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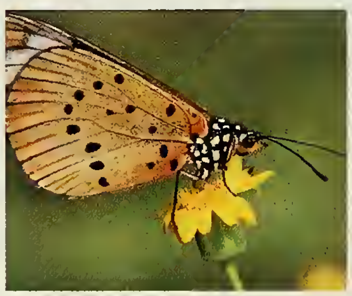
NATURAL HISTORY

FEBRUARY 2003 VOLUME 112 NUMBER 1

FEATURES



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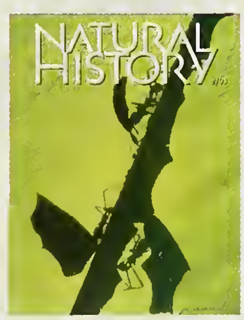
COVER
Leaf cutter ants (Atta colombica) *cultivate and protect a fungus, which they eat.*
PHOTOGRAPH BY CHRISTIAN ZIEGLER

STORY BEGINS ON PAGE 50



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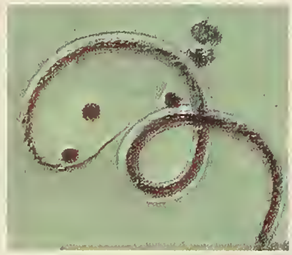

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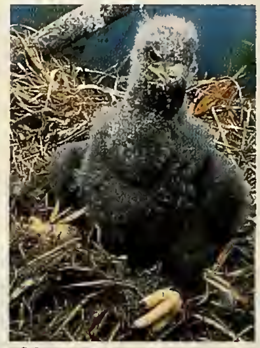

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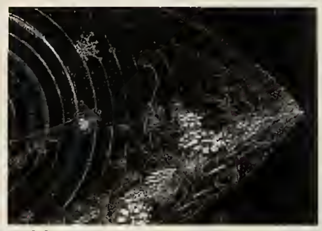

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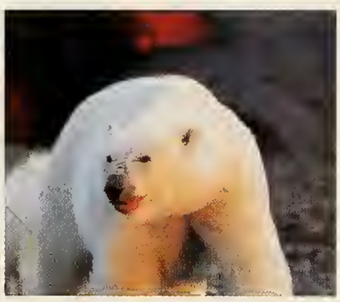

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Majestic humpback whales share coastal waters with 10,000 year-old icebergs.

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New Engines of Evolution

Last month I noted that part of what many people don't like about science stems from its conclusion that we human beings don't occupy the center of the universe. But another great source of discomfort about science is its insistence that change is a pervasive feature of the world. Evolutionary change, of course, has long been a thorn in the side of many conservative Christians. Change in the heavens, the very model of permanence and order, seems to fly in the face of common sense. Maybe it's fortunate that our resistance to change is balanced by the fact that one human lifetime is too short for anyone to notice many of the grandest changes in nature. Yet the capacity of science to take the long view, to study events that take far more than a lifetime to unfold, often makes science the bearer of unwelcome tidings that undermine our yearning for stability.

Take evolution. One consequence of Darwinian evolution by natural selection is that as the world changes, what lives and what dies can change as well. In this month's cover story, Christian Ziegler and Egbert Giles Leigh Jr. document the subtle but pervasive effects of one world-changing event—the construction of the Panama Canal—on the ecology and biodiversity of the Panamanian tropical forest (see "Biosphere III," page 50). Other changes with substantial effects on the world's genetic history—agricultural breeding, the transport of species from one region to another—are too slow to be perceived without specialized techniques. Daniel G. Bradley, in his "Genetic Hoofprints" (page 36), describes how the magic lantern of DNA analysis has shed some surprising light on the evolutionary history of cattle since their domestication 10,000 years ago.

But what about the mechanisms of evolutionary change? What gives rise to the changes that individuals present for testing by natural selection? For much of the history of Darwinism the answers have been genetic mixing through sexual reproduction and random genetic mutation. But random mutation has seemed to many the Achilles' heel of the theory: the known rates of random mutation have seemed inconsistent with the time available for the observed biodiversity on Earth to have evolved.

