an event has occurred.

Fourth, I believe that the public health system is ill prepared to deal with bioevents. Reporting is haphazard, and the signal is not being sought. (Actually, I should say "was" not being sought; these days the public health system is much more vigilant for attacks involving the sorts of agents I've mentioned.) Our stockpiles of vaccines and antibiotics to combat some of these agents are inadequate, and we have no surge capability in our health-care system. Our hospitals are designed to

When all the Kaopectate disappears off pharmacy shelves, you know something has happened!

Some 3,000 physicians report daily on the incidence of flu to the National Flu Surveillance Network, which puts maps of flu incidence on line (http://www.fluwatch.com/ above). European physicians also keep track of flu in their countries, as illustrated below for three successive weeks in the spring of 1999. Such surveillance systems already form the backbone of the sort of disease tracking essential to defense against a biological attack.

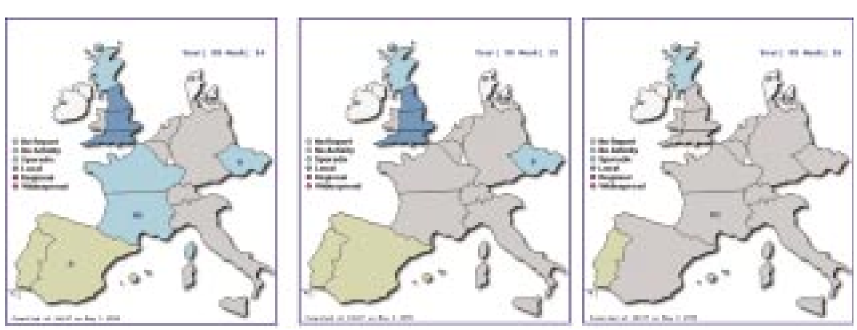
run at capacity for economic reasons; we try to keep the beds filled, just as we try to keep airline seats filled, so any surge associated with a biological attack would severely tax the system. But the United States is a leader in biomedical technology; can't we harness some of that technology to do a better job on biodefense?

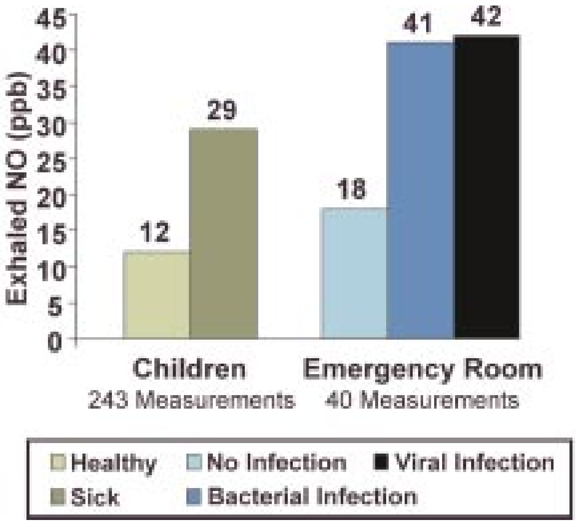
I like to compare the potential of our public health system to the situation in the 1950s, when the federal government decided to build the interstate highway system. Those roads were put in ostensibly for national security reasons: we were going to move tanks or missiles or troops over those roads. Of course, we never had to do that, but the roads turned out to be a tremendous benefit to us for civilian travel and commerce. In the same way now, addressing the public-health issues important to biodefense will have many salutary effects beyond defense.

Let me now take you through some of the things that, two and a half years ago, we thought the government should be doing to respond to those threats. One is to strengthen public-health information systems. It is extraordinarily important to detect an attack as quickly as we can. We can use that knowledge to contain contaminated areas, to prevent new exposures, and to stem epidemics of contagious agents. And we can start treating people who have been exposed before they start showing symptoms. The sooner we can pick up an attack, the better off we will be. The question is: how can we do that?

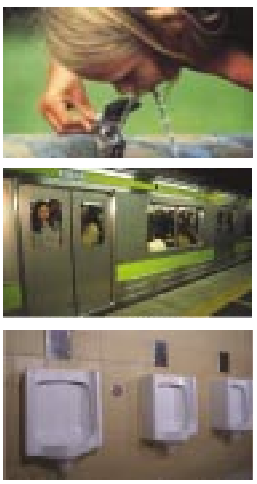
One way is to collect and mine existing data. The health system produces all kinds of information about the health state of the population. We have billing and insurance records (and certainly the billing records, in my experience, come in very promptly!). We also have admissions to emergency rooms—the symptoms that people show there, the lab results, and so on. And we have pharmacy sales. (When all the Kaopectate, for example, disappears off pharmacy shelves, you know something has happened!) What you want to do is collect and analyze this sort of data to look for the natural patterns, the natural variability, and then look for anomalies in the data.

In our report we pulled out a couple of examples to illustrate what could be done. The map of western Europe below shows the incidence of flu during three successive weeks in the spring of 1999. The colors of the countries are changing as the flu comes and goes, as reported by physicians in the European health system. In this country, we found a Web site hosted by a commercial drug company that produces a drug for flu. It has a reporting network of physicians across the country, and you can sign up for a weekly e-mail telling you the incidence of flu in your state in any given





Measuring exhaled nitric oxide (produced by the body's immune system to fight infections) could predict disease before its onset. In the clinical studies at left, presymptomatic sick children showed higher levels of nitric oxide, as did (presumably already sick) emergency room patients.



Facility sampling to monitor the health of the population could make use of all sorts of existing "facilities."

week. So, we already have the beginnings of surveillance systems, and steps have been taken toward more sophisticated reporting systems.

The next thing we suggested that might be done is facility sampling—anonymously monitoring the population with some specificity in terms of time and place. This could be a device like a smoke detector sitting somewhere in a room, analyzing what people are breathing in and out, or analyzing people's sweat, sputum, and so on. You can imagine numerous opportunities for this: drinking fountains, pay phones, and spaces where people are confined close together, such as subways, buses, and elevators. There are obvious public health spin-offs here. Although the data aren't very specific, you might be able to use them to track TB, flu, and so on.

Another way of monitoring the health state of the population is wearable instrumentation. Non-invasive means of measuring pulse, blood pressure, respiration, temperature, blood sugar, and so on have already been developed, and you can imagine packaging all of them in something that could be worn on the wrist. If you combine those data with some time-averaging, geolocation, and cellular telemetry, you could monitor the health state of the population in real time. You wouldn't have to do it for everybody; perhaps people with existing medical conditions might volunteer to wear such a thing. Or you could ask that first responders wear it. There are obvious privacy issues, but probably a lot of interesting science would result from it, in addition to the biodefense aspects.

We should also be investing in presymptomatic triage—testing to determine who has been infected before they get sick. Knowing who has been infected can be used to stem an epidemic by contagious agents. You can use such tests to deploy medicines and quarantine or allocate hospital resources efficiently.

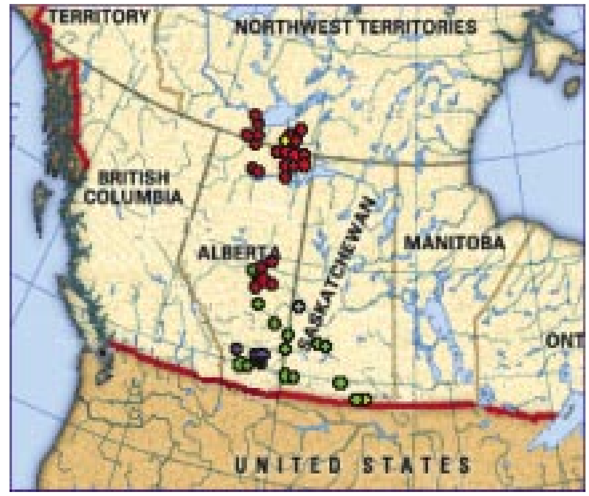
Such testing can exploit the increasingly sophisticated analysis of simple molecules—nitric oxide, for example, a gas the body's immune system produces to fight infections. Above are some measurements of the nitric oxide in children's exhaled breath. You can see that healthy children showed low amounts; sick children showed increased amounts—before they were actually exhibiting symptoms. They got sick a few days later. Similar results have come from emergency room visits, although I think these people were already sick when they checked in. Such technologies will have obviously useful clinical applications quite beyond biodefense.

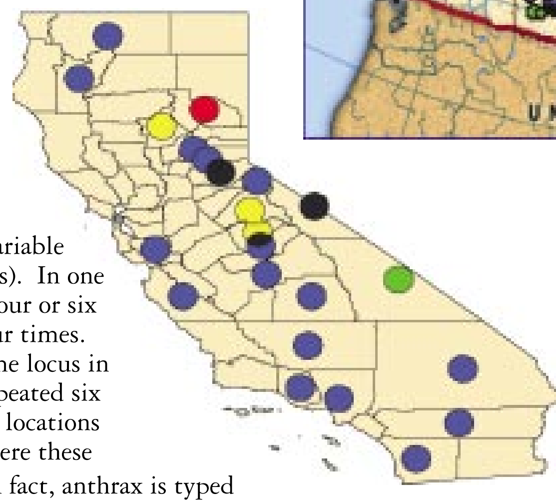
Besides monitoring people, we can also utilize sensors for the environment. One no-brainer is a better field detector for anthrax. We've seen so many false positives and some negatives reported in the news in recent weeks. We need something reliable and robust for the field. Another thing we can do is area surveillance for anthrax and other bioagents. A number of people have suggested putting biodetectors on every street lamp or at every intersection, but it turns out that this would cost a lot of money. You would need about 10,000 sensors to cover the Los Angeles basin. Just one of the 20 or so air-quality-monitoring systems that are currently deployed in the basin costs about $100,000 a year to run. So we'd be looking at a billion-dollar investment. Of course, there would be some economies of scale, but it's still an awful lot of money.

Instead, we might deploy sensors on municipal vehicles—police, fire, and postal vehicles, and subways and buses. These drive around the city; they are where the people are; they have power and communications. And every bus pulls into a depot at the end of its run, where the sensor could be removed and checked. You wouldn't even have to put them on every bus.

We need to learn more about the bioscience of biological pathogens. We've all heard a lot about the Ames strain of anthrax; how was that source determined? Bacterial genomes show repetitive

The geographical distribution of naturally occurring anthrax in the Canadian Rockies (right) shows that the same strains tend to show up clustered together. The same is true of plague outbreaks in California over the last few decades (below). An international database of bacterial strains would allow rapid determination of a foreign bioagent.





patterns, called VNTRs (Variable Number of Tandem Repeats). In one strain, a simple pattern of four or six bases might be repeated four times. In another strain, at the same locus in the genome, it might be repeated six times. There are numerous locations throughout the genome where these kinds of repeats happen. In fact, anthrax is typed by looking at the number of repeats at eight loci in the genome. (Humans, by the way, are typed by looking at 13 loci in the genome.) Many naturally occurring anthrax strains have been analyzed in this way, and maps (above) made of their geographical distribution. Sometimes you see a few outliers, which you can trace to, say, a cattle drive that has moved a particular strain from one place to another. In the map of plague in California over the last several decades, you can again see a spatial segregation of the strains. If we build a worldwide database of bacterial genomes, we will be better able to tell whether or not a bacterium is foreign, whether it is native or has been introduced in a particular locale, and perhaps where it came from.

The first thing we should be doing from an organizational standpoint is erecting a scientific infrastructure for biodefense. We should be getting national labs, academia, and industry working on these things and arrange efficient mechanisms for transferring the technology out to the field.

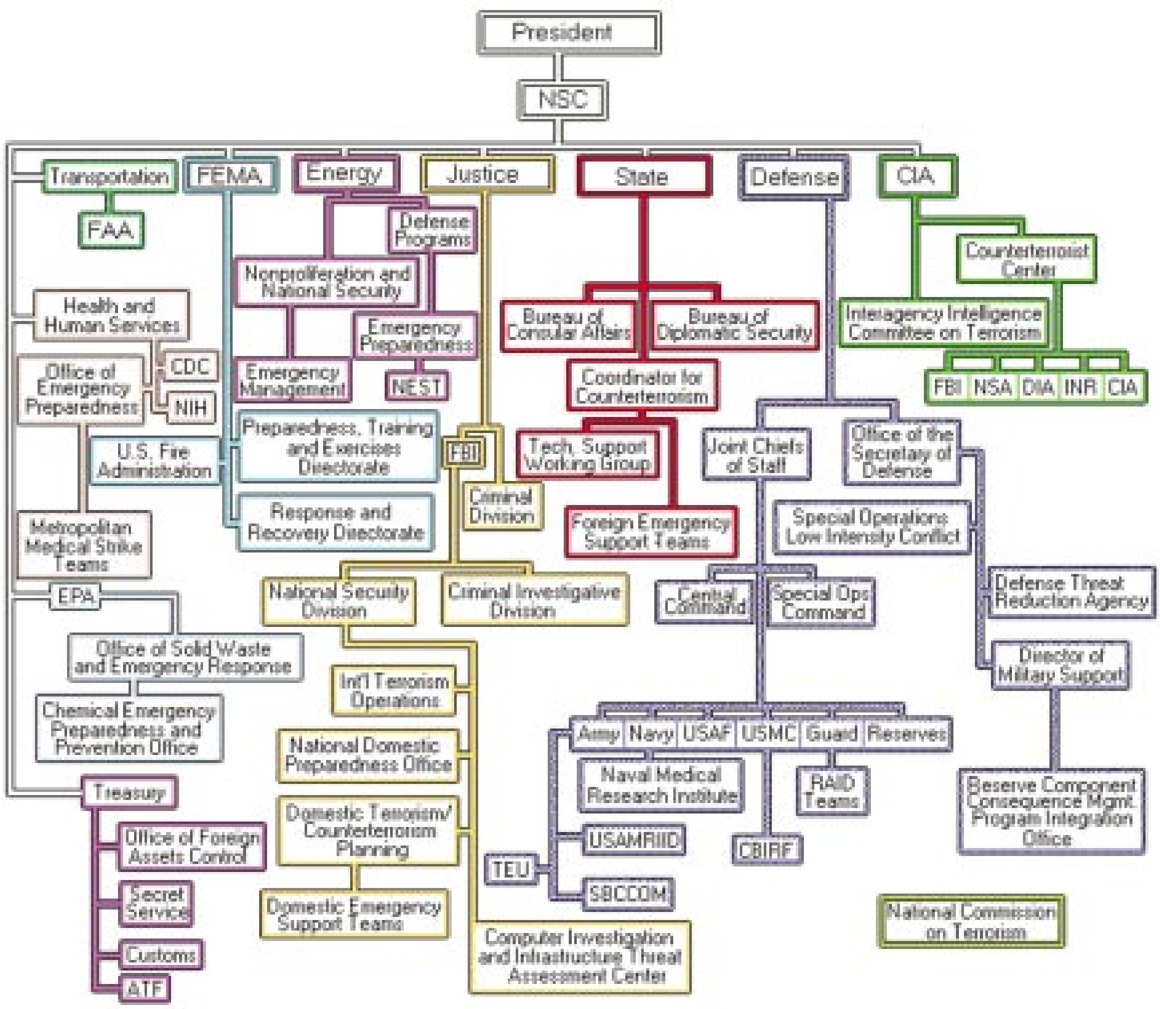
Let me say a few words about protecting people in buildings. There are many existing systems in buildings that could do a better job of protecting us. Some of them, such as those used to combat "sick-building syndrome," already involve keeping small particulates out of buildings and could be put to dual use. Lots of very simple technologies work very well; for example, the so-called HEPA filters that you've heard about, which stop fine particles. We can install scrubbing systems in the building that clean the air as it circulates. We could put positive pressure in buildings to keep particulates outside. Simple estimates of what it would cost to do this in office buildings come up with about tens of dollars per person per year—not a bad investment.

Finally, a lot of this is not about technology; it's about getting all parts of the system to play together well. The first thing we should be doing from an organizational standpoint is erecting a scientific infrastructure for biodefense. We should be getting national labs, academia, and industry working on these things and arrange efficient mechanisms for transferring the technology out to the field. This is not being done right now. We should also foster an operational infrastructure. There are lots of players involved here, and we need to clarify and adjust their roles and responsibilities. Who has the right to forcibly decontaminate an area? To impose quarantine? To determine the use of stockpiled medicines? We're starting slowly to address some of these questions as we run exercises with the various government agencies. And, of course, we need to train our frontline responders in how to deal with the various bioagents.

The organization chart on the opposite page, of federal agencies that deal with bioterrorism, is two years old. A more recent one that the Bush administration has been passing around Congress is even more complicated than this. The problem here is that there are many players who have complementary and overlapping capabilities and responsibilities. Just think about it for a minute: we're worried about intelligence matters; we're worried about law enforcement—catching the bad guys; we're worried about public health and medical care; we're worried about science and technology; and we're worried about agriculture as well. There are a host of other issues, and the various parts of the government that are associated with these functions are not used to working together. The big thing that Homeland Security Director Tom Ridge has got on his plate is to try to get everybody singing from the same page. It's not so easy to do.

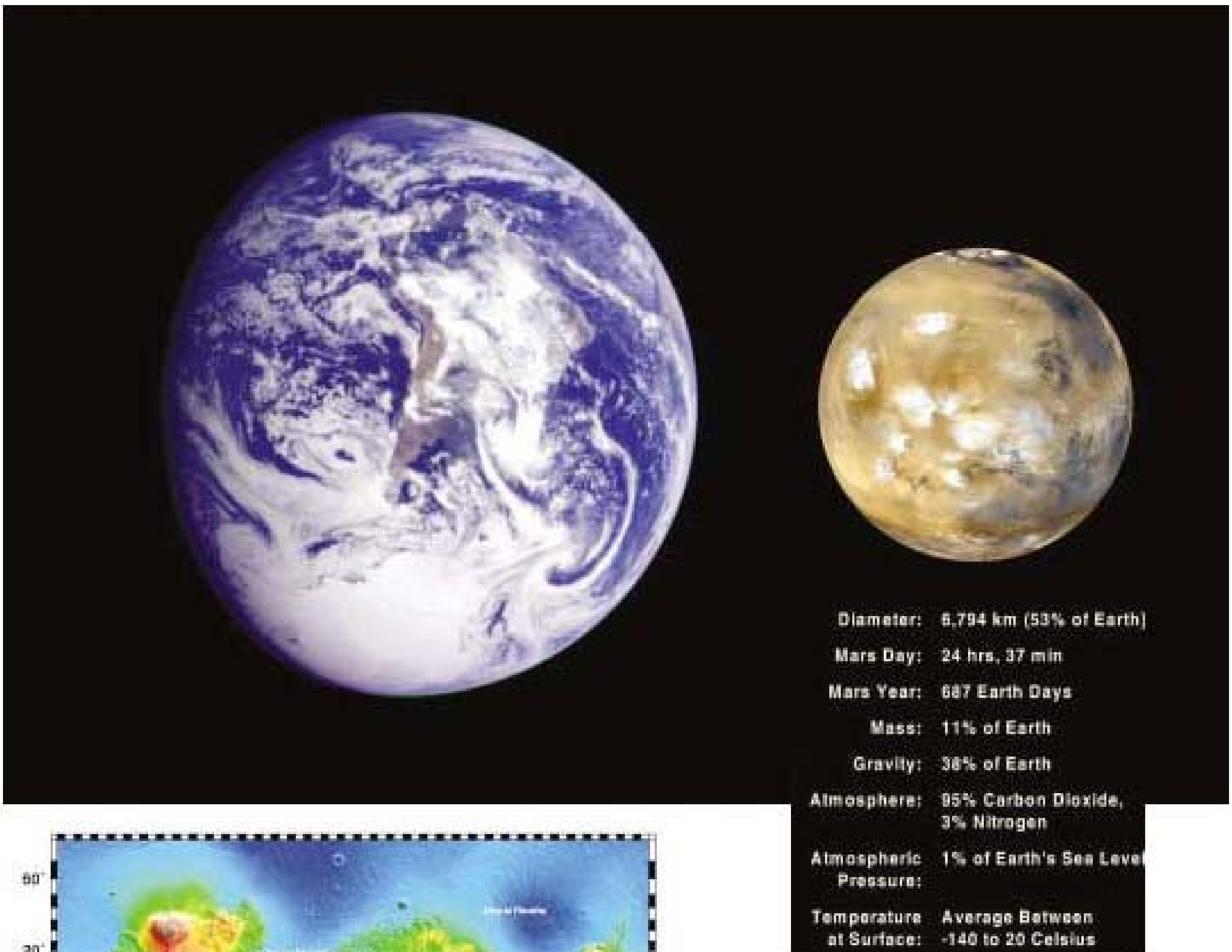
I'll leave you with some take-home points. One is that the present preparation for biodefense doesn't meet the full spectrum of homeland threats that are plausible. What do I mean by this? We *are* able to deal with a fair number of threats that we can imagine. There are, however, some plausible threats that we can't yet deal with. Some of the scenarios highlight what they are (of course, reasonable people can differ on what the word "plausible" means). But there is cause for optimism because there *are* steps that can be taken to bolster our defenses, and in some cases these are, in fact, being taken now. □

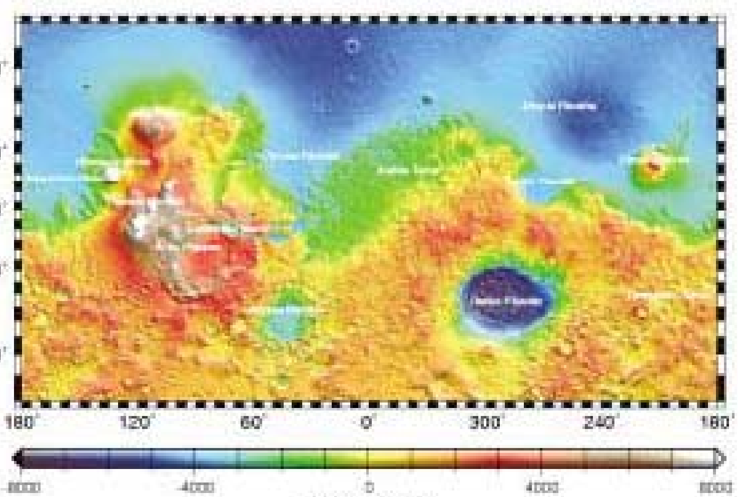
*Steve Koonin graduated from Caltech in 1972, left Pasadena briefly to earn his PhD from MIT in 1975, and returned in the same year as assistant professor of theoretical physics. He has stayed at Caltech ever since, becoming associate professor in 1978 and full professor in 1981. Koonin served as chair of the faculty from 1989 to 1991 and was appointed provost in 1995. His research interests include theoretical nuclear and many-body physics, nuclear astrophysics, and computational physics, but he has also ventured broadly outside his field into current issues of public concern: refuting cold fusion (*E&S*, Summer 1989); global climate change as measured by "earthshine" reflected back from the moon (*E&S*, Winter 1994); as well as biodefense and national security.*



Vast numbers of federal agencies have their fingers on some aspect or other of bioterrorism. Coordinating these agencies and getting them to cooperate in the name of efficiency will be a major problem for homeland defense. This chart is from the 1999 report; the current one wouldn't fit on the page.

PICTURE CREDITS: 30, 32, 33 – NASA/JPL; 30, 33, 34, 35 – NASA/GSFC; 31, 35, 37, 38, 39, 40, 41 – NASA/JPL/MSSS; 36, 38, 41 – NASA/Arizona State University; 39, 41 – NASA





Mars Global Surveyor: A Success by Any Measure

by Arden L. Albee

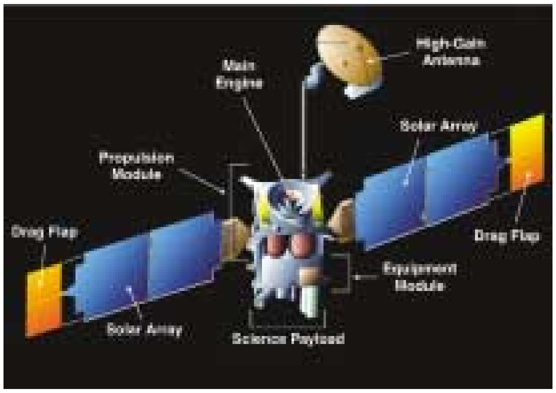
Opposite: Not quite peas in a pod, but certainly fraternal twins, Earth and Mars are shown to scale in these images from Galileo and the Mars Global Surveyor. Clouds mark the summits of several dead volcanoes, including the three Tharsis Montes, arranged in a diagonal line like the stars on Orion's belt, and the mighty Olympus Mons above and to their left. To their right the Valles Marineris canyon system slashes across the planet's belly like a giant gallbladder scar. The relief map was made from Mars Orbiter Laser Altimeter data.

Above: The Mars Orbiter Camera makes a daily weather photo of the entire planet.

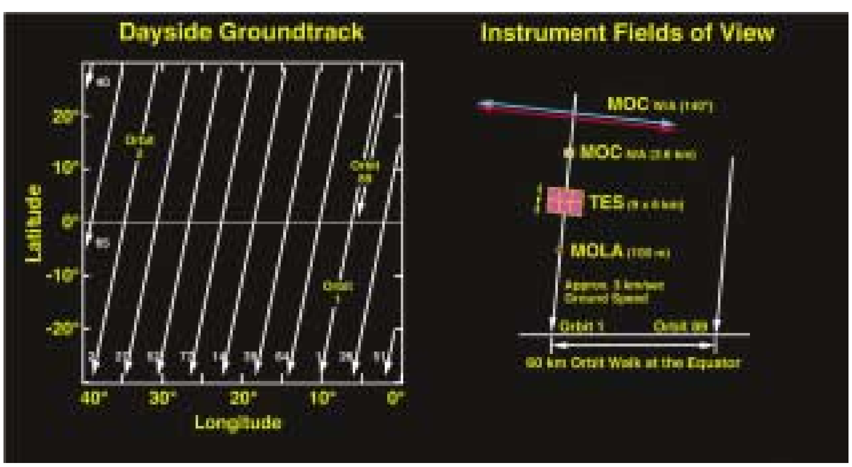
We are fascinated by Mars because it is the most Earth-like of terrestrial planets, and it's the first one humans are likely to visit. It looks familiar—it's got peaks, valleys, and clouds. The Mars day is almost the same length as our day, but the Mars year is twice our year. The surface temperature ranges from 20° Celsius, which is like a nice summer day in Iowa, to –140° C, which you don't even want to imagine. Mars has almost the same tilt on its axis that Earth does (23.98 versus 23.44 degrees), so it has seasons. They're quite pronounced because of its orbit, which is much more elliptical than Earth's, and the southern summer is shorter than the northern summer. Even though Mars's atmosphere is only 1 percent of our atmosphere and is almost all carbon dioxide (CO_2), the climate-modeling approaches that have been developed for Earth can be applied because both are rapidly rotating planets with shallow atmospheres whose winds are influenced by topography. Their atmospheres are heated similarly—sunshine warms their surfaces, which in turn heat their atmospheres. However, Earth's atmosphere is moderated by the oceans, which act as a heat reservoir and smooth out seasonal temperature swings. Mars doesn't have oceans, lakes, rivers, or rain. The Martian atmosphere is controlled by the warming of the subsolar region (the region where the sun is directly overhead), to which it responds very rapidly. Any liquid water that should happen to appear on the surface would evaporate immediately, but evidence suggests this was not always so—early Mars could have been like early Earth, with a warmer, wetter, thicker atmosphere. Since liquid water seems necessary for life to exist, we want to know, Did life develop there? If not, why not? If it did, did it die out? Or is it still there, hidden in water in the rocks? What does Mars have to tell us about what can happen to Earth's climate?

The Mars Global Surveyor, or MGS, replaced the Mars Observer, which was lost on arrival at Mars in 1993. Both spacecraft essentially combine a weather satellite and a LANDSAT into a single orbiter to get integrated global data sets—on climate, weather, surface morphology, geology, topography, the geodetic figure, gravity anomalies, and the magnetic field—to answer the big questions about Mars's history and evolution. The MGS team is also examining potential landing sites to help choose ones where spacecraft can touch down safely, yet still find interesting geology. In order to do all this, MGS moves in a nearly circular, nearly polar orbit, looking at the whole planet as it spins underneath. We orbit the planet 12 times a day, and every 89 orbits, or roughly eight days, we come back over almost the same spot. The orbit is sun-synchronous, so it's always 2:00 below us—2:00 p.m. on the day side, 2:00 a.m. on the night side—giving us a constant lighting angle. The instruments are co-aligned so that they all look at the same piece of land, and they always face Mars so that we get round-the-clock data. (It's quite a challenge for spacecraft designers to keep the instruments pointed at Mars, the high-gain antenna aimed at Earth, and the solar arrays facing the sun all at the same time—you have to use lots of wrist joints!) Each of our instruments has more computing power and more memory than any entire spacecraft that JPL had launched until then—a tremendous advance. MGS has returned more than two trillion bits of data so far, which is more than any other mission.

MGS has five instruments, each of which is operated by its Principal Investigator, or P.I. The Mars Orbiter Laser Altimeter, or MOLA, bounces a laser pulse off the planet, and the time of the pulse's flight measures the distance to the surface. (Of course, you have to know the spacecraft's location to a very high accuracy.) MOLA's global map, which has a spatial resolution of 1/64th of a degree and a vertical resolution of 30 meters, is better than our best global map of Earth at this point. This map is based on a set of laser footprints 130 meters in diameter whose positions are known to



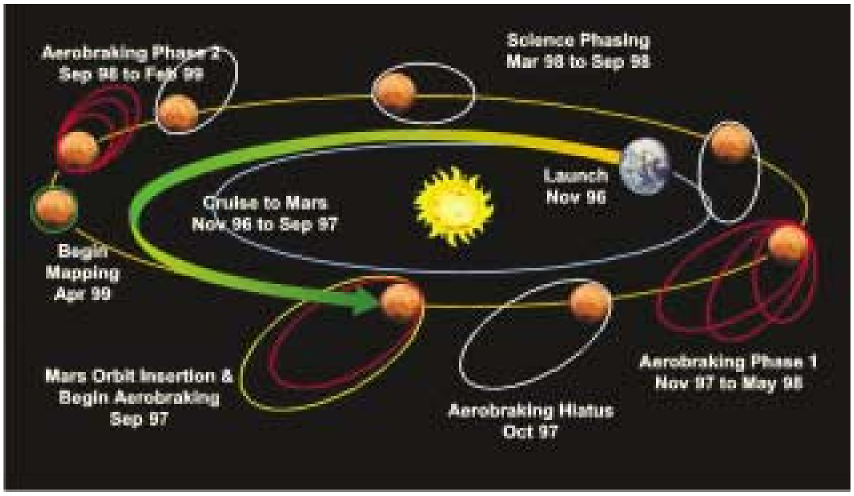
Above: The spacecraft's principal parts. Right: Most of the instruments look straight down from a platform on MGS's belly. The Mars Orbiter Laser Altimeter (MOLA) is the copper-colored mirror that's sprouting a mushroom. The tall kitchen trash can to its left is the Mars Orbiter Camera (MOC), and the mailbox below that is the Thermal Emission Spectrometer (TES). (The magnetometers are mounted on the outer tips of the solar panels.) The paper towel holder is the Mars Relay Antenna, provided for later missions. Below: The overlapping orbits and fields of view.



less than 1 meter vertically and 100 meters horizontally. The laser fired 640 million times before a chip in the firing circuit failed on June 30, 2001—the longest-lived laser ever put in space. We would not have been too surprised if it had lasted only a month, and it worked for four years! David Smith at NASA Goddard is the P.I. The Mars Orbiter Camera, or MOC, acts like three cameras in one. It has a wide-angle mode that can view the entire planet at once at a resolution of 250 meters per pixel at nadir—the point directly below the spacecraft—and 2 kilometers per pixel at the limb, which is the edge of the planet's disk. All these images are stored in the camera's computer, and once every 24 hours the camera's software edits the wide-angle strips that have been collected during each orbit, down to a resolution of about 7.5 kilometers per pixel. The data are then compressed and sent back to Earth, where we assemble them into a global mosaic to make an image much like the weather photos you see on the nightly news. The near-nadir strips are likewise edited and assembled into regional maps with a resolution of about 300 meters per pixel—not quite enough to pick out the Rose Bowl, but plenty to see the parking lot. And the narrow-angle, high-resolution mode, at 1.4 meters per pixel, can see things about the size of a Volkswagen. That's a staggering quantity of data, so we'll cover less than one percent of the planet that way over the life of the mission. Still, we've obtained more than 100,000 high-resolution images, or twice as many as the two Viking missions combined. MOC's P.I. is Michael Malin, of Malin Space Science Systems, who got his PhD from Caltech in 1976.

The thermal emission spectrometer, TES, is an infrared (IR) spectrometer that takes atmospheric data and maps the surface's composition—the latter at 3 kilometers per pixel. The P.I. is Arizona State University's Phil Christensen. The Magnetometer/Electron Reflectometer first looked for a global magnetic field, which we didn't think existed. If no such field was found, they were to make crustal magnetic maps at a resolution of 100 kilometers. Mario Acuña from Goddard is the P.I. And finally, the radio-science experiment uses the spacecraft's radio to do two other things while sending back data. First, it measures Mars's atmospheric pressure. As the spacecraft goes behind the planet, the radio signal passes through the atmosphere. By analyzing the signal, you get a very accurate profile of the atmospheric pressure in 200-meter increments all the way down to the surface. The radio also enables us to map Mars's gravity field, and I'll talk about that in more detail later. The radio-science P.I. is G. Leonard Tyler, from Stanford.

MGS is about half the size of the Mars Observer, and wasn't able to carry all of its instruments. (The others are being flown on later missions.) We also launched on a relatively small rocket, so we couldn't carry the fuel to fire the engine long



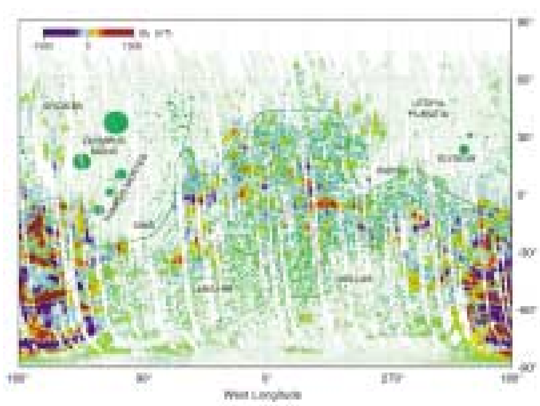
The plane of MGS's orbit remains almost constant relative to the sun, while Mars's sun-facing side slowly turns beneath. The original plan was to go from a 45-hour elliptical orbit to the 118-minute circular mapping orbit by the time Mars arrived at the right edge of this diagram. Instead, the October '97 hiatus was the month-long pause during which the team figured out what to do about the fluttering solar panel, and the March '98 – September '98 "Science Phasing" was the bonus period in which the gravity and magnetic fields were mapped.

enough to put us directly into our circular mapping orbit on arrival. So we intended to aerobrake instead, by treating the solar panels as if they were wings and dipping into the very top of Mars's atmosphere once every orbit. The drag gradually slows the spacecraft and circularizes the orbit. The original plan was to begin mapping in March 1998, but as you will see life doesn't always work out as planned. We had a perfect launch on November 7, 1996, a beautiful sunny day, after a one-day weather delay. But then when we unfolded the solar panels for the flight to Mars, there was quite a clunk, and one panel's wrist was damaged.

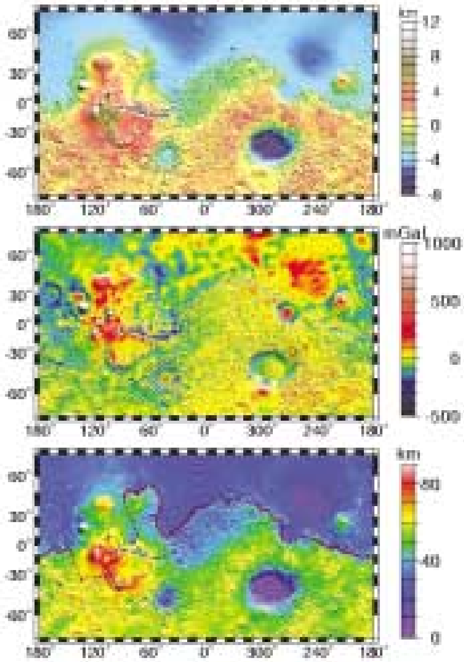
This turned out to be a blessing in disguise, though it could have been catastrophic. We weren't sure whether the weakened panel would hold, so we began aerobraking very cautiously. And then suddenly came a day when the atmosphere was denser and our broken wing began to flutter. We paused for a month to say, "What are we going to do?" I give credit here to Glenn Cunningham, a smart project manager who never forgot that the real goal of the mission was science. The plan was to go into orbit at about the 6:00 p.m. position, begin aerobraking, and let the planet gradually move under us until we got to 2:00 p.m. But because of the broken wing, we simply could not aerobrake that hard—we could not put that amount of pressure on it. Glenn agreed with the scientists to take an extra Earth year to get over to the opposite position—2:00 a.m. instead of 2:00 p.m. The illumination angle was the same, but now we were traveling *up* on the daylight side of the planet instead of *down*. In a sense, we're operating in reverse. And what turned this near-catastrophe into a scientific triumph was that we had to spend a long time in an orbit whose low point was about 175 kilometers, which is ideal for mapping magnetic and gravitational fields, because it gets in under the ionosphere. The orbit's low point slowly moved up, over the North Pole, down the back side, and under the South Pole before we got to 2:00 a.m., so we got good coverage of most of the planet. We would never have had the guts to design a yearlong delay into the mission, but when it worked out that way we got exceedingly valuable data sets.

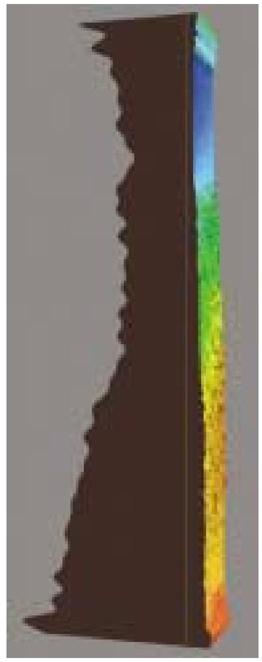
I'd like to share with you the highlights of what we've found, which I've organized into a somewhat arbitrary Top Ten list à la David Letterman, working from the inside of Mars outward. First is the magnetic field. Earth's magnetic field keeps the tissue-damaging high-energy particles called cosmic rays at bay. We immediately found that Mars has no global magnetic field, so it doesn't have that protection. (Mars's thin atmosphere also offers no protection from the sun's ultraviolet (UV) radiation, which is even more damaging—the planet's surface gets a UV dose equivalent to what we use to sterilize operating rooms.) These cosmic-ray and UV fluxes are something to consider when looking for Martian life, or planning a human presence on Mars.

But we did find, later, that Mars has remnant magnetism—fossil bar magnets in its crust, if you will. On certain orbits we'd come down through the ionosphere and suddenly find a very large local magnetic field. In the map below, the red spots are strong upward-pointing magnetic fields and the blue spots are strong downward-pointing ones. The crust anomalies were a tremendous surprise, and we still don't fully understand them. The fields tend to line up somewhat, so many people said, "Hey, maybe this is evidence of plate tectonics, like the magnetic stripes in the spreading ridges on Earth's seafloors." But these fields are very, very old—they are concentrated in the southern hemisphere, which is much more heavily cratered than the northern hemisphere and therefore older. And the magnetism has been destroyed around Hellas, a vast impact crater that itself dates from the first several hundred million years of



The fossil magnetic features, with some topographic landforms drawn in. The line that very roughly follows the equator marks the boundary between the ancient terrain of the southern hemisphere and the relatively young north. The strongest fields are found in the old crust.