Now the scientific understanding of change itself is changing. In his "Invasion of the Gender Benders" (page 58) John H. Werren describes one way that microorganisms are playing a key role in evolutionary change. The microorganisms that Werren studies are parasitic bacteria that survive by changing the reproductive process in their hosts. Some of these bacteria change their male hosts into females. Some kill all their hosts that happen to be male. Some make their hosts parthenogenetic, rendering the need for sexual reproduction irrelevant. Bacteria with such diabolical talents are not confined to some small and obscure corner of nature. They affect at least a fifth of all insect species, and perhaps as many as 70 percent. And their activities have broad implications for humanity. In a companion piece to Werren's article, T.V. Rajan eloquently recounts how microbiologists discovered that some of the same bacteria play a role in several of the most devastating pestilences that afflict humankind: elephantiasis and river blindness (see "The Worm and the Parasite," page 32).

The lesson of Werren's story is an apt one for our times (with apologies to Geoff Mack): "Change is everywhere, man."

—Peter Brown

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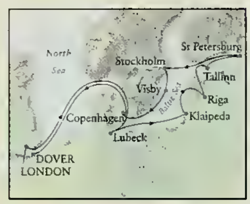

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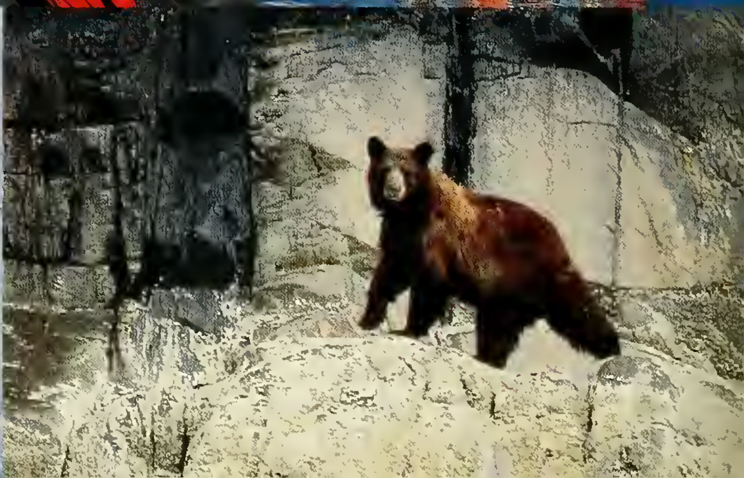

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THE NATURAL MOMENT

Raw Bar

Photograph by **Howie Garber**

◄ *See preceding pages*

As their Latin name, *Ursus maritimus,* indicates, polar bears are true seafarers: they spend most of their lives aboard ships of shifting pack ice, patrolling for stowaway seals. In winter, ice floes bring bears to the edge of Alaska's northern coast, where the creatures may come ashore briefly. By early summer they head north again, sticking close to their melting, mobile hunting ground.

Occasionally, though, a bear misses the boat. The sow pictured here with her two cubs was one of fifty-five polar bears that failed to follow the shrinking ice this past September and ended up on Barter Island—the largest island in the Arctic National Wildlife Refuge.

Photographer Howie Garber was careful not to disturb the protective mother as she breakfasted with her cubs at the edge of the Inupiat village of Kaktovic. The three bears had been tearing into remnants of a bowhead whale, recently caught by the villagers on an authorized hunt. The whale carcass is visible in the background.

Females with dependent young, eager for a reliable food source, may be the most common visitors to such whale carcasses. But no one knows whether cubs fed onshore will master the lessons they'll need once they return to the ice.

—*Erin Espelie*

LETTERS

A Matter of Gravity

In his "Universe" column ["Going Ballistic," November 2002], Neil deGrasse Tyson eloquently covered many different and interesting aspects of "free fall." Of particular interest to me was his discussion of the chaotic motion of the planetary orbits and of the slingshot effect that can give spacecraft a planetary boost. (The motion of an object is chaotic if at each moment it can move in infinitely many possible directions, resulting in an erratic path. Think of the motion of a leaf blown about by the wind, or a drunk trying to walk a straight line.)

The chaos of planetary orbits is extremely subtle, and it takes careful measurement to notice it. But if a space probe passes a body such as the Moon in such a way that the probe is almost captured by the body's gravitational pull, the probe will usually linger for a few hours in the vicinity of the larger body, moving in a complicated, chaotic fashion before leaving abruptly on another path that is difficult to predict. The effect is called weak ballistic capture.