Above: Global maps of Mars's topography (top) and gravity (middle) can be mathematically merged to derive the crustal thickness (bottom). The crust is relatively thin under the northern plains and beneath the big impact basins of the southern hemisphere, but quite thick under the Tharsis uplift region. Above, right: A vertically exaggerated slice through the crust along 0° longitude, from the north pole to the south. The crust is about 40 kilometers thick under the northern plains and 70 kilometers thick in the far south.

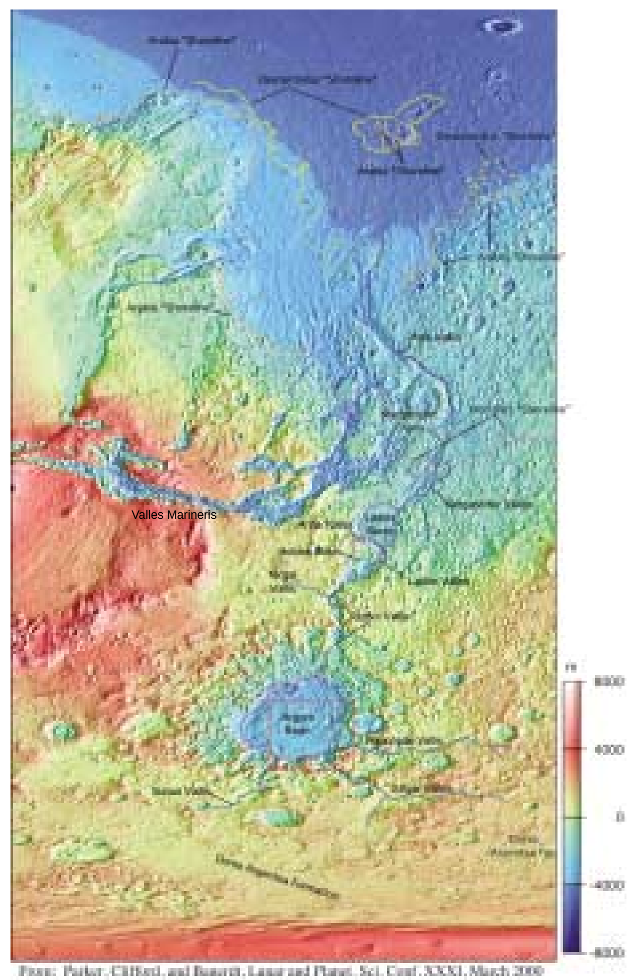
Martian history. These anomalies are 10 times stronger than any we know on Earth, and it boggles the mind as to how they could have formed—you'd need a hot, molten core with vigorous convection to create the magnetic field, but at the same time you'd need to cool the crust quickly enough to lock in the field by crystallizing the rock. We don't yet know how this might occur.

Let's turn to number two, which is Mars's figure and gravity field. By figure, I mean the planet's shape, which we now know very, very accurately. Mars is egg-shaped. The northern hemisphere is flattened, and Mars's center of figure is offset to the south of the planet's center of gravity by nearly three kilometers, so that the top hemisphere is skinnier and six kilometers lower than the bottom.

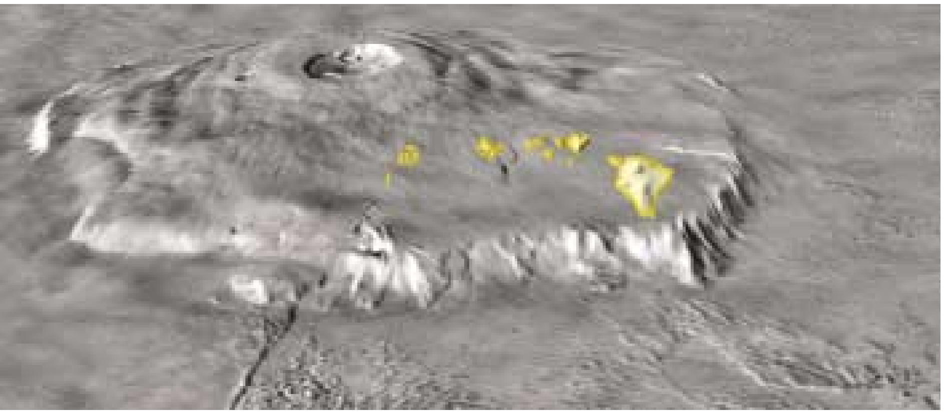
When we combine topography with gravity measurements, we begin to learn about the planet's interior. Well, how do we map gravity? Imagine you're orbiting Earth and approaching Mount Everest. Its mass is going to pull on you, and you'll speed up slightly; once you pass by, the mass will pull you back slightly. If you are emitting a continuous radio signal, the Doppler effect will shift its frequency very minutely, allowing us to measure your instantaneous acceleration and deceleration, and map the gravitational field. If we do, we'll find Mount Everest didn't speed you up and slow you down as much as it ought to. On Earth, mountains are like icebergs—light crustal rock floating on the denser upper mantle, with most of their bulk below the surface. This bulk displaces the mantle rock, so there's not as much mass as there would be if the mountain were simply piled on top of the crust. So this allows us to ask, how strong is the crust? Is it supporting these big mountains by its own strength, or do they have deep roots that help buoy them up?

It turns out that the mountains in the southern hemisphere of Mars are quite well compensated, which is to say they have deep roots, whereas in the north, they don't so much. That may just be a matter of time, because the southern hemisphere is so much older—the mountains in the north may not yet have sunk to their buoyant depth.

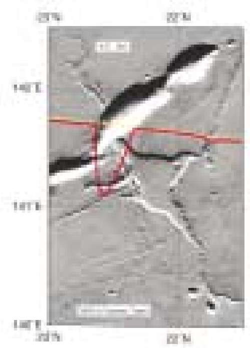
Number three on my list is topography. As I mentioned before, there's a pole-to-pole slope from the southern hemisphere downhill to the north that would have controlled the flow of water on early Mars. Besides measuring Mars's shape, MOLA has produced high-resolution topographic data that geologists can use to make detailed contour maps to interpret the landforms we are seeing. For example, coming out from the Argyre Basin there is a series of channels, many times the length of the Mississippi-Missouri river system, that has been successfully traced even though the channels are disrupted in places by later craters. The channels lead up to a vast low area in the north that could have been the site of an ancient ocean. We can draw a contour, or a couple of contours, around



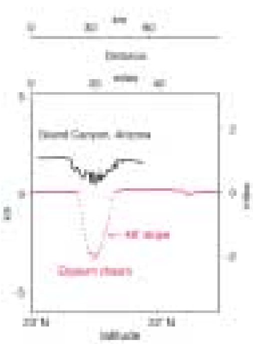
The Argyre Basin's complex drainage system, with three putative shorelines drawn in. The Valles Marineris helps drain the Tharsis region.



This 3-D view of Olympus Mons was made from MOLA topography data and a Viking image. The vertical relief is exaggerated tenfold. The state of Hawaii has been superimposed on the image to roughly the same horizontal scale.



Above: The MOLA elevation profile (red) of an anonymous chasm in Elysium Planitia. (MGS's ground track is shown in yellow.) The steep slopes indicate it may be relatively young and uneroded. Below: The deepest part of the Grand Canyon, for comparison.



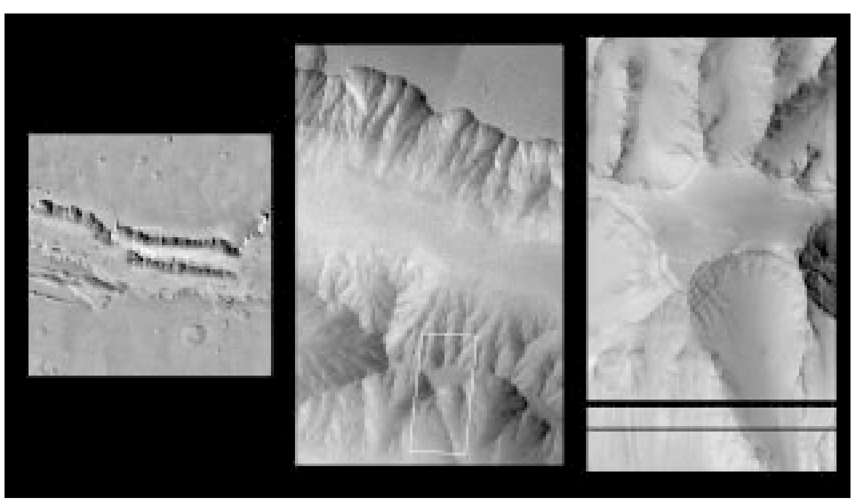
it that some people believe represents shorelines. We can also trace upslope from Argyre all the way back to the south polar cap and show that water, or some fluid at least, flowed down from the cap, filled Argyre Basin, overflowed it, and successively filled up a series of basins downstream before ending up in the north. But, oddly, the MOLA topography shows faint traces of big craters under the northern plains. We used to think that they had been resurfaced by very thick accumulations of volcanic and sedimentary material, but it now looks as if the surface layer is relatively thin. How to make the plains so flat if there's an ancient surface not far underneath is one of those mysteries we have to work on.

You have to keep the scale of these features in mind. The Valles Marineris, which is a branch of this channel system, would stretch from San Francisco to New York City. And the chasm at left is so small it doesn't even have a name, yet it is twice as deep and just about as wide as the Grand Canyon. Olympus Mons is so huge it would dwarf the entire state of Hawaii, yet once you get across the bounding scarp, its slopes are as gentle as Iowa's. How Mars came to have such large features is still an open question.

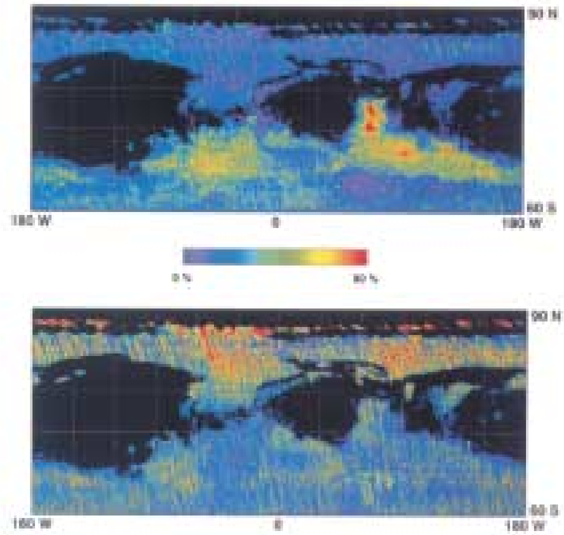
Fourth comes volcanism in the planet's early history. Mariner found Martian volcanic constructs—among them Olympus Mons and the Tharsis Montes, the latter being part of an area more than twice the width of North America that's been uplifted by some four or five kilometers. But we found thick, massive, layered beds that are probably volcanic strata in the walls of the Valles Marineris. So before the fluids carved the canyons, a sequence of volcanic rocks, probably basalts, were laid down. Such early extensive volcanism is a new element in Mars's history.

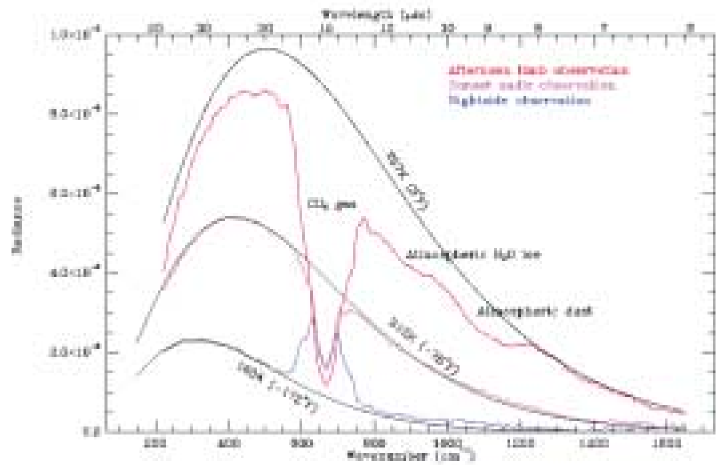
Number five is mineralogy and weathering. The TES spectra mapped on the next page show volcanic rocks over much of the planet. The black areas on the map have very weak spectral features that are difficult to interpret, and are probably regions of fine-grained dust. Dust particles do not give good spectra because of their size, which approaches the wavelength of infrared light and therefore doesn't interact with it strongly.

I need to take a moment to explain how we interpret IR spectra. If a bulk material has no absorption features—a so-called black body—it



From left: Zooming in on a section of the Valles Marineris. The white outline in each image shows the field of view of the image to its right. The closest view shows distinct rock layers ranging from a few meters to a few tens of meters thick. The resolutions are 230, 80, and 6 meters per pixel; the first two images are from Viking.





From: Christensen et al., Journal of Geophysical Research, Volume 106, Number E10, 2001, p. 23,844.

Above: Global TES maps of basalt (top) and andesite (bottom) abundances. Basalt is a dark volcanic rock formed when thin, runny lava oozes out onto the surface and hardens, as in Hawaii. Andesite is closely related to basalt, but forms from slightly more viscous lava with a higher silica content. The fact that the basalt is found in the older south and the andesite in the younger north indicates that some process within Mars altered the ratio of silicon to the other elements over time. Above, right: Some TES spectra of Mars, fitted to black-body curves. There is a peak for CO_2 instead of a trough in the nightside spectrum because the atmosphere is warmer than the surface and therefore emits, instead of absorbs, infrared radiation.

shows a nice, smooth curve whose height depends only upon its temperature. Even though it's not a black body, we can fit a black-body curve to the general shape of Mars's spectrum in order to determine its temperature. And since the smooth spectral curve has been eaten away by dust, water ice, and CO_2, all of which absorb in the infrared, we can measure their amounts by the depths of their absorptions. Furthermore, we get quite different spectra depending on whether we're looking through the atmosphere out into space or directly down toward the surface. So we can tell whether the absorption features are caused by material in the atmosphere or on the ground, and we can measure the atmospheric and surface temperatures separately. And once we subtract out the atmospheric CO_2, the water-ice clouds, and the airborne dust, the remnant spectra tell us there's basalt on the surface.

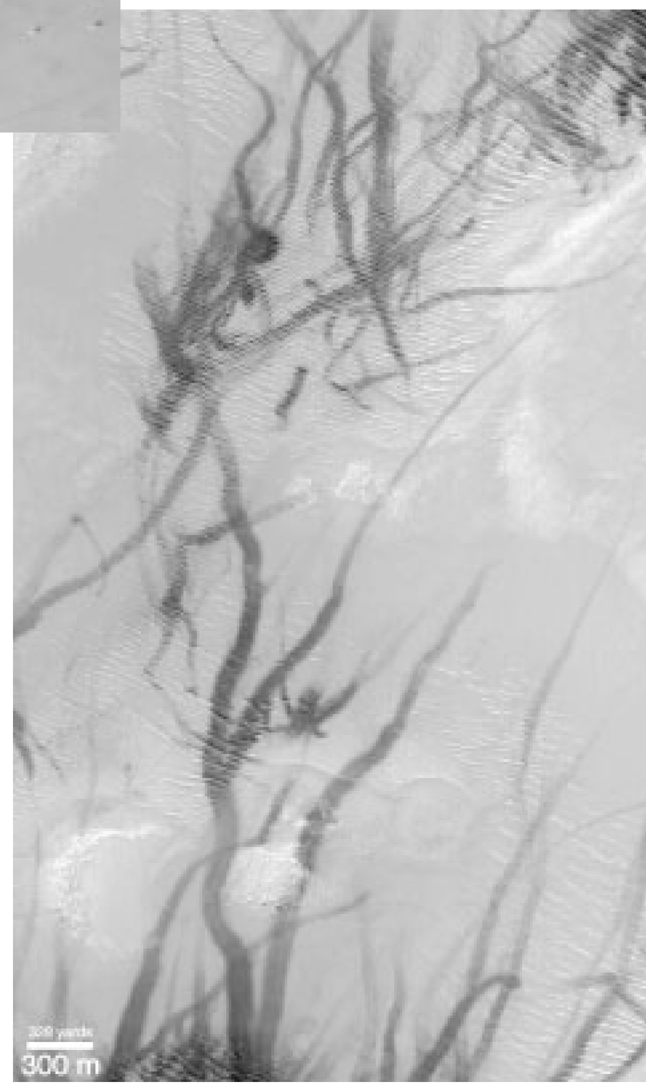
The key thing is that we don't see any products of hydrous weathering, which indicates that the rocks have not been exposed to water for any significant length of time. This is big news. After Viking, we had a picture of Mars as being covered with clays and other highly weathered material. That picture is now dead. We find volcanic minerals—plagioclase, pyroxene, and olivine—that on Earth rapidly absorb moisture and turn into hydrated clays, but we do not find the spectra of clays on Mars. Nor do we find quartz, which is the most common product of weathering on Earth and the chief component of Earth's sand; nor sulfates and carbonates, which tend to precipitate from liquid water and might indicate places where life could be or might have been. (There are probably some sulfates and possibly carbonates present in the dust, but at an abundance so low we can't positively identify them.)

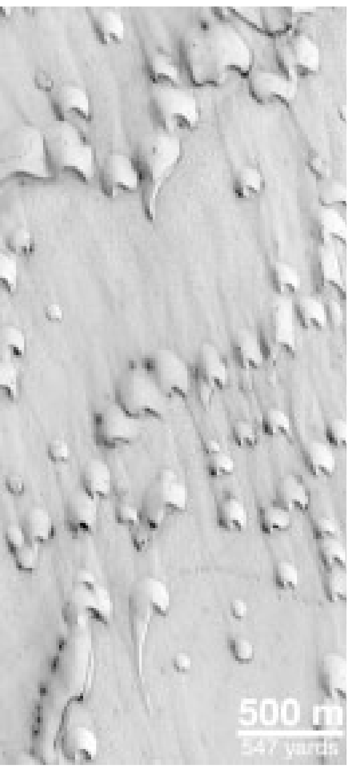
We *have* found a large area of coarse-grained hematite centered, coincidentally, at 0° latitude and longitude. Hematite forms in hydrothermal environments—hot springs, in other words, like at Yellowstone Park—and is also made by certain species of bacterial and other forms of life. So this is a prime candidate for a landing site for the '03 mission. Detecting hematite is Top Ten item number six.

Number seven is aeolian processes. Aeolus was the Greek god of the winds, and he rules Mars (or should I say Ares?). It's been known since the first telescopes that Mars has seasonal dust storms, but we found widespread layering indicative of loess deposits. Loess is a fine-grained, wind-blown material found in great quantities in China, where it started accumulating after the last Ice Age. The wind carries dust in from the deserts to the west and builds up deposits hundreds of meters thick. On Mars, the deposits have been laid down, partially eroded away, laid down again, and so on, until hundreds of layers are visible in some places. This appears to have been going on for three billion years, and the deposits can be several kilometers thick.

The wind also makes sand dunes. We find them all over Mars, and in particular they ring the north polar cap. Unlike the dust, the dunes are coarse-grained enough to give identifiable spectra, and they look like basalt, similar to the black-sand beaches of Hawaii. (Remember, Mars has lots of sand, but no quartz.) The dunes are typically dark relative to the lighter-colored, fine-grained dust, a coloration that gets exaggerated when we enhance the image contrast to bring out the details. At right are barchan-like dunes, meaning they are crescent-shaped. The crescents' horns always point downwind—a very handy meteorological tool for us! We often see small, bright ripples between the dunes, which means that there are several sizes of wind-blown features that were generated in an unknown sequence. Sometimes we see dunes going across an older, cratered surface that got worn smooth as it aged. These dunes are grooved as if all the sand grains somehow got cemented together, and the solidified surface was worn away by the

From left: 1. A field of dark dunes on the floor of Kaiser Crater, which lies at 46°S, 340°W. 2. These grooved dunes in Herschel Basin (15°S, 228°W) were overlain on an older, cratered surface. 3. Several dust devils and their shadows can be seen in this 88-kilometer-wide view of northern Amazonis Planitia. Note also the two craters that are almost filled with dust. 4. These dark streaks are caused when dust devils strip off the light-colored dust to reveal the darker surface beneath.



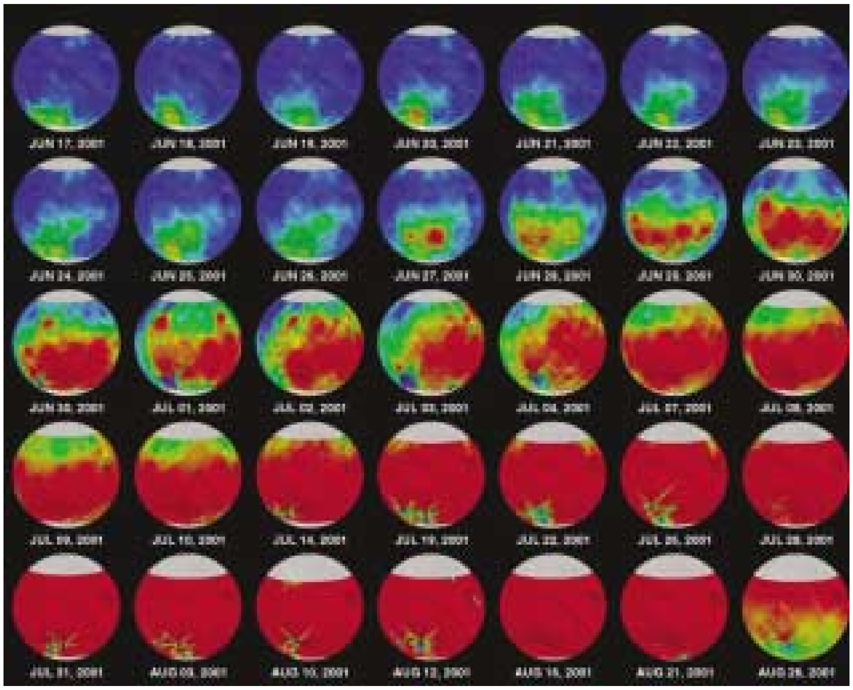


Barchan dunes, white with CO_2 frost, near the north polar cap. The dark patches in this springtime scene are sand, which is being revealed as the frost evaporates. Thus they appear to bloom, like vegetation, moving Arthur C. Clarke to suggest that they might be mangrove trees.

wind—another puzzle. Many dunes show dark streaks that look like dust avalanches, and sometimes two shots of the same area taken several months apart show differing streak patterns. The atmospheric dust slowly covers the streaks and they turn grayer and disappear, until eventually there's enough dust for a fresh avalanche.

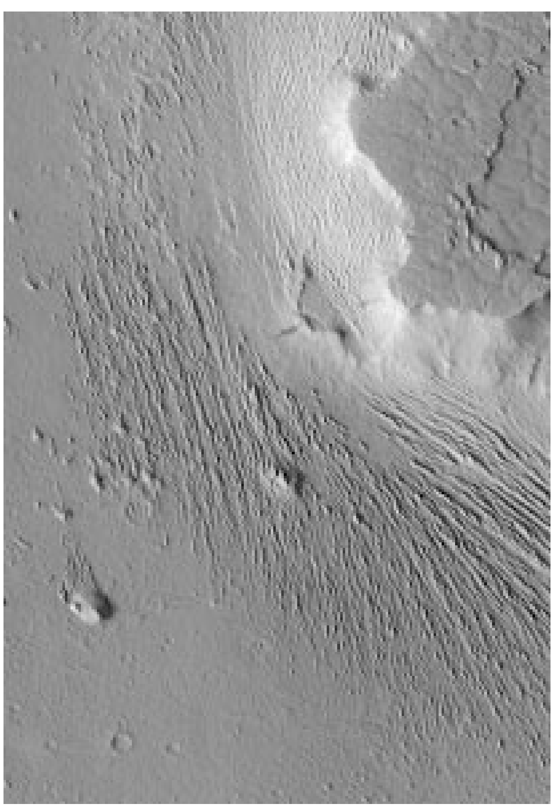
We also see dark, wandering tracks that look like seaweed on the seafloor. They're the tracks of huge dust devils, and they're just everywhere in the dune regions. In some cases, we can even see the dust devils' shadows, and because we know the angle of the sun we can measure their height. The one marked by the arrow is about 8 kilometers tall.

We've known since Mariner 9 that global dust storms also occur. The last truly big one was at the time of Viking, 20 years ago, but in June we got a whopper that formed in Hellas Basin in the south and then boiled up to the north. This is the first time we've been able to track such a storm from its birth to try to understand exactly how it begins. We don't know what the triggering mechanism is. On Earth, it takes a stronger wind to pick up dust than sand, so you start the sand blowing first and it kicks up the dust. Whether that's true on Mars, we don't quite know. It may be that there are electrostatic forces involved, so that the wind itself can lift the dust. The global storms occur only during the particular times of the year when we get violent winds—and not every year. Part of the reason we do global climate modeling is to try to understand what triggers the violent winds. Is it certain times of day? Larger than normal seasonal effects? Or is it something else? TES can measure the atmosphere's opacity, giving us detailed data on the actual amount and distribution of dust. This has shown us that although the dust storms are global events—producing planet-enveloping dust clouds—the storms themselves remain localized. Throughout the storm, the dust that fed the global plume was only being kicked up in a few isolated regions.



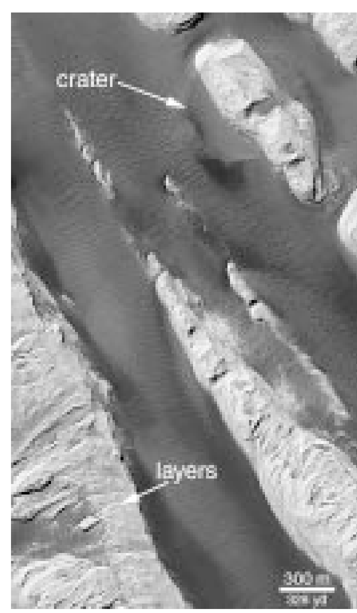
Above: Global TES maps of the great dust storm of 2001. Opacity ranges from clear (blue) sky to you-can-barely-see-the-sun (red).

Below: Yardangs, a kind of wind-carved ridge, are particularly prominent in the Medusae Fossae, a region of easily erodable layered rock near the Amazonis Planitia. This image is about five kilometers from top to bottom.

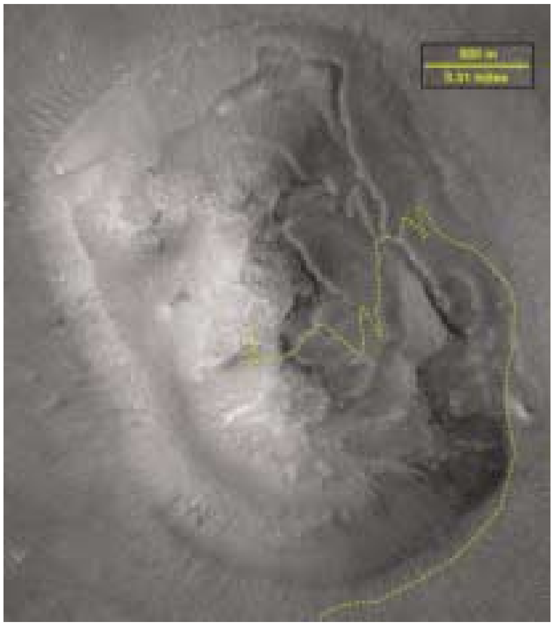


We know that roughly half of Mars has lots of dust coating everything. We measure the albedo, which is the surface's brightness, and the nighttime surface temperature, which tells us how fast it cools off, and we calculate a property called the thermal inertia. The finer a material is, the faster it loses heat at night—if you go to the beach after dark, the big slabs of cement in the sidewalk will be warm underfoot long after the sand has turned cold. Thus, low thermal inertia indicates regions with a lot of dust. The dust varies in thickness. When you look at relatively recent features you see a rough but muted surface, as if a blanket of snow has fallen. But some craters in the layered regions are filled to overflowing with heavily compacted dust layers many kilometers thick, although some people think it's silt from little lakes that once stood in the craters. (We might find out for sure soon, as some of these filled-in craters are prime landing sites for the '03 mission.) Even in the cleaner areas, the dust obscures everything to a degree we hadn't anticipated. This has implications for choosing landing sites for future robotic, and eventually human, missions. All that dust means that even at a scale of 1.4 meters per pixel, our cameras can't really tell us what the surface looks like. It's difficult to interpret the terrain.

I find it fascinating to observe the results of wind carving. At left are "yardangs"—long, eroded features caused by blowing sand, in this case eating away a mesa whose top is protected by a more durable layer. Such features are very common. And below is a puzzle from Viking—a "white rock" that overlies a crater. Many people thought it was a soft gypsum (calcium sulfate) deposit, but it turns out again to be a fine-layered, fine-grained material—remember, we've found no sulfates of any sort. It was deposited on an old surface that had craters on it. The deposit was then dissected away by erosion, and finally the dark dunes filled in the resulting valleys. So you have an entire geological history in one photograph. Mars has a complex history, and even with 100,000 high-resolution photos, we are nowhere near understanding it fully.



Erosion also left its mark on Cydonia Planitia, where Viking took that famous image of the Face. MGS's first look at the Face had the sun in the opposite direction from the Viking shot, so we made a negative image to mimic Viking's



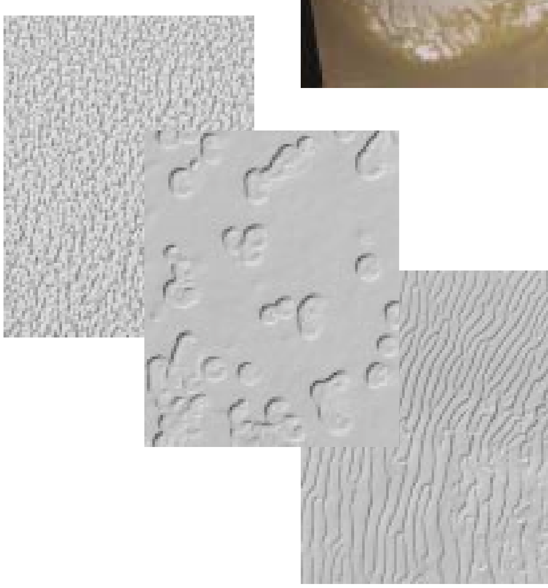
The Face (41°N, 10°W) is actually a steep-flanked butte or mesa, like those seen throughout the American West, surrounded by an apron of boulders. Climbing it would make a nice outing, and NASA's Jim Garvin has already prepared the trail guide. The hike is approximately 5.5 kilometers or 3.6 miles one way, with a total elevation gain of nearly a thousand feet. It is rated easy at start and midsection, with some very steep sections in between. The time to the summit is about two hours; take plenty of water and oxygen. Begin by skirting the scree slopes at the base to the middle of the east side, where there is a breach in the battlements. Climbing through here leads to a smooth traverse that becomes a circuitous path to the summit, where there is a flat, circular patch about 100 meters in diameter from which to enjoy the breathtaking views. Regrettably, there are no picnic facilities or rest rooms.

lighting conditions. Then just this year we revisited the site, rolling the spacecraft 25 degrees to target the Face squarely. At 1.56 meters per pixel, this is our best view of the area. In fact, it's so good that Jim Garvin, chief scientist for NASA's Mars Exploration Program, has published a trail guide on how to climb it. We've also made a topographic map of it with MOLA data.

Number eight on my Top Ten is the polar caps. MOLA measured their thicknesses precisely enough to give a reliable estimate of their water volumes, and even track the thicknesses of their seasonal accumulations. (One-third of Mars's atmosphere freezes out and snows onto the poles each winter.) We've traced their seasonal changes over a full Martian year—TES mapped in detail how the caps retreated and advanced with the seasons, and, of course, MOC took pictures. Each pole changes from year to year, as you can see from these two photos of the residual north cap—the part that doesn't evaporate in the spring—taken a Martian year apart. And the two poles are quite unlike each other, so how they managed to evolve differently is a puzzle. The north residual cap has a cottage-cheese texture; the south residual cap has, in many places, a Swiss-cheese texture, and in other places a fingerprint texture. The residual cap on the North Pole is water ice, and the seasonal cap is carbon-dioxide ice. What's going on at the South Pole isn't quite as clear, but the residual cap seems to have, in addition to the water ice, some permanent CO_2 ice that might behave differently and explain those weird patterns. (CO_2 freezes into "dry ice," the stuff you use to make smoky punch bowls on Halloween.) And as this article goes to press, it's been found that the holes in the Swiss cheese are bigger this year, showing that CO_2 is being lost to the atmosphere, which may be growing thicker as a result. Whether this is a random variation or a long-term trend is a very good question.

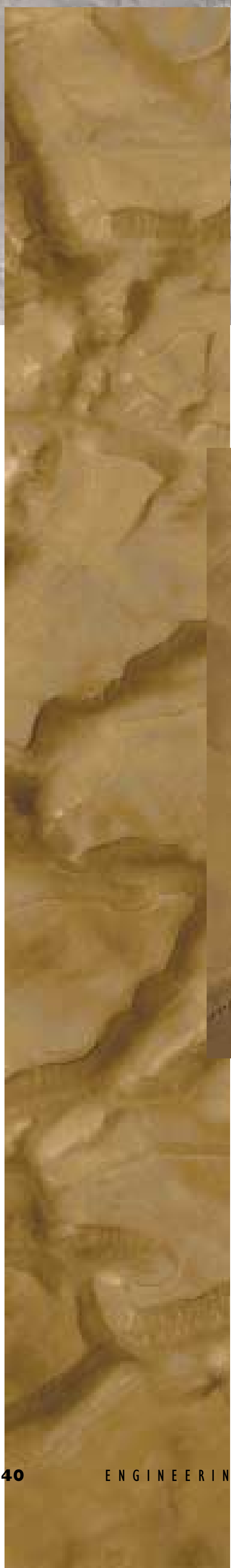
Number nine is channels and sapping, both of which are signs of liquid water. The channels are quite old, but the sapping, which I'll explain in a moment, might represent liquid water near the surface of Mars in the very recent past, and possibly even in the present day. Big, sinuous channels that look very much like they were carved by fluids were found by Mariner 9. However, on closer inspection, they lack the small central channel found in Earth's water-carved valleys and canyons down which the river actually runs. Instead, we see dunes down their centers. But MOC found a place where that central channel is still preserved.

Recently, we have seen features on cliff faces that



Above: The residual north polar cap, seen here in two successive Martian summers, is about 1,100 kilometers across. Sand dunes form the surrounding ring of dark material.

From left: The cottage cheese, Swiss cheese, and fingerprints are depressions ranging up to a few meters deep.



These gullies in Gorgonum Chaos (37°S, 170°W) were formed by water emanating, or sapping, from a prominent dark layer a few hundred meters below the top of the mesa. The close-up covers an area some six kilometers square. (The black-and-white image is from Viking, the synthetic-color images are from MGS.)

suggest sets of V-shaped gullies originating from a layer just beneath the top of the cliff. It looks as if the gullies are being cut by water emerging from that layer. This is called "sapping," and implies that there is subsurface ice that, under certain conditions, can melt and produce water. The gullies are quite widespread and found in many different environments. Unfortunately, there's no way yet to land a spacecraft in one of them, but it is certainly something we'd like to investigate. Another piece of evidence is the random pits at right. Somehow or other, material was removed from beneath the surface, which then collapsed. And we see polygonal patterns on the northern plains that look like what you find in Alaska or Siberia, which says that there's probably ground ice not far under the surface.

And, finally, number ten is atmospheric dynamics. In some ways, this may be the most important thing we've done. We've been in orbit for four Earth years, so we've acquired almost two Martian years' worth of data that we're now putting together to try to understand Mars, and, we hope, Earth. At right is an example. The top panel is a big storm front coming off the west coast of Africa. These storms move west, dumping dust on Bermuda and Florida, and then circle around and dump dust on London and Paris and Berlin. Below it is a similar front on Mars—a big, hook-shaped dust storm coming off the North Pole. Some of them are very dramatic—to their right are six hours' worth of one. And our daily planetwide weather photos show numerous water-ice cloud masses. (There really is a substantial amount of water in the atmosphere, but it's all in the form of ice crystals; we also find CO_2-ice clouds at the right time of year.) Because the water-ice clouds are at 0° C, TES can track their progress across the planet by their temperature. Twelve times a Martian day, TES gets a full set of temperature, pressure, and dust profiles of the atmosphere along our orbital track, and we interpolate between the tracks to make global maps.

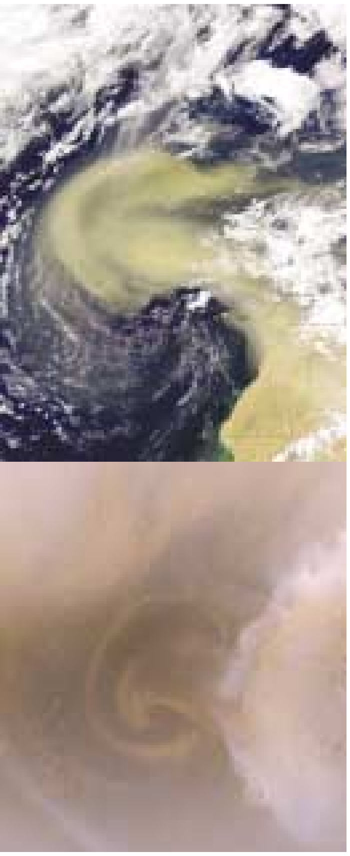
We can make movies of the images and TES maps to track the air masses and see how Mars's atmosphere operates over a long period of time, just as we're trying to make sense of the weather on Earth. And just as for Earth, much of the work is done with massive computer programs in which you include all the physics and topography you can, and then look at how points in the atmosphere move, and follow their temperatures and pressures. This gives you a forecast that you compare to the actual weather you observed, and then you go back and modify your model as needed.

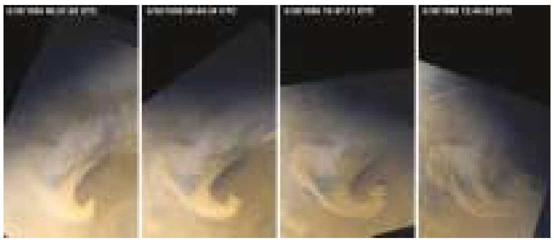
Assistant Professor of Planetary Sciences Mark Richardson used a global climatic model running on a cluster of computers to look at the motion of the air masses. The model starts with nice, even bands of color that act as tracers, and as it runs, the red gradually disperses into hook-shaped clouds like we saw on Mars.

What of the future? On October 23, Mars Odyssey went into orbit around Mars. It is now aerobraking, just as MGS did, but for various mission reasons it really needs to finish in three months, so it is being braked very aggressively. We are helping to protect it by keeping an eye out for dust storms. It's pretty quiet on Mars now, but a big dust storm would cause the atmosphere to heat and expand. If Mars Odyssey dips too deeply into the rising atmosphere, it could be seriously damaged by overheating.