In 1990, I designed a new kind of route to the Moon for the Japanese spacecraft *Hiten,* requiring three months instead of the usual three days for the spacecraft to make the trip and leading to weak ballastic capture. The resultant chaotic motion offered a lot of flexibility to mission planning.

Permanent capture could be achieved using almost no fuel, an attractive option because *Hiten* carried so little. A more complicated plan was successfully followed, however: the craft stayed in weak capture for a few hours, then moved away from the Moon for six months to explore the Earth-Moon system, and finally returned to the Moon for placement in permanent capture. It turns out that weak capture is a slow version of the slingshot effect; recently weak capture was mathematically proved to be truly chaotic.

Edward Belbruno
Princeton University
Princeton, New Jersey

The figure-eight orbit that Neil Tyson mentions, as well as other newly discovered solutions to the old three-body problem, are so elegant that a name has been coined for them: choreographies. The figure eight is only the simplest example; other orbits are wildly more complex, with shapes that look more like fluttering butterflies. And those three-body orbits have been quickly generalized to even more fascinating dances for four or more bodies. Animated examples can be viewed on the Web at www.ams.org/new-in-math/cover/orbits1.html.

As a theoretical astrophysicist working in stellar dynamics, I am sobered by the fact that great mathematicians and physicists worked on the three-body problem over the past three centuries without having any idea that orbits of this kind were awaiting discovery. And who knows what else there is to be found. It is not only with telescopes that new astronomical objects can be discovered. With even a small personal computer, a lucky guess, and enough persistence, anybody is now in a position to find new solutions to age-old problems of a kind that were completely beyond what Newton and the Le's and La's of celestial mechanics (Leverrier, Legendre, Lagrange, and Laplace, to name a few) could handle.

Piet Hut
Institute for Advanced Study
Princeton, New Jersey

Neil Tyson's article brought to mind my own attempt to dig a hole from Oklahoma to China. I was seven or eight at the time and asked my dad if I could dig down behind the house. "Sure, honey," he replied, barely looking up from the paper. The project was called off several weeks later when his tractor nearly fell into the hole. I was terribly disappointed, but now I have learned that a major catastrophe was averted.

First of all I would have been vaporized by the fierce heat of the iron core. At best I would have popped out in the southern Indian Ocean, which would have been dangerous because I couldn't swim. At least it is a relief to know the ocean water pouring into the tunnel

would have surged back and forth, rather than flooding the Midwest.
Gloria Jones-Wolf
Elk Falls, Kansas

The Shark Has Sharp Turns

In his "Biomechanics" column on the hammerhead shark ["Head Turner," November 2002], Adam Summers reports that the shark does not bank its winglike head as it turns. He thus dismisses the idea that the head provides lift and maneuverability, as does the wing of an aircraft. But sharks are different from aircraft in two important respects (apart from the obvious ones).

First, water provides sharks with substantial buoyancy, whereas air does not confer the same benefit to aircraft. Second, a shark can make a yawing (sideways) turn without banking, simply by bending its body and adjusting vertically oriented fins to keep from sinking. Airplanes turn while remaining aloft primarily by controlling the positions of ailerons mounted on horizontally oriented wings.

Nevertheless, the shark's head may help the animal maneuver—if not in making sideways turns, then at least in pitching it up or down. In that respect, the forward position of the large head is optimal, though further analysis is needed to confirm any such hydrodynamic function.
Frank E. Fish
West Chester University
West Chester, Pennsylvania

Wings and Stings

In his tale of initiation into the pleasures and perils of rainforest field research ["Bites of Passage," October 2002], Nathan Welton writes that the "mad scientists" of La Selva Biological Station, in Costa Rica, "happily spend their days plucking the wings off aerial insects and crucifying them on Styrofoam boards." As thirty-year veterans of research at La Selva and co-directors of the ongoing Arthropods of La Selva (ALAS) project—an effort to make an inventory of all the major groups of insects, spiders, and mites at the station—we don't mind being tagged in good fun as "mad scientists."