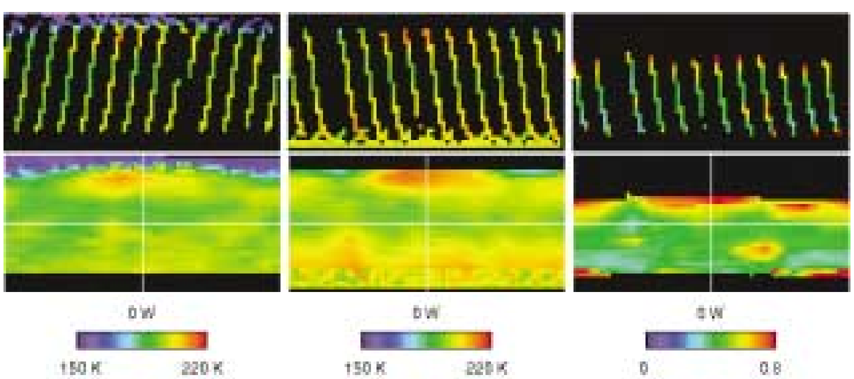
In early 2004, JPL's twin Mars Exploration Rover (MER) landers and the European Space Agency's Beagle lander will go to sites our data helped to select, and we will be monitoring the bulk of their descent and landing maneuvers. Once they have touched down safely, these landers will use MGS's Mars Relay Antenna, provided by CNES, the French space agency, to send some of their data back to Earth. We will also continue to acquire scientific data of our own. Once we are done supporting these new missions (the landers' nominal lifetime is 60 days, but of course we're all hoping they'll last a lot longer then that), we'll tilt the spacecraft 16 degrees into a gravitationally stable attitude that should enable us to continue to use all the surviving instruments through 2004.

In conclusion, Mars Global Surveyor has collected more information about the Red Planet than all previous missions combined, and its discoveries show Mars to be a very different planet from what was believed at launch. The mission is an incredible success, whether measured in dollars per data bit (0.00007 cents per bit), by number of papers published (hundreds, and people are just getting started looking at the data), or by the number of times we've appeared on the cover of the journal *Science* (six, at last count). □





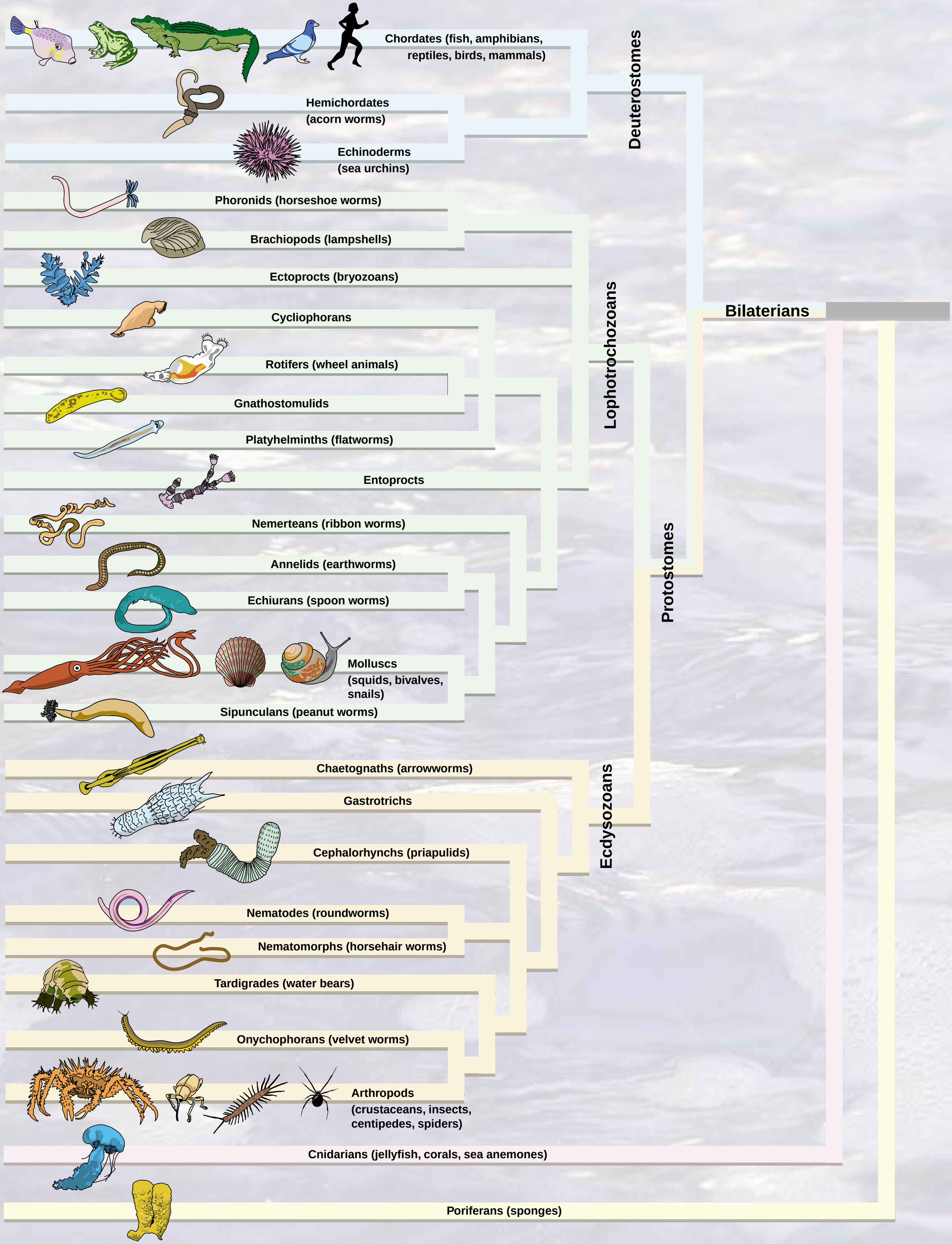
Left: A Saharan dust storm (top) extends 1,800 kilometers out to sea in a SeaWiFS image from February 2000; this spring dust storm on Mars (bottom) extends about 900 kilometers from the north seasonal cap. Both images are at a scale of 4 kilometers per pixel.
Above: This summer storm whipped up fast and furious, and lasted well into the next day. The white clouds are water ice; the yellow to brown clouds are full of dust.



Above: A day's worth of some TES data, from the actual orbital strips to the global maps. Shown here are the average nighttime temperature, daytime temperature, and dust opacity for September 17, 2001.

Professor of Geology and Planetary Science Arden Albee got all his degrees in geology from Harvard in the '50s and came to Caltech in 1959. He served as JPL's Chief Scientist from 1978 to 1984, and Caltech's Dean of Graduate Studies from 1984 to 2000. During his spare time, he has been Project Scientist for the Mars Observer and the Mars Global Surveyor. The Mars Global Surveyor was built by Lockheed-Martin and is managed by JPL for NASA. The MGS team, the fruit of whose hard work is described here, includes people in science, government, and industry from all over the world.

This article is based on a Watson lecture given on October 9, 2001.


Chordates (fish, amphibians, reptiles, birds, mammals)
Hemichordates (acorn worms)
Echinoderms (sea urchins)
Deuterostomes
Phoronids (horseshoe worms)
Brachiopods (lampshells)
Ectoprocts (bryozoans)
Cycliophorans
Rotifers (wheel animals)
Gnathostomulids
Platyhelminths (flatworms)
Entoprocts
Nemerteans (ribbon worms)
Annelids (earthworms)
Echiurans (spoon worms)
Molluscs (squids, bivalves, snails)
Sipunculans (peanut worms)
Lophotrochozoans
Chaetognaths (arrowworms)
Gastrotrichs
Cephalorhynchs (priapulids)
Nematodes (roundworms)
Nematomorphs (horsehair worms)
Tardigrades (water bears)
Onychophorans (velvet worms)
Arthropods (crustaceans, insects, centipedes, spiders)
Ecdysozoans
Protostomes
Bilaterians
Cnidarians (jellyfish, corals, sea anemones)
Poriferans (sponges)

Animal Evolution: A View from the Genome

by Barbara Ellis

How did animals evolve, in the words of Darwin, "from so simple a beginning endless forms most beautiful and most wonderful"? How did the simple bodies of the first truly multicellular animals lead to six-legged insects, five-armed starfish, four-legged mammals, and legless snakes? Where did novelties such as insect wings and bird feathers come from? There's now a way, without having to rely on the patchy and often nonexistent fossil record, to trace back the origins of the different body plans and anatomical structures that give the animal kingdom its rich diversity. The evolutionary history of the animal kingdom is embedded in the genomes of the animals alive today, and can be studied in the laboratory.

This breakthrough has come from developmental biology—the study of how embryos develop—and it's created a huge upsurge of interest in the evolution of development. In fact, a completely new field of bioscience (colloquially referred to as evo-devo), in which evolutionary biologists, developmental biologists, paleontologists, and phylogeneticists share their expertise, is taking shape. Things are moving forward rapidly, and fascinating new insights into animal evolution are being published almost on a weekly basis.

To investigate the genetic changes that led to the evolution of different body plans, it's very important to have an accurate idea of the evolutionary relationships (phylogeny) of the animals alive today—to know who is descended from whom. Molecular phylogeny, such as comparing ribosomal DNA, has recently clarified a lot of the doubtful relationships. The "family tree" system of animal classification, with single-celled animals at the base and humans at the top, is out of favor nowadays, because it implies that evolution has a direction, and it's going our way. The branching diagram shown opposite, called a cladogram because it links clades (groups of animals who have all descended from a common ancestor), is a much more accurate way of showing relationships. Pairs of clades related by a common ancestor are linked by straight lines, so every branch in a cladogram is a "Y" (or a tuning-fork shape, as here). Most animals are now known to belong to a huge clade called the Bilateria, a name that refers to their unifying feature of bilateral symmetry; the body plan has a right-left axis, and a front-back axis and a top-bottom one, too. All bilaterian animals evolved from the same ancestral animal. The next most closely related clade to the Bilateria includes jellyfish, sea anemones, and corals (collectively called the Cnidaria), while sponges (the Porifera) are more distantly related.

Bilaterians are a step up in multicellular complexity from jellyfish and sponges, which have just two tissue layers—the ectoderm and the endoderm. The Bilateria have a third tissue layer, the mesoderm, between the ecto- and endoderm. And although cnidarians have some functional differences between layers of cells, only bilaterians have the complex 3-D arrays of cell types called organs.

The bilaterian lineage divided early on into two clades: the deuterostomes, which gave rise to the vertebrates and their cousins, and the protostomes. The latter divided again into the ecdysozoans and the lophotrochozoans. Insects, spiders, crustaceans, nematodes (roundworms) and the like are ecdysozoans, a name that derives from the fact that they all molt ("ecdysis"), while the lophotrochozoan clade embraces molluscs, earthworms, flatworms, and many lesser-known phyla (one of which, the Cycliophora, has only one member, discovered a few years ago on the mouthparts of the Norwegian lobster). Nowadays, each of these three great clades has a set of characteristics unique to that clade, but many—those inherited from the original bilaterians—are common to all three. By comparing what's unique and what's shared between descendants of common ancestors, it is now possible to work out the genetic changes that have given us the wonderful anatomical variety that we see all around us today.

This current picture of the evolutionary relationships among multicellular animals—i.e. the order in which they branched from common ancestors—is based mainly on ribosomal DNA analysis. The watery backdrop is the "gene pool" of the Beckman Institute.

A remarkably well-preserved upper Lower Cambrian fossil of a segmented worm, about 525 million years old, from the Chengjiang deposits in South China.

The first bilaterians evolved in the remote Precambrian, perhaps as much as 600 to 1,200 million years ago, from an ancestor shared with the cnidarians. Precambrian fossils are extremely rare, but with the current upsurge of interest in evolution, palaeontologists are searching world-wide for more, and they'll doubtless find them. Already, the 590- to 550-million-year-old Doushantuo deposits in southwest China have yielded some microscopic animal fossils bearing a striking resemblance to the embryos of modern bilaterians. It looks pretty certain now that the major evolutionary diversification of the bilaterians into the three primary clades also occurred in the Precambrian. The Cambrian period (545–490 million years ago) has an abundance of fossils, in striking contrast to the Precambrian, and they reveal a flamboyant blossoming of body plans and novel structures. During this era, almost all the major animal groups on earth today made their appearance, although one prominent group, the vertebrates, didn't appear until the Silurian, 100 million years later.

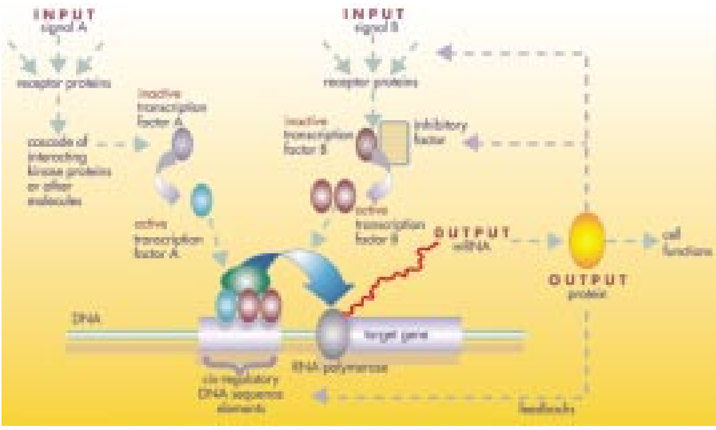
What made the bilaterians so much more successful than their cnidarian relatives, enabling them to spread out across the planet; adapt to life in seawater, freshwater, land and air; and grow as large as dinosaurs and whales? Their diversity and complexity are the result of having a larger complement of genes or gene families, a more sophisticated system of gene regulation, and, in particular, an "abstract patterning" mechanism for building body parts during development. In his new book, *Genomic Regulatory Systems: Development and Evolution*, Eric Davidson, the Norman Chandler Professor of Cell Biology, whose pioneering work on regulatory gene analysis contributed greatly to the current progress in understanding evolution, calls this abstract patterning mechanism "the secret of the bilaterians."

Development is a difficult task for a multicellular animal. It starts life as a single cell, which divides over and over again as quickly as it can into many, initially almost identical, cells, which then differentiate into specialized tissues and organs and anatomical structures such as limbs and wings. And every member of a species must develop correctly in the same way, each and every time. So why does one small, round cell develop into a sea urchin and another very similar one into a mammal? An obvious answer would be that the genes are different. But they're not: data from the genome sequencing projects, which have now provided full sequences for a variety of animals, has confirmed what was already becoming apparent from other research—bilaterians all have the same basic set of developmental genes. Some have duplicate copies and some have lost a few during evolution, but there's an astonishing commonality. Which presents an intriguing paradox: if the genes are the same, how come there are so many different types of animals?

"In development it is as if the wall, once erected, must then turn around and talk to the ceiling in order to place the windows in the right positions, and the ceiling must use the joint with the wall to decide where its wires will go."

At the molecular level, development involves the execution of a remarkable genetic program that regulates the construction of an organism. Of the thousands of genes in the genome, most are used at some time during development, and their deployment must be controlled accurately in space and time. The answer to the paradox lies not in the genes, but in the gene regulatory program, a program unique to each species. In some ways, writes Davidson in his book, this genetic program can be likened to an architect's blueprint for a large and complex building. Different buildings—perhaps a railway station and a cathedral—can be made from the same set of stones. It's the blueprint that dictates the different arrangement of the stones to make the different buildings. Similarly, different animals can be made from the same set of genes by following different blueprints. But animal blueprints also have to be interactive. "In development it is as if the wall, once erected, must then turn around and talk to the ceiling in order to place the windows in the right positions," he writes, "and the ceiling must use the joint with the wall to decide where its wires will go." Development also means a progressive increase in complexity; new populations of cells are generated, each of which reads out a genetic subprogram. And all the time, these populations are being instructed to expand to a given extent, through cell growth.

There's no "master gene" that coordinates development, the way a site foreman would oversee the implementation of an architectural blueprint. Each cell of the embryo has the same complete set of genes, derived from the fertilized egg cell. What makes one cell different from its neighbor depends on which genes are expressed, or turned on, to make proteins that have some function in the cell or transmit signals between cells, and which genes are blocked. Instead of a



Courtesy US Department of Energy Genomes To Life program, DOEGenomesToLife.org

An example of how a *cis*-regulatory element works. Signals A and B, which can be intra- or extracellular, activate transcription factors A and B along a signalling pathway. On reaching the *cis*-regulatory element, they help to initiate the synthesis of mRNA by RNA polymerase situated at the beginning of the target gene. The mRNA is translated into a functional protein (perhaps another transcription factor), which also provides feedback loops into the system.

single site foreman, the genes in each cell are controlled by short sequences of DNA called *cis*-regulatory elements. (*Cis*- means they're part of the DNA, as opposed to molecules that are *trans*-, not part of the DNA.)

With impressive foresight, way back in 1969, Davidson and colleague Roy Britten, now Distinguished Carnegie Senior Research Associate in Biology, Emeritus, proposed a theoretical model for such a system of genetic regulation. The underlying logic turned out to be more or less correct, but it wasn't possible to know for certain for another 30 years; only now are the tools of molecular biology (many of them developed by the Davidson group) good enough to detect such very small sequences of DNA and to analyze their function. A gene is thousands of base pairs long (a base pair is one "rung" of the DNA ladder), but the *cis*-regulatory elements have sequences of only a few hundred base pairs.

In essence, each *cis*-regulatory element functions like a tiny but very powerful biological computing device.

Cis-regulatory elements are usually adjacent to the gene they control but, just to make things more interesting, they can sometimes be several thousands of base pairs away along the chromosome. Although a few genes are controlled by just one *cis*-regulatory element, most are regulated by more than one, and some have a whole chain of them strung out along the chromosome. They're essentially "devices that make choices," says Davidson. Each *cis*-regulatory element has, on average, four to eight regulatory proteins, called transcription factors, associated with it. These proteins bring information to the *cis*-regulatory element from the world outside the cell nucleus, from other genes within it, and from neighboring cells (see diagram, above). When these transcription factors arrive (by diffusion) at the *cis*-regulatory element, they "dock" onto their own particular "landing bay," a very short sequence of DNA specific just to that transcription factor. Whether or not a transcription factor docks depends on its concentration and sometimes on its activation by other molecules, the cofactors. The *cis*-regulatory element "reads" the multiple inputs from the different transcription factors that dock—there could be one telling it what cell type it's going to become (muscle, nerve, or bone, for example), another to say where it is in relation to the other cells around it, yet another announcing that the cell is going to divide—and based on all this information the element produces a single output, an instruction that activates the gene or, as often as not, blocks it.

In essence, each *cis*-regulatory element functions like a tiny but very powerful biological computing device. The information-processing function of the *cis*-regulatory element is the link between the things that are happening in each cell and the response of the genes to them. And as the *cis*-regulatory elements are part of the DNA sequence, they're hardwired into the genome, and any changes in their sequence (such as by mutation, insertion or deletion of bases) are passed on to future generations—something that is of great significance in evolution.

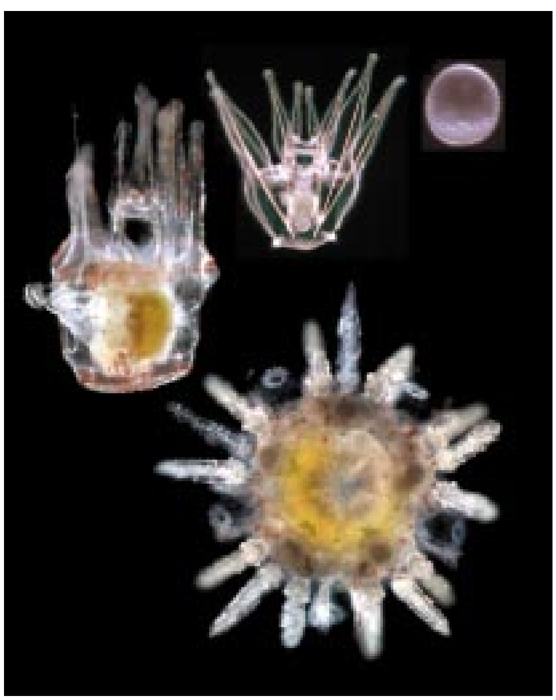
As transcription factors are proteins, they're also encoded by genes, and these genes in turn are controlled by *cis*-regulatory elements. During development, certain genes that encode transcription factors play a very important role; they're known as the regulatory genes, and they choreograph the highly successful abstract patterning system of bilaterian development.

The first bilaterians probably developed in a way still seen in the embryos of many modern invertebrate marine animals. When a fertilized egg cell from such an animal starts to divide, the cells of the embryo get to know the cell type they're going to be as soon as they're born, and their "differentiation gene batteries"—sets of genes that are all expressed at the same time in a coordinated way so that the proteins they encode define the cell type—are turned on straight away. They're coordinated because their *cis*-regulatory

Davidson learned much about the ordering of complex perceptions from his father, leading American abstract expressionist painter Morris Davidson.

In the pattern-formation system of development, "a simple snapshot taken during developmental time in the animal will not resemble any parts of the structure that will finally emerge. Until the final stages, it'll look like abstract patterns."

In the sea urchin, pattern formation remodels the larva into an adult form. From top (not to scale): embryo at the blastula stage; 8-arm larva, a small early rudiment of the adult body growing at the left-hand side of the stomach; metamorphosing larva with arm tissue contracting and tube feet of the 5-sided adult emerging from the side; one-week-old sea urchin juvenile.

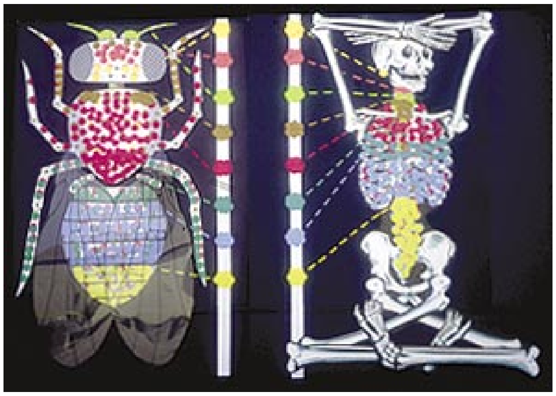


C. Arenas-Mena *et al.*, *Development*, 2000, 127, 4631-4653. © Company of Biologists Ltd.

elements all respond to the same regulatory-gene transcription factor. This "direct cell-type specification" way of developing is an effective way of producing a free-swimming, self-feeding larval stage as quickly as possible, but it can only work when a small number of cells are involved, and seriously limits embryonic size to the product of about 10 cell-division cycles, or a few thousand cells.

If a more sophisticated system of development—abstract patterning or, to give it its full name, pattern formation by stepwise regional specification—hadn't evolved, bilaterians would never have grown any bigger or more complex than their jellyfish cousins. But as increasingly complex *cis*-regulatory control subcircuits were set up over time, linking regulatory genes encoding spatial transcription factors with those responsible for signalling pathways and growth control, larger embryos with new body structures could develop. Astonishingly, the subcircuits set up in those early days, more than 550 million years ago, are still used today by all bilaterians. Most types of invertebrate animals still use direct cell-type specification to get to the free-swimming larval stage, with pattern formation taking over after that to remodel the larva into an often very different adult form (as in the sea urchin, lower left). Interestingly, some groups that evolved after the appearance of the first bilaterian groups, such as the insects and the vertebrates, escaped this basic mechanism and devised their own ways of turning eggs into embryos.

In the pattern-formation system of development, "a simple snapshot taken during developmental time in the animal will not resemble any parts of the structure that will finally emerge," writes Davidson. "Until the final stages, it'll look like abstract patterns." Early on, basic elements of the body plan such as the anterior-posterior axis and left-right symmetry are established. Later pattern-formation events define the spatial organization of the main parts of the body plan—head, tail, forelegs, hindlegs—then even later pattern-formation events define the detailed and smaller elements, such as the arrangement of the limb digits. Each stage involves the partitioning off of one group of



Above: The *hox* genes are aligned in the same order on the chromosomes of fruit flies and humans. This diagram indicates roughly which body parts are patterned by which *hox* gene (courtesy Ed Lewis).

Right: Spider from Corcovado National Park, Costa Rica (courtesy L. E. Gilbert, Integrative Biology, University of Texas at Austin).

cells into subgroups by the expression of regulatory genes encoding transcription factors. There can be a whole cascade of transcription factors, sometimes linked through signaling pathways, each of which controls the activity of other regulatory genes further downstream at the next level of regulation, which could again be genes encoding other spatially expressed transcription factors, and so on. Eventually, the gene batteries that make the differentiated tissues and organs are switched on, and it's only at this stage that an observer would start to see recognizable body parts emerging from the abstract picture. That's why it's called abstract patterning.

So the key players in the complex genetic program for pattern formation are the genes that encode the regulatory transcription factors and their *cis*-regulatory elements. Let's look at the best-known set of these, the *hox* cluster. In 1978, eight linked *hox* genes involved in the development of body segments in *Drosophila melanogaster*, aka the fruit fly, were discovered by Ed Lewis (PhD '42; now Morgan Professor of Biology, Emeritus). Lewis had been patiently working away on *Drosophila* in Kerckhoff Lab since 1939, and Davidson, who joined Caltech in 1970, and was already thinking about how development and evolution could be interlinked, feels he was fortunate to have been in the same department at that time. "Ed was always upstairs, and he used to say hey, come and look at this," he recalls. "I immediately realized that Ed's genes were some of the most interesting genes being worked on in the biology division." Lewis was awarded the Nobel Prize for his work in 1995 (see *E&S,* 1996, No. 1).

In the fruit fly, *hox* genes play an important role in the development of body segments. The key feature of these genes is order. They are ordered in the genome as two clusters in a long segment of the DNA on one of the chromosomes, and in space, the genes are expressed in the same general order along the body as that in which they lie along the chromosome. The first and second gene of one cluster is expressed in the head segments, then the third gene comes on a little farther posterior in the thorax, and so on. *Hox* genes have been found in every animal type looked at, and are always involved in anterior-posterior patterning of the body. "We were all surprised at that," Davidson recalls. No one had expected to find that humans had the same developmental genes as flies (left).

Even more surprising was finding that regulatory genes have been so highly conserved throughout evolution that they're sometimes even *interchangeable* between animals. Some fly *hox* genes have functioned well when transplanted into mice, and some mouse *hox* genes can replace those of flies. The *pax6* gene is particularly interesting. One of the important transcription factor-encoding regulatory genes, *pax6* is involved in development of the vertebrate eye. Its fruit-fly equivalent, *eyeless* (having these different gene names is confusing, but scientists had no idea, when they found and named them in their own particular lab animals, that they were dealing with the same genes) regulates development of compound insect eyes, with their numerous eyelets. Vertebrate and insect eyes are very different in construction, building materials, and the way they work. So what would happen if the *eyeless* gene of a fly was transferred into a mouse embryo? A mouse with fly eyes? No—the mouse develops a normal *mouse* eye, even using a fly gene. If a human *pax6* gene was transplanted into a spider, spider eyes would develop. No spiders would look out from their webs with six big, blue human eyes, unfortunately (or perhaps fortunately). Moreover, if *eyeless* or *pax6* genes are made to function in a different part of an embryo, the cells there form an extra, ectopic eye—frogs have grown extra frog eyes on their backs, flies have developed fly eyes on their legs (lower left).

The explanation for these unexpected results is that *pax6* is a regulatory gene active in a growing field of undifferentiated cells near the top of the embryonic patterning cascade mentioned earlier. It encodes a transcription factor that sets up a train of events leading to the formation and patterning of an entire structure (the eye), but it doesn't control the actual *construction* of the eye (such as the lens, the cornea, the optical pigment), which is done by batteries of genes further along in the development program. Mice always grow mouse eyes because the fly's *eyeless* gene activates the mouse's own eye-differentiation gene batteries, which go on to make all the parts for a mouse eye. To explain the ectopic eyes, think of the undifferentiated field of cells as a clean slate, prepared to respond to any of a number of regulatory genes that start a differentiation program. Inducing *pax6* to run in undifferentiated back cells of a frog embryo, or leg cells of a fly embryo, activates the eye-differentiation gene batteries in those cells. In fact, *pax6* works at the terminal differentiation

Czerny, T. *et al., Mol. Cell* 3, 1999, 297-307. © Elsevier Science

Ectopic eye induced on the leg of a fruit fly by forcing the expression of a fly homolog of the *pax6* gene in the embryonic leg.

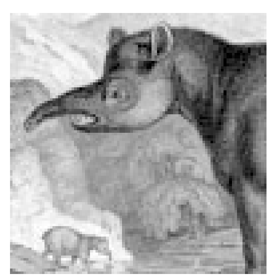
The eyes of squids, flatworms, flies (top row) and vertebrates (bottom row: trumpet fish, human, heron) use different optical principles and visual pigments and are constructed from different materials, but their development is always initiated by the same *pax6* gene. (Animal photos courtesy BioMEDIA ASSOCIATES, www.ebiomedia.com.)

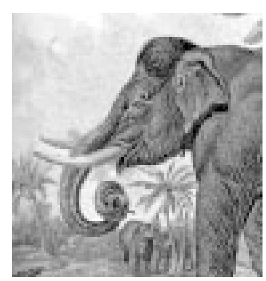
stages of eye formation as well, because over time, regulatory genes can gain extra functions in new areas and at several different levels of the cascade, and this can lead to the creation of new structures that, when preserved by natural selection, contribute to new animal forms.

How do pattern-formation systems reinvent themselves, and animal forms change, during development? One of the most important ways is by cooption, which is when a regulatory gene gains control of a new target site downstream, or controls the same apparatus but in a new area of the developing animal. The hypothetical regulatory gene followed through three different stages of evolution in the box on the opposite page shows how this could happen. Over time, the system becomes more and more complicated as the downstream effects of the gene affect more gene batteries; but all the while, the gene is still used for its ancestral function—to start development of the structure in the embryo. Cooption is rather like walking, writes Davidson. "One linkage, upstream or downstream, stays where it was last put and bears functional weight, while the other moves; and then, if its move is useful, it may serve as the functional anchor while the first changes. After a few such 'steps', all the linkages surrounding a given phase of activity of a regulatory gene may be different from the ancestral stage."

Normally, mutations to any of the genes active in the early stages of embryogenesis are just too disruptive to be survivable, and the mutation dies with the embryo. But if the cooptive change was such that the gene carried on doing its old job in addition to the new one, a viable, but somewhat different, animal could result, one that might survive to adulthood and pass this cooption on to its offspring. Small genetic changes in *cis*-regulatory control happen continuously in all animals. When they're at a downstream level of development fairly close to the final differentiation stages, they cause small differences between animals of the same species, the sort that breeders take advantage of. However, if *cis*-regulatory control of particularly significant *upstream* regulatory genes changed, there could be far more significant changes. A duplicated subset of the vertebrate *hox* cluster, for instance, was coopted to patterning limb development in vertebrates about 350 million years ago, a serendipitous evolutionary change that resulted in paired limbs—and enabled vertebrates to swim, walk, run, and fly their way all over the world.

If a *cis*-regulatory module controlling the timing of cell division gained a downstream gene controlling commitment—that moment in a cell's life when it stops developing and resigns itself to being an adult cell type forever—areas of the body could grow bigger or smaller. Let's imagine that this happened in the nose of a developing tapir, and that the program that determines the number of cell divisions changed from six to 10 cycles. There would be a 60-fold increase in size, and a baby tapir would be born with a bigger nose. This

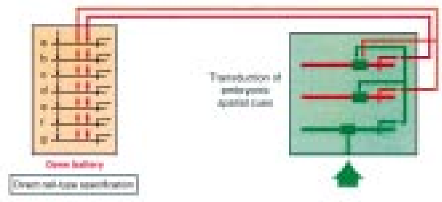




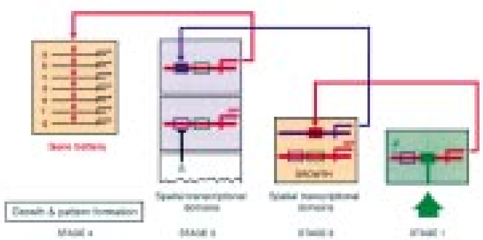
would be inherited by its offspring, so eventually lots of long-nosed tapirs would be running around. And if there was an evolutionary advantage in having such an extended nose, or if it increased the tapir's breeding success, a new species might eventually arise. Could this explain how the elephant got its trunk? It's far too simplistic a way of looking at speciation, of course,

COOPTION

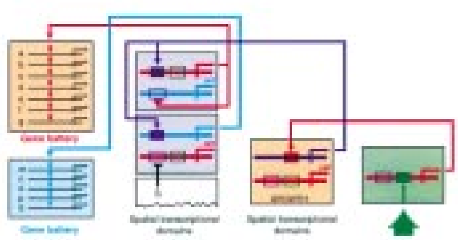
Three evolutionary stages of an imaginary pattern-formation system for a body part, showing how a simple system can gain complexity by cooption. The colored boxes are transcriptional domains, groups of cells whose state depends on the product of a gene (represented here as a thick horizontal line) of the same color. The short bent arrows indicate gene activation (transcription).



Stage 1, above, shows a simple, direct cell-type specification network. A green gene giving spatial cues from the embryo activates orange and red genes; all are regulatory genes encoding transcription factors. The gene battery encodes proteins used for some differentiated cell type and has *cis*-regulatory elements (a–g) that respond to input from transcription factors encoded by the orange and red genes.



In stage 2, a pattern-formation system has evolved. Focusing only on the red gene, we see it now activates a new, purple regulatory gene and a growth circuit. The purple gene product, another transcription factor, activates a second *cis*-regulatory element acquired by the red gene (which can be repressed by spatial signals from the embryo). The red gene is now activated by *cis*-regulatory interactions of the purple gene product with the purple *cis*-regulatory element of the red gene. It then activates the gene battery.



In stage 3, the pattern-formation process is even more elaborate. A new blue regulatory gene has been coopted by introduction into its *cis*-regulatory system of a *cis*-regulatory element that responds to the purple transcription factor (purple solid box). This blue gene activates a new, blue gene battery, which works in a different area of the embryonic structure being formed, thus increasing the complexity of this body part. The red gene now controls both the ancestral gene battery and the new one. But at all three stages of evolution, the green gene starts activation of the red gene, and the red gene still activates the gene battery that starts development of the body part.

but it shows how the evolution of developmental programs could play a role.

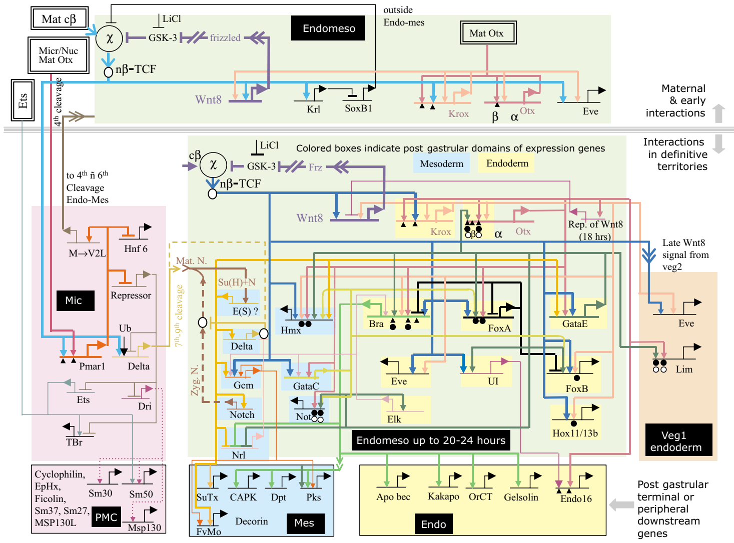
The Davidson lab at Caltech is at an advanced stage of mapping the entire network architecture of the *cis*-regulatory elements that control just 50 to 60 genes involved in the formation of the endomesoderm—the cell layers that produce most of the internal organs and tissues—in the sea urchin embryo, and of finding out how they're linked to one another by the regulatory transcription factors. It's an ambitious task, with layers and layers of complexity to unravel, and no one has dared attempt it before. But what they've found so far, Davidson says, is "extraordinarily interesting and illuminating," and he's optimistic: "Pretty soon I think we will understand the network. It's the evolutionary history of the animal, its heritage—it tells each gene what inputs it'll listen to throughout the life cycle. The *cis*-regulatory elements that control each gene enable it to respond to what it will encounter in every cell, every time, for the life cycle of the animal. That's what is hardwired into the genome. The network gives us a map of all these connections."

To investigate *cis*-regulatory elements involved in embryonic development and pattern formation requires fertilized eggs or one-cell embryos, because genes have to be injected into them to see what effect they have on their development. The beloved lab animal of the Davidson group, the California purple sea urchin, *Strongylocentrotus purpuratus*, provides them with an unlimited supply. "Years ago when I came to Caltech," Davidson recalls, "we built a huge egg-to-egg culture system at Caltech's Pacific outpost, the Kerckhoff Marine Laboratory in Corona del Mar, and we found sea urchins to stock it by diving for them." Once one of the regularly working scuba divers himself (see *E&S,* 1987, No. 4), he now mainly uses contract divers to do the work. The sea urchins live about 30 to 60 feet down in the coastal waters, and have few natural enemies except the occasional fish, sea otters and fishermen supplying Japanese restaurants. For molecular developmental biologists, the sea urchin embryo has many virtues, including transparency, incredible fecundity, high tolerance for micromanipulation, easy gene transfer, and a simple embryology. Best of all, it grows into a larva that swims, feeds, and looks after itself in a matter of days. "Sea urchins are great for *cis*-regulatory analysis," Davidson says. "You do something with the eggs one day, and you get results the next. There's no need to wait until they grow up and have offspring."

To map an entire regulatory system, the Davidson lab has developed a new set of technologies for finding genes expressed in the endoderm or mesoderm at different times—they've found hundreds, which they're now sorting through to find the ones most central to the process. Then they intend to analyze the way in which these genes are regulated; that is, how they're connected in the network through their *cis*-regulatory regions. The *cis*-regulatory elements are notoriously difficult to find; the very short stretches of bases for each one are hidden in millions of base pairs of no apparent function, the so-called "junk DNA", but that's another story. To locate the regulatory elements, they're enlisting the help of evolutionary conservation: when the nucleotide sequences around these genes are compared among different species of sea urchins whose common ancestor is millions of years old, only regions that have a use remain unchanged. All parts of the DNA sequence that don't bind proteins can change over this long a time, so the short, unchanged segments will stand out in these comparisons. And these identical little patches that are the same between the different species have turned out to be the *cis*-regulatory elements—a very interesting finding. *Cis*-regulatory analysis comes next—this is really what the Davidson group is best known for. A short fragment of DNA containing the *cis*-regulatory element is isolated, attached to another piece of DNA that encodes a traceable protein (usually colored or fluorescent), and injected back into the embryo. The cells of the developing embryo in which the protein appears are the ones in which the gene regulated by that *cis*-regulatory element is active. This way, the network connections can be checked. The final stage is to "knock out" genes to find the effect on all the other genes in the system. All the results are fed into an impressive computational model, the "wiring diagram" (shown opposite), that's updated every week on the lab Web page (www.its.caltech.edu/~mirsky/endomeso.htm) as the results come in. Eventually, it will show where and when each gene is expressed throughout the various stages of endomesoderm development. It's going to be a lot of work, but once complete regulatory systems have been mapped for key members of the different animal clades, their similarities and differences will reveal the precise role of development in the evolutionary history of animals, something no one would have believed possible just a few years ago.