But there is no humor in the cruel image of crucifixion, which implies the intentional imposition of an agonizing death. Ethical entomologists, certainly including all who work at La Selva, use the most humane methods available to kill arthropods (freezing or fast-acting chemicals) before mounting them as study specimens. We take lives, however small, only when there is a legitimate scientific reason to do so, and nobody we know plucks wings off insects.
Robert K. Colwell
University of Connecticut
Storrs, Connecticut

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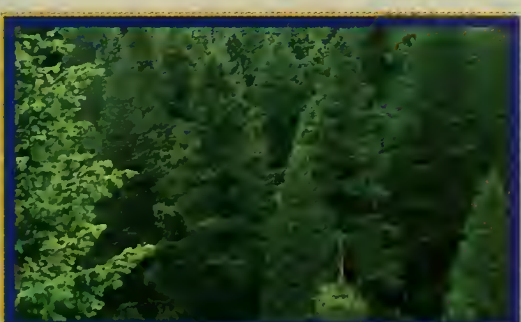

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CONTRIBUTORS

Howie Garber ("The Natural Moment," page 10) practices emergency room medicine in Salt Lake City, Utah, but he finds wildlife photography "as challenging and exciting" as his day job. Garber has received numerous prizes, including the 1997 BG Wildlife Photographer of the Year in the "Landscape (Wild Places)" category. A 500-millimeter lens enabled him to photograph a mother polar bear and her two cubs from a reasonably safe distance. More of Garber's photographs are on view at www.wanderlustimages.com.

"Cattle is in the blood," is the way **Daniel G. Bradley** ("Genetic Hoofprints," page 36) describes himself. A lecturer in genetics and a fellow at Trinity College, Dublin, Bradley grew up on a small farm in northern Ireland and recalls tending cattle on spring mornings before going to school. Even today not all his work is done in the lab. To help trace the origins of African cattle, he has traveled several times to western Africa and, with help from the U.N. Food and Agriculture Organization, he has visited remote pastoral villages in Guinea and Guinea-Bissau. He once drove through a desert strewn with spent rocket shells to reach an area of Chad that is home to huge-horned African Kuri cattle.

On January 26, 2001, when a magnitude 7.6 earthquake struck the Indian state of Gujarat, **Susan Hough** ("Shaken to the Core," page 42) immediately began to search the Internet for first-person accounts of the event. She knew the Indian quake would be invaluable for calibrating the intensity of a series of mid-continental earthquakes that shook southeastern Missouri nearly two centuries ago. Hough is a geophysicist at the U.S. Geological Survey in Pasadena, California, and the author of the book *Earthshaking Science: What We Know (and Don't Know) about Earthquakes.* **Roger Bilham** is a professor of geology at the University of Colorado in Boulder and an associate director of the Cooperative Institute for Research in Environmental Sciences. In the past three decades he has done extensive geodetic surveying in India and Tibet and completed numerous investigations of historic Indian earthquakes. He is the author of more than 130 articles on earthquake-related processes.

Christian Ziegler and **Egbert Giles Leigh Jr.** ("Biosphere III," page 50) teamed up in Panama to document the way animals and plants have adapted to life on a small island in a tropical forest. The result is their book *A Magic Web: The Tropical Forest of Barro Colorado Island* (published last month by Oxford University Press; see www.amagicweb.com). Based in Vancouver and Panama, Ziegler *(left)* is a wildlife and nature photographer and writer with a background in biology. His work has appeared in magazines throughout the world, and in 2001 he won a prize in the BG Wildlife Photographer of the Year Competition. Leigh *(right)* is a tropical ecologist with thirty years' experience on Barro Colorado as a staff scientist for the Smithsonian Tropical Research Institute.

When **John H. Werren** ("Invasion of the Gender Benders," page 58) began his graduate studies in biology at the University of Utah, he focused on behavioral ecology, investigating how and why parasitic wasps manipulate the proportion of males and females in their progeny. But he found that there were also "genetic parasites" that altered the sex ratio. Some of the parasites turned out to be microorganisms. After completing his Ph.D., he entered the U.S. Army, and, as he describes it, "in one of those funny coincidences, the Army decided that I would work on water bacteriology, despite my having no formal training in bacteriology. So I learned a lot of bacteriology and, in collaboration with a colleague back in Utah, found a male-killing microbe in the parasitic wasps." Now a professor of biology at the University of Rochester in New York, Werren studies *Wolbachia* bacteria and their role in the evolution of new insect species.

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By Stéphan Reebs

Bill Scanga, *Living Room (Tom & Jerry)*, 1997

HEEDLESS YOUTH Sometimes teenagers seem drawn to risky behavior like moths to porch lights. But among adolescent mammals, they're not alone. Novelty-seeking—the urge to explore unknown environments—seems to surface at this stage of development. Perhaps the behavior is related to the need to seek one's fortune, or at least living space and reproductive partners, outside one's natal group.