Soon, biologists will be able to work back, like comparative linguists who reconstruct extinct protolanguages from languages still spoken today, to the last common ancestor of all the Bilateria. As Davidson writes: "Although the ancestors of modern animals are extinct, the evidence of how they worked is still swimming, walking, flying around outside, in the form of the DNA of the modern bilaterians." And when groups of animals become extinct, what the planet is actually losing is their specific developmental-gene regulatory

Purple sea urchins at Kerckhoff Marine Lab during a winter harvesting campaign for rare nucleoproteins such as transcription factors, left, showing some of the 1,500 males and 1,500 females being spawned. A gravid female deposits about 10 million eggs (top left), so a total of 15 billion eggs can be collected, which are poured into 4-liter beakers (top right) and mixed with sperm from the males. Growing the fertilized embryos for 24 hours to the 200-cell stage provides 3 trillion nuclei from which workable amounts of nucleoprotein can be extracted.



The full regulatory gene network for endomesoderm specification mapped so far in the sea urchin embryo, showing all the linkages functional in different places and at different stages of the developmental process. Each short horizontal line represents the *cis*-regulatory element responsible for expression of a gene, and a short bent arrow extending from it indicates gene transcription. The colored lines connect transcription factors from the gene that encodes them to the *cis*-regulatory element or elements that they affect. This "wiring diagram" will get increasingly complex as more gene interactions are mapped.

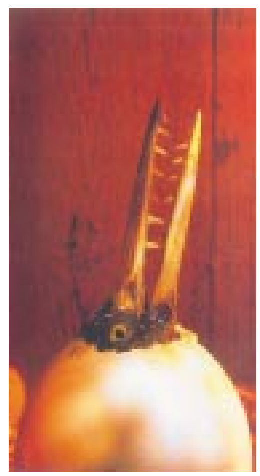
networks—while the genes live on in other species.

Those ancient regulatory genes conserved in common by the three great clades, it is argued, must have been present in the original bilaterian. These include *hox, pax, orthodenticle* (for the nervous system), and quite a few others, so perhaps our ancestor swimming in Precambrian seas amongst the jellyfish was a small animal with a head end and a tail end, bilateral symmetry, a gut, nervous system, photoreceptor organs, and possibly some outgrowths or appendages. It's still only a blurred image, but it will get clearer as more regulatory gene networks are mapped.

Could we rewind evolution to restore extinct regulatory networks? Already, a team at the University of Southern California has succeeded in hatching chicks with tooth buds in their beaks; birds lost their teeth at least 60 million years ago. Other teams have had some success in giving snakes back their legs, and regenerating the eyes of eyeless cave fish. Could this be the way to reconstruct extinct animals? Admittedly it's a long way from a chicken with teeth to a complete dinosaur, but it's food for thought.

More than 600 million years of evolutionary experimentation have put the regulatory genes of the original bilaterians to many new uses in different areas of a developing embryo, to give us the rich diversity of animal life that we see all around us today. And the DNA in every cell of every animal alive today carries within it a forensic record of the changes that have happened over those millions of years. Deciphering it will keep the Davidson group and others busy for years, but we'll have a much better understanding of who we are and where we came from by the time the 200th anniversary of Darwin's birth comes around in 2009. □

Right: Could extinct animals eventually be recreated by restoring their lost regulatory networks in modern descendants? Artwork courtesy Chris Draper.



Davidson's book, Genomic Regulatory Systems: Development and Evolution *is published by Academic Press, 2001. For an introduction to the subject, try* From DNA to Diversity: Molecular Genetics and the Evolution of Animal Design *by Sean Carroll, Jennifer Grenier, and Scott Weatherbee, published by Blackwell Science, 2001.*

PICTURE CREDITS:
42-43 – Doug Cummings

The Copenhagen Interpretation: Exploring Science on Stage

Michael Frayn's play *Copenhagen*, which opened in London in 1998, in New York in 2000, and finally made it to Los Angeles in late 2001, explores what might have been said during a 1941 meeting of Niels Bohr and Werner Heisenberg at Bohr's home in the German-occupied capital city of Denmark. Although in the end all the ambiguities and "uncertainties" remain, the three characters (including Bohr's wife, Margrethe), with the knowledge of hindsight "when all are dead and gone," reenact various drafts of the purpose of Heisenberg's visit—and the ultimate question of why Heisenberg did not build an atomic bomb for the Nazis.

Caltech interest in the play naturally ran quite high, and on December 10, in a packed Beckman Auditorium, Caltech hosted a panel, "The Copenhagen Interpretation," convened "to consider the broader scientific, historical, philosophical, and artistic dimensions of this encounter and its dramatization." The panel was moderated by Steve Koonin, provost and professor of theoretical physics, who, in some non-Caltech aspects of his professional life, also is involved with "nuclear weapons and the scientists who are concerned with them." Emphasizing that there was no script for the evening—"think jazz performance rather than chamber ensemble"—Koonin introduced the rest of the panel: Bob Christy, Institute Professor of Theoretical Physics, Emeritus, who had worked on the Manhattan Project and was known for his experimental, as well as theoretical, work; Diana Barkan Buchwald, associate professor of history, and general editor and director of the Einstein Papers Project; Hank Stratton, who plays Werner Heisenberg in the Los Angeles production of the play; Marge Leighton, a close friend of the Bohr family (and widow twice-over of Caltech physics professors Tommy Lauritsen and Bob Leighton); and Jay Labinger, administrator of the Beckman Institute, who often writes on the historical, cultural, social, and literary aspects of science (see his review of two other science plays in *E&S*, 2001, no. 1).

After Hank Stratton described the play briefly (but told the audience they'd have to "spend 55 bucks" to get the rest of it), Diana Barkan Buchwald, a historian of science, outlined what was going on in physics at the time: fission had been discovered in Berlin in 1938 by Lise Meitner, Otto Hahn, and Fritz Strassmann. Bohr brought the news to America in 1939, she said, but by 1940 the Germans were increasingly isolated, and

In the Los Angeles production of Michael Frayn's *Copenhagen* at the Wilshire Theatre, Len Cariou (right) appeared as Niels Bohr, Mariette Hartley as Margrethe Bohr, and Hank Stratton as Werner Heisenberg.

At the Nuclear Physics Congress in Rome, 1931; from left: Robert A. Millikan, Marie Curie, and Werner Heisenberg. Ten years later, the international physics community would no longer be sharing research on nuclear physics.

Allied scientists, in a self-imposed embargo, stopped publishing any work on fission. "By 1939 both sides were planning to use fission either for a bomb or for a reactor or both." Einstein wrote his famous warning letter to President Roosevelt in August 1939 (see *E&S*, 2000, no. 3), urging him to make contact with Enrico Fermi and Leo Szilard, who were working on chain reactions. Buchwald placed the birth of the Manhattan Project at the end of 1941, when James Conant convinced the government that a bomb had to be built.

Bob Christy recalled being a grad student at Berkeley in the spring of 1939: "I remember the excitement of the news of fission and how every week a new experiment verifying this was being done and reported. It was an exceedingly exciting time." But by the time Christy joined the Manhattan Project in Chicago in 1942, the pure excitement had given way to urgent determination. Many of the project's senior scientists, he said, who had been forced out of Europe and had personal recollections of the Hitler regime, "were deeply concerned about the possibility that Hitler would develop a bomb before it was accomplished elsewhere."

Getting back to the actual characters in the play, one of the "complementarities" in the play, said Koonin, "is between the slow-moving but very deep Niels Bohr, who does his papers over many times until he gets to perfection, and the more mercurial Heisenberg, who shoots from the hip and is usually pretty accurate." How accurately are they portrayed? Marge Leighton and her husband, Tommy Lauritsen, went to Copenhagen in 1952–53 and spent much time with the Bohr family, who "treated Tommy as another son." She described Bohr as "so soft-spoken you could barely hear him. . . . I wanted to hear everything he had to say, so I was practically sitting on his lap in order to hear him." (Obviously such low volume wouldn't work on stage.) Bohr talked more about artists and writers than scientists, she said; he was a great admirer of Mark Twain. When she saw the London production, she was shocked at the portrayal of Margrethe Bohr as "shrill and confrontational," rather than the gracious person she remembered. Mariette Hartley, who plays Margrethe in the Los Angeles production, is better, said Leighton.

The discussion of dramatic license brought the panel to a particular line (which Stratton could, of course, deliver on command) near the end of the first act—when Heisenberg confronts Bohr about Bohr's participation in the Manhattan Project. When Bohr says Robert Oppenheimer tormented himself after the bomb, Heisenberg replies: "Afterwards, yes. At least *we* tormented ourselves a little beforehand. Did a single one of them stop to think, even for one brief moment, what they were doing?"

That line comes from Heisenberg's postwar recollections, said Buchwald, who claimed it reveals Heisenberg's self-righteousness, which many consider unwarranted. Someone who had been, at the very least, an active participant in German war preparation has no right to be asking that sort of question, she said, and it's also in hindsight; there's no evidence of what Heisenberg actually thought at the time. And furthermore, Buchwald insisted, "scientists in the United States and England *did* stop to think about what they were doing."

Christy confirmed that "it was certainly a major preoccupation of Bohr himself. . . . I know that during his visits to Los Alamos, he and Oppenheimer had lengthy discussions on the question of international control and how to deal with this new phenomenon they were beginning to produce."

It was pointed out that Lise Meitner, who fled from Germany to Sweden, refused to come work on the Manhattan Project. On the other hand, said Christy, Meitner's nephew, Otto Frisch, and Rudolf Peierls, both refugees in England, first

PICTURE CREDITS: 52, 54 – Joan Marcus; 53, 55, 56 – Caltech Archives

The Bohrs and Heisenberg duke it out on stage. Danny Kaye singing "Thumbellina" it's not.

showed that building a bomb was feasible. Interestingly, Frisch and Peierls were listed as enemy aliens, added Buchwald, and "excluded from officially working on what was called the Tube Alloys Project, the English precursor of the Manhattan Project." They were, instead, assigned to work on radar, "which they didn't know very much about, but they continued to work on fission on their own."

Returning to Heisenberg's line about morality, which has caused much controversy among scientists and historians, Stratton (who insisted he wasn't just trying to defend his character) argued that the controversy it has provoked is all the more reason to keep the line in the drama and not ignore it. "It sparks a debate."

This led to the subject of science as drama. "Science can certainly be good drama," said Jay Labinger, "but it presents problems." Like Leighton, Labinger had first seen the London production and told the story of walking into the theater ahead of a couple of Americans, one of whom said to the other, "I'm not so sure this *is* a musical, you know." He wondered throughout the play how the science was going over with "people who were expecting to hear Danny Kaye sing 'Thumbelina.'"

"If you want to communicate scientific concepts," said Labinger, "you tend to fall back on dialog like, 'You remember how we discovered this, and so-and-so taught us that?' I think the first half of the second act dies a little bit when there's too much of that. But to a large extent this play somehow avoids that. Part of it is that the scientific content isn't essential to the play. You can get a lot out of it and miss all the science. It's enriching, certainly, and the more you get, the better, but it's not central."

"But certainly in the present play," commented Koonin, "understanding something about the uncertainty principle and complementarity—all the things that go into the Copenhagen interpretation of quantum mechanics—makes Frayn's construction look that much more clever." He compared Labinger's view with watching *The Simpsons* on TV: "You can watch it at the level of your kids" or enjoy it at another level.

Discussion then turned to the question of just how difficult it was to construct a nuclear device, and why it was such a daunting task at the time. "How can it be that the Germans really got it so wrong, when in retrospect the physics is pretty simple?" asked Koonin. What was so daunting was the separation of the uranium isotopes, replied Christy. The Germans thought it was impossible and just gave up, but Christy knew of at least five projects in this country that were exploring this before the Manhattan Project got under way. The Americans were also pursuing the production of plutonium from a reactor as an alternative to U^{235}, Christy said. But the Germans "hadn't done anything to plan a real production effort," even though they had already, before Heisenberg's meeting with Bohr, demonstrated that "a sub-critical reactor of their design would multiply neutrons and therefore showed the way to making a full-size reactor that would produce plutonium."

"So what was different?" asked Koonin. "Why did the Americans pursue this so vigorously, and the Germans seem to have done it in a rather desultory manner?"

Physics was done differently in this country, said Christy, who described Ernest Lawrence's cyclotron operation at Berkeley as the beginning of Big Science. "He made a big machine. The nuclear physics was kind of a sideline with him; he had lots of people there working with him who did the nuclear physics because he had the machine." It was the combination at Berkeley that was so important—the experimental physicists, the theoretical physicists, the engineers, and the chemists working as a team, attending seminars, and talking with one another. There was a similar kind of teamwork at Caltech, said Christy, but on a smaller scale. "Tommy Lauritsen's father, Charlie, had an accelerator program here. Oppenheimer was a close friend of Charlie Lauritsen and also of Ernest Lawrence. The combination of the theoretical and experimental physics and the engineering was the way physics was done in many institutions in this country." Tommy Lauritsen went to Copenhagen in 1939 and started work on an accelerator there, added Leighton, but left when the Germans occupied the country.

The structure of science was different in Germany, said Buchwald; theoreticians and experimentalists didn't often meet. "The received view among historians about the failure of the German atomic project has been that Heisenberg wasn't a good enough plumber. He wasn't good with his hands. He was a theoretician who didn't know how to put together a big group, how to collaborate with technicians and engineers."

"And yet Germany, and more generally Western Europe, was the right atmosphere to create this marvelous science of quantum mechanics," said Koonin, "A great community of people working together, but in a theoretical way more than in an experimental way."

There was some discussion about how much science Heisenberg did after the war. Not much, everyone seemed to agree. Koonin heard him give a seminar at MIT in the early '70s, and Christy remembered a seminar he gave at Caltech on some field theory that was way out of the mainstream. Leighton also remembered meeting Heisenberg at Caltech after the war and said that Tommy gave him a pretty rough time about his war activities. Buchwald added that although Heisenberg became very important in postwar Germany—he held several high positions and was a leader of the scientific community—he was always very concerned about his war reputation. Bohr was actually very generous with Heisenberg after the war, she said, and they met at international meetings. But he was badly received in this country. "There are anecdotes about meetings in the United States in the first years after the war, about people walking around with a drink in one hand and a notebook in the other, so they wouldn't have to shake Heisenberg's hand," said Buchwald.

Stratton rose to the defense of his man, whose skin he has to inhabit eight times a week. "I think he's the most complex character in the play. . . . I have a deep compassion for him but also have huge personal problems with his actions, as

From left: Tommy Lauritsen, Max Delbrück, Niels Bohr, and Paul Epstein on the Caltech campus in June 1959.

The combination of the theoretical and experimental physics and the engineering was the way physics was done in many institutions in this country. —*Bob Christy*

I'm sure the international scientific and historical community does as well. But that's all the more reason to expose them in theater," said Stratton. Buchwald then mentioned the long tradition of plays about science and noted in particular Brecht's *The Life of Galileo* and Dürrenmatt's *The Physicists*, both of which were written in the aftermath of World War II and dealt with scientists' responsibility and guilt.

In closing, Koonin posed a single question for each panelist a la the McLaughlin Group. "Central to the play are the many interpretations of the meeting between Bohr and Heisenberg. What did Heisenberg come to ask or to tell his mentor and collaborator, Niels Bohr? The play goes through the scene at least three times, offering different explanations each time around. So what do *you* think Heisenberg said to Bohr at the 1941 meeting? Was it the question about morals that's in the play? Did Heisenberg try to pump Bohr for information about the Allied program? Did he tell him that he was sabotaging the German effort? Did he ask Bohr to make a pact mutually renouncing nuclear weapons work? What do you think?" (The answer may come out soon when the Bohr family releases an unsent letter to Heisenberg.)

It occurred to Christy that Germany lacked a cyclotron, which was necessary for learning how to deal with plutonium. And Bohr had one for his neutron experiments. "So my thought is that maybe he went there to secure the cooperation of the Bohr Institute in studying various problems with their cyclotron." He qualified this by saying he wasn't sure he believed it, though.

Labinger changed the question: ("Punt!" called Koonin.) "Will it make any difference at all to our response once we have this answer? What if, after the letter, it turns out that actually they never met at all, but they agreed to tell the story so Heisenberg would get his travel expenses reimbursed or something like that. I just don't see how that's going to influence what we think about the *play*, which is an exploration of alternative possibilities."

"It depends on where you're sitting and what you observe," said Leighton. "You're not being dishonest; you're just bringing what you have to it. And the scientists observing it—what they think happened depends on what they're bringing to it."

Buchwald agreed up to a point. "The play tries to tell us that history is uncertain. I completely agree that what goes on in the hearts of men in difficult times when they meet and talk may, even a year or two later, change or be very uncertain. But there are other aspects of this encounter that are not so uncertain. We know that Bohr got very angry, and so most of us suspect that Heisenberg was trying to pump him for some sort of information." She pointed out that other German physicists, such as Max von Laue and Max Planck, wrote at the time about how they felt about the war, "whereas everything we know about how Heisenberg *felt*, we know only from his retrospection. Everything we know about what he *did*, we know from the historical record. So the ambiguity should be allowed, but, I think, only so far."

Koonin closed with his own prediction: "I think Heisenberg was trying to gain some advantage for Germany, either by asking Bohr to cooperate with the German nuclear effort or by asking him to forego working on the Allied effort." Koonin thought Heisenberg had figured out that building a bomb was going to be really tough and doubted whether the Germans could pull it off, while fearing that maybe the Allies could. "So he was either trying to get Bohr's expertise or, more likely, just saying to Bohr, 'Hey, let's just not push on this because it's not going to work anyway.'"

A lively question session followed. The *Copenhagen* panel, including the questions, can be viewed on line at http://atcaltech.caltech.edu/theater/. □ —*JD*

The play tries to tell us that history is uncertain. I completely agree that what goes on in the hearts of men in difficult times when they meet and talk may even a year or two later change or be very uncertain. But there are other aspects of this encounter that are not so uncertain. —*Diana Buchwald*

As the panelists noted, the Bohr family has decided to release (on February 5) a letter Bohr wrote to Heisenberg but never sent. According to an account in The Times *of London January 6, the few people who have seen it say the letter reveals that in their 1941 meeting, Heisenberg confided the shocking news that the Germans (and he himself) were working on building an atomic bomb for use in the war. His motive for this confidence is apparently unclear from Bohr's letter, which he wrote in response to Heisenberg's claim in a 1958 book that he had always intended to sabotage Hitler's nuclear effort.*

PLUMBERS

The Americans were good "plumbers," and the Germans were not. That's one view to come out of the Caltech *Copenhagen* panel on why the Germans didn't manage to build an atomic bomb and the Americans did.

Although he was not involved directly in the Manhattan Project, no one exemplifies American (and Caltech's) superior physics/plumbing collaboration better than Charles Christian Lauritsen. After training as an architect in his native Denmark, Lauritsen emigrated in 1917 and, although never an actual plumber, designed ships in Boston, worked as a professional fisherman in Florida, and produced radio receivers in California. As chief engineer for a radio manufacturer in St. Louis, he was impressed by a lecture given there by Robert A. Millikan. Millikan was equally impressed with Lauritsen and lured him to Caltech in 1926 to design equipment for his experiments on the cold emission of electrons from metals. By 1929 he had earned his doctorate in physics under Millikan, and in 1932, when it was demonstrated that machines could be used to disintegrate nuclei, Lauritsen already had an X-ray lab ready to roll. Out of Lauritsen's early radiation experiments grew the Kellogg Radiation Laboratory and Caltech's long history of distinguished research in nuclear physics and astrophysics, including the Nobel Prize-winning work in nucleosynthesis of Willy Fowler, a graduate student of Lauritsen's.