To check for teenage recklessness in a small mammal, Simone Macrì and her colleagues at the Italian National Institute of Health in Rome placed mice of varying ages, one at a time, in the center of an elevated structure with four narrow passageways that led radially outward. Two passageways were enclosed by transparent protective walls; two were bounded only by slightly raised edges, thereby offering less protection against tumbles. Each mouse wandered wherever it wanted for several minutes while the biologists watched.

The adolescent mice made some 80 percent more entries into the unprotected passageways—and entered them with less hesitation—than did the preadolescents or the adults. Yet all the mice spent about the same amount of time exhibiting a body posture that typically indicates anxiety and risk assessment. Interpretation? The adolescent mice were aware of the dangers associated with the open-sided passageways, but adopted a devil-may-care attitude nonetheless. (And they don't spend much time watching TV at home with the family.) ("Risk taking during exploration of a plus-maze is greater in adolescent than in juvenile or adult mice," *Animal Behaviour* **64:**541–46, October 2002)

GRAIN GAIN Nearly every day, more than half the people on Earth eat rice, a dietary staple grown mostly in flooded fields. Unfortunately, the roots of rice plants are a source of nutrients for microorganisms that, under the anaerobic conditions prevailing in flooded ground, generate substantial amounts of methane gas. After carbon dioxide, methane is the second most damaging greenhouse gas in the atmosphere.

Not only is more methane released in the rainy season than in the dry season, as one would expect, but greater amounts of methane come from rice paddies with lower-than-average yields of grain. A team of Dutch and Filipino biologists, led by Hugo Denier van der Gon of Wageningen University in the Netherlands, thought they knew why. The level of methane production, they suggested, could depend on how much carbon is available to the microorganisms once the plant has used up whatever carbon it needs to make its grains of rice. During the wet season, as well as in unproductive fields, each plant makes fewer grains, so more carbon could be making its way to the microorganisms near the roots, and more methane would be produced.

The biologists tested their idea by removing part of the stems where the rice grains develop; as predicted, the larger the segment removed, the more methane was released. And when they boosted photosynthesis—and therefore carbon production—by adding nitrogen, even more methane was given off. The investigators also noted an ancillary advantage, implied by their findings, of developing new rice varieties able to bear more grains per unit biomass: more food per plant goes hand in hand with less greenhouse methane. ("Optimizing grain yields reduces CH_4 emissions from rice paddy fields," *Proceedings of the National Academy of Sciences* **99:**12021–24, September 17, 2002)

Rice fields, Assam, India

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EXPERIMENT OF THE MONTH When marine biologist Scott A. Eckert first tracked the deepwater dives of leatherback sea turtles in the Caribbean, his data told him the animals were spending middays at or just below the surface. He presumed they were basking in the sunshine, as reptiles often do. Eckert, who is a member of the scientific staff at the Hubbs Sea World Research Institute in San Diego, had attached depth recorders to the turtles' shells, but the instruments were naturally silent about the turtles' horizontal movements. Not entirely satisfied with his assumptions, he decided to verify them.

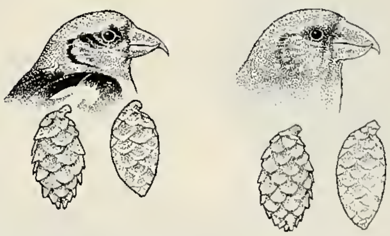
Leatherbacks dwell primarily in the open ocean, but in their breeding years the females drag themselves onto beaches fairly regularly to lay their eggs. When seven females came ashore to nest on Saint Croix, Eckert fitted each one with a harness that included a custom-built marine speedometer. At sea, if a turtle surfaced to soak up the rays, the speedometer would pop out of the water, the recording device would pause, and the logged speed would drop to zero. (In earlier attempts to measure swim speeds, boats followed the turtles, a technique that some biologists suspected could have altered the turtles' behavior.)

Ten days later, when the turtles returned to their onshore nests, Eckert retrieved the data loggers. Contrary to his expectations, they showed that the leatherbacks never loafed: they swam almost constantly, day and night, at about a mile and a half an hour. At night they often dived for jellyfish, but in the middle of the day they glided horizontally about six feet