Accelerators followed the X-ray tubes, and Charlie's son, Tommy, who earned his PhD at Caltech in 1939 (under his father), was building a Van de Graaff accelerator like its Caltech model for Niels Bohr's lab when the Germans invaded Denmark in 1940. Charlie Lauritsen died in 1968, Tommy in 1973.

Robert Oppenheimer, who held joint appointments at Caltech and Berkeley during the '30s, was a good friend of Lauritsen's, as was another theorist, Richard Tolman. "Many times they sat after lunch in some old weather-beaten wicker chairs in the sun outside the High Voltage Lab discussing the great happenings of the day in physics," recalled Fowler (*E&S*, March 1982). Fowler went on to say that "Charlie did more than guide our graduate careers. He taught us how to use a lathe, how to bring the mercury back down in the stem of a Macleod gauge by gently tapping without breaking it, how to outgas the vacuum tube after repairing a leak by painting it with shellac, and a million and one other practical things in the nuclear lab of those days."

Perhaps if Heisenberg had learned a few "practical things" and sat around in the sun talking to men who could build machines, things might have turned out differently.

What follows is excerpted from an exchange of e-mails between Jack Roberts, Institute Professor of Chemistry, Emeritus; Doug Smith, managing editor of *E&S*; and Mike Tyszka, visiting associate in biology regarding one of the Core 1 science-writing essays published in the last issue, "The Promise of Portable MRI," by John Ferguson.

Jane:

I was rather embarrassed to read in *E&S* that the writer of the NMR article placed one of the greatest of Harvard's physicists, Edward Purcell, as leader of a team from of all places, MIT, and "discovered" (more appropriate would be "demonstrated") NMR in condensed matter. It was discovered by I. I. Rabi quite a few years before in the gas phase and earned him a Nobel prize. . . .

Perhaps the student papers might be better at least read by someone working in the field.

Jack

Dear Professor Roberts,

I apologize for the misaffiliation of Edward Purcell with MIT instead of Harvard. That, alas, was my error, not the student's. The original sentence in John Ferguson's essay read:

"The official birthday of NMR was in 1946 when two American teams led by Bloch and Purcell independently discovered that by adding another, smaller field to the original, larger magnetic field interesting results would follow."

E&S style is, where practical, to include people's full names and affiliations the first time they are mentioned in an article. So in the process of (lightly) editing the piece to conform to our style, I supplied the missing information. In this case, I went to the Nobel Prize Internet Archive, and pulled out his biography <http://www.nobel.se/physics/laureates/1952/purcell-bio.html>, where I found the following:

"He returned to the United States in 1934 to enter Harvard University, where he received the Ph.D. degree in 1938. After serving two years as instructor in physics at Harvard, he joined the Radiation Laboratory, Massachusetts Institute of Technology, which was organized in 1940 for military research and development of microwave radar. . . .

"The discovery of nuclear magnetic resonance absorption was made just after the end of the War, and at about that time Purcell returned to Harvard as Associate Professor of Physics."

I interpreted that last sentence to mean that he made the discovery (or demonstration) at MIT, and then promptly returned to Harvard, where, as the bio goes on to say, he remained for the rest of his career. . . .

Ferguson's paper was read by his mentor, Michael Tyszka, who is a visiting associate in biology here and a clinical MRI researcher.

sincerely,

doug

Thanks for your clarification. . . .

The distinction between discovery and demonstration is an interesting one and to me often neglected. In my view the official birthday of NMR was NOT actually in 1946.

In 1946, the physics of NMR was well known, but the problem of detecting resonances in condensed matter was really a matter of guesswork, because no one was sure how long the relaxation times would be, possibly too long or possibly too short. Purcell used paraffin and Bloch used water and fortunately both worked. So they discovered that it was practical, but it was hardly a basic discovery of the phenomenon, which had been done earlier by Rabi. There was a Dutch physicist, named Gortner, who had all the right ideas ahead of Bloch and Purcell, but who missed, possibly on the relaxation-time front, when he tried the experiment with less-favorable compounds.

There is always a potential problem when the young people review an old field: the writers of the historical articles that are consulted often do not know themselves what actually transpired. For NMR, there is an encyclopedia, the first volume of which is devoted to stories by many of the living early participants telling what they think happened. Perhaps a lot of those are not wholly accurate, but at least they were there!

Best wishes,

Jack Roberts

Dear Doug and Prof. Roberts,

There's actually a paper about the Purcell issue which reveals how close Harvard came to missing out: "Purcell's Role in the Discovery of NMR: Contingency versus Inevitability," by Mark Gerstein, American Journal of Physics, 62: (7), 596-601, July 1994.

You can find a web copy at: http://bioinfo.mbb.yale.edu/hyper/mbg/Purcell/Purcell.txt

Sorry I missed this during proofing. On reflection, I agree with Prof. Roberts regarding the NMR birthday. If I was to make a call, I'd add Torrey and Pound to the Harvard/MIT venture and Hansen and Packard to the Stanford group. I always like to credit Stern and Gerlach (1933) for the molecular beam nuclear magnetic moment demonstrations, which ultimately led to the NMR of Rabi et al. in 1939. . . .

Many thanks for bringing these points up. Education continues indefinitely.

Mike Tyszka

Biological Imaging Center

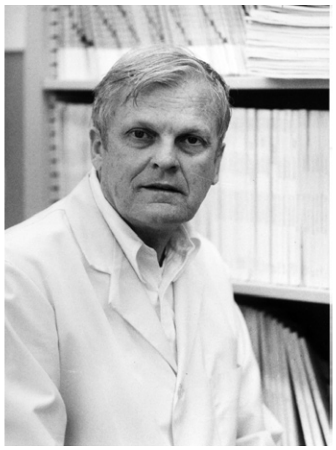
And here's the relevant passage from that paper:

"During World War II, Purcell, [Robert V.] Pound, and [Henry C.] Torrey were members of the MIT Radiation Laboratory, henceforth referred to as the Rad Lab, where they worked developing better radar for the military. . . . Shortly after the end of the war in August 1945, Purcell, Pound, and Torrey got together at a restaurant on Massachusetts Avenue in Cambridge for lunch. The Rad Lab was closing, and

Purcell, Pound, and Torrey remained there only to contribute reports to a twenty-eight-volume series on the advances made during the war. It was a hot summer day and their discussion turned to possible areas of postwar research. Purcell brought up the idea of using a magnetic field to split the energy levels of a hydrogen nucleus (i.e., a proton) and using the resonance frequency of a radio signal to measure the nuclear magnetic moment of a proton. . . .

The first order of business was to assemble the apparatus necessary to carry out the experiment. In particular, they needed to get a magnet strong enough to split the energy levels. Purcell initially wanted to use the one in the MIT cyclotron, but the MIT authorities were not too enthusiastic about this. Their frugal attitude was quite a change from the generosity of the Rad-Lab administrators during the war. Purcell then managed to persuade J Curry Street to let him use the magnet with which Street had discovered the muon in 1937 at Harvard. □

James O. McCaldin
1922 – 2001



James O. McCaldin, professor of applied physics and electrical engineering, emeritus, died November 23.

McCaldin earned his BA in mathematics from the University of Texas in 1944 and his PhD in engineering from Caltech in 1954. He spent the early decades of his career in industry. He worked in telemetry at Arabian American Oil Co. of New York in 1952, in physical metallurgy at General Motors Corp. from 1954 to 1956, at Hughes Aircraft Co. as head of the semiconductor materials department from 1956 to 1961, and at North American Aviation Science Center as semiconductor leader from 1961 to 1968.

He joined Caltech in 1968 as an associate professor of applied science, was named professor of applied science and electrical engineering in 1973, and professor of applied physics and electrical engineering in 1976. He had been professor, emeritus, since 1983. McCaldin was known for his carefully thought-through advice to both graduate and undergraduate students and for making the freshman Solid-State Electronics Laboratory course one of the more enjoyable academic possibilities of the freshman year.

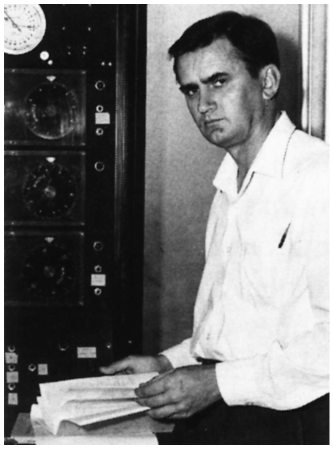
McCaldin was one of the pioneers in some of the technology that made the semiconductor revolution possible. He did early work on semiconductor interfaces, on thin film growth, on planar construction for silicon devices, and on ion-implantation doping of silicon, which has been of great practical importance. In a 1973 issue of *Engineering and Science*, McCaldin and his coauthor, James W. Mayer, discussed the ways in which crystal growth was revolutionizing the electronics industry, noting that the structures giving rise to metal-semiconductor contacts were smaller than anticipated—in some cases a few hundred Angstroms in thickness. "With improvements in instrumentation and fabrication skills, it may soon be possible to reduce this thickness to, perhaps, atomic dimensions," they wrote.

At the time of McCaldin's retirement, Professor of Applied Physics Thomas McGill wrote: "His research has always been characterized by an adventuresome but scholarly development of a new concept that has frequently later become one of the keys to important technological developments."

McCaldin was editor of the journal *Progress in Solid State Chemistry* from 1969 to 1976, and invented several patented technologies. He was a member of the American Physical Society, a former chairman of the Southern California section of the American Institute of Mining, Metallurgical, and Petroleum Engineers, and a former secretary of the Southern California and Nevada section of the Electrochemical Society.

He is survived by a brother, Roy McCaldin. □

Gordon J. Stanley 1921 – 2001



Gordon J. Stanley, one of the founders of Caltech's radio astronomy program and former director of the Owens Valley Radio Observatory, died December 17 in Monterey, California.

A native New Zealander, Stanley earned his diploma in 1946 at the New South Wales University of Technology in Sydney, Australia, and then joined the Commonwealth Scientific and Industrial Research Organization (CSIRO) as senior technical officer in the radiophysics laboratory. The CSIRO at the time was one of the three most important radio astronomy laboratories in the world. In 1949, Stanley and his colleague John Bolton made the first three optical identifications of discrete radio sources: two galaxies, M 87 and NGC 5128, and a galactic supernova remnant in the Crab Nebula. Work was then just beginning on matching up the thousands of radio sources in the sky with stars or galaxies.

When Caltech president Lee DuBridge and Jesse Greenstein, professor of astrophysics and founder of Caltech's astronomy department, began lobbying in the early '50s to establish a radio astronomy group, their attention was quickly attracted to what was going on in Australia. By 1955 they had imported both Bolton and Stanley to Pasadena. It was Stanley who selected the remote site 250 miles north of Pasadena near Big Pine that was to become the Owens Valley Radio Observatory (OVRO), and Stanley and Bolton began construction on the first two 90-foot dishes, which were dedicated in 1958. Stanley also published a number of papers on radio observations of Jupiter. When Bolton returned to Australia in 1960, Stanley became first acting director and then director of OVRO, a post he held until 1975.

Stanley played a major role in a proposal to build an interferometer array consisting of eight radio antennas, each 130 feet in diameter, at Owens Valley. The array would have been the largest radio observatory in the world, covering an area two miles by three miles. Funded by the National Science Foundation, the first antenna was dedicated in 1968, but has remained the only dish, after the Caltech project lost out to the national Very Large Array in New Mexico in a competition for funding.

During his tenure as director, he supervised the reconstruction of the original 90-foot dishes, improving their wavelength coverage by a factor of 10.

Later in his career, after leaving OVRO, Stanley focused on other applications of interferometers, including the development of an innovative device to measure sea-ice temperature and another that measured the temperature of the upper atmosphere.

Stanley returned to OVRO for its 40th anniversary celebration in October 1998. He recalled the observatory's early days and concluded his talk with a stanza from one of his favorite Australian bush poets, Banjo Paterson:

"And the bush hath friends to meet him
and their kindly voices greet him
In the murmur of the breezes and the
river on its bars,
And he sees the vision splendid of the
sunlit plains extended,
And at night the wondrous glory of the
everlasting stars."

His family also included the stanza in their obituary. Stanley is survived by his wife, Helen; three children: Teresa Stanley, Luise Phelps, and Stephen Stanley; and three grandchildren. □

Honors and Awards

Tom Apostol, professor of mathematics, emeritus, is being honored for his distinguished career by the Friends of Hellenic Studies and the Basil P. Caloyeras Center for Modern Greek Studies. He was feted on November 3 on the campus of Loyola Marymount University.

Philip Hoffman, professor of history and social science, has been selected along with coauthors Gilles Postel-Vinay and Jean-Laurent Rosenthal to receive the Economic History Association's Gyorgy Ranki Prize, which recognizes "the outstanding book on the economic history of Europe, published in 1999 and 2000." The award is for their book *Priceless Markets: The Political Economy of Credit in Paris, 1660–1870*. Postel-Vinay has been a visiting professor of history at Caltech, and Rosenthal received his PhD in social science from the Institute in 1988.

Matthew Jackson, professor of economics, is the first winner of the Social Choice and Welfare Prize, to be awarded by the Society for Social Choice and Welfare at its sixth annual international meeting, to be held at Caltech in July 2002. The prize is given "to honor young scholars of excellent accomplishment in the area of social choice theory and welfare economics."

Wolfgang Knauss, the von

At the January annual meeting of the American Astronomical Society, Wallace Sargent, the Bowen Professor of Astronomy, received a certificate for the Henry Norris Russell Lectureship, the AAS's highest honor, which recognizes "a lifetime of eminence in astronomical research." Presenting the award was the president of the AAS, Anneila Sargent, professor of astronomy and director of the Owens Valley Radio Observatory and the Interferometry Science Center. (Photo by Richard Dreiser, © 2002, American Astronomical Society.)

Kármán Professor of Aeronautics and Applied Mechanics, has been selected by ASME International (The American Society of Mechanical Engineers) to receive its Warner T. Koiter Medal, to be presented during ASME's 2001 International Mechanical Engineering Congress and Exposition, November 11–16 in New York City. The award "recognizes the effective blending of theory and application of applied mechanics, and leadership in the international solid mechanics community."

Dan Kevles, the Koepfli Professor of the Humanities, Emeritus, was awarded the George Sarton Medal by the History of Science Society at its annual meeting in Denver, on November 10. The medal is the society's highest award and honors George Sarton, the founder of *Isis*, the leading journal of the history of science. "The award recognizes distinction in scholarship, impact through writing and leadership in the profession. It has been awarded annually since 1955 to an outstanding historian of science selected from the international scholarly community."

Andrew Lange, the Goldberger Professor of Physics, has been elected a fellow of the American Physical Society "for developing a new generation of bolometers that operate in the submillimeter and employing them to determine the geometry of the universe."

Anneila Sargent, professor of astronomy and director of the Owens Valley Radio Observatory and the Interferometry Science Center, has been selected to give the Selove Lecture at the University of Pennsylvania during the spring 2002 semester. A colloquium comprising two talks—one suitable for the entire department at a level grad students can appreciate, the second for specialists in the speaker's field—the Selove Lecture was established by Fay Ajzenberg-Selove to honor her husband, Walter.

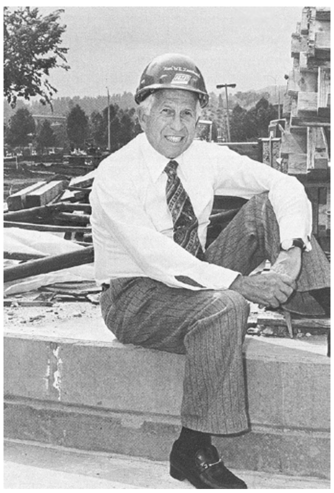
John Schwarz, the Brown Professor of Theoretical Physics, has been selected to receive the 2002 Dannie Heineman Prize for Mathematical Physics, which he will share with Dr. Michael Green of Cambridge University. The citation will read, "For your pioneering work in the development of superstring theory," and the prize will be awarded at the American Physical Society's April 2002 meeting, to be held in Albuquerque, New Mexico.

Kip Thorne, the Feynman Professor of Theoretical Physics, received an honorary doctor of science in November from the University of Glasgow on the occasion of that school's 11th (550-year) jubilee. He also has been honored with several lectureships: the Arthur Holly Compton Memorial Lecture, Washington University in St. Louis, in February 2001; the Inaugural Herzberg Memorial Lecture, Canadian Association of Physicists, in June 2001; and the George Darwin Lecture, Royal Astronomical Society, in December 2000.

Alexander Varshavsky, the Smits Professor of Cell Biology, has received the 2001 Louisa Gross Horwitz Prize for "breakthrough work on the ubiquitin system, the mechanism by which the cell maintains a proper and healthy balance of proteins." He shares the award with Avram Hershko, Distinguished Professor at the Technion—Israel Institute of Technology. Columbia University bestowed the awards December 11 at a ceremony and black-tie reception at the Low Library Rotunda on Columbia's Morningside campus.

Peter Wyllie, professor of geology, emeritus, has been awarded the Leopold von Buch Medal "in recognition of his scientific research on the petrology of crystalline rocks, and also for his service in publicizing the importance of geosciences for society." Wyllie received the medal, which is accompanied by honorary membership in the German Geological Society, at a ceremony on October 4, during the society's annual meeting in Kiel, Germany. □

Good Neighbors



William E. Leonhard, the former CEO of Parsons Corporation, and his wife, Wyllis, have been extremely generous to the institution they considered their neighbor when they lived in Pasadena.

Leonhard earned his BS in engineering from Pennsylvania State University in 1936 and a master's degree from that other institute of technology, MIT, in 1940. After 28 years in the military, Leonhard retired from the Air Force with the rank of brigadier general at the age of 46. He then spent two years as project manager for the United Technology Center's Titan III booster rocket program before joining Parsons, the Pasadena-based engineering firm in 1966. He served as CEO of the company from 1975 to 1990.

In 1985, Leonhard devised and executed a plan to turn Parsons into a privately held company through an employee stock ownership plan (ESOP). Although a somewhat controversial move at the time, it proved to be very forward-thinking and attracted top-quality talent to Parsons. Every Parsons employee was allocated shares in the ESOP—except Leonhard, who wished to avoid any hint of self-interest. He did, however, receive cash when the ESOP purchased the Parsons shares he already owned. Upon receipt of his first distribution from the Parsons stock, Leonhard paid his taxes to the IRS, and the very next day donated the rest of the money to MIT, Penn State, UCLA, Harvey Mudd College—and Caltech.

The Leonhards were members of the Caltech Associates when they lived in Pasadena (they returned to Pennsylvania in the early 1990s). During that time Leonhard became acquainted with many members of the Caltech faculty and frequently engaged them in discussions about technical problems and collaborated on projects of interest on campus.

The Leonhards established the William E. Leonhard Professorship in Geology, first held by the late Sam Epstein and currently by the division chair, Ed Stolper. Leonhard has also made Caltech the beneficiary of a $1 million life insurance policy that will ultimately establish an endowed merit scholarship fund.

Leonhard offered a simple explanation for his generosity: "My wife and I are too old to change our lifestyle. We are amply rewarded by helping deserving young people preparing for and achieving successful careers in their chosen fields."

Above: Bill Leonhard as CEO of Parsons Corporation. Right: Two Leonhard Professors of Geology—Ed Stolper, who was named the Leonhard Professor in 1990, when Sam Epstein, who had held the chair since 1984, retired and became the Leonhard Professor, Emeritus. Epstein died last September. (Photo and text by Carolyn Swanson.)

For information contact:

Chris Yates, JD
Susan A. Walker, CFP
Carolyn K. Swanson
Office of Gift and Estate Planning
California Institute of Technology
Mail Code 105-40
Pasadena, California 91125
phone: (626) 395-2927
fax: (626) 683-9891
planned_gifts@caltech.edu
www.gep.caltech.edu

Engineering & Science

California Institute of Technology
Pasadena, California 91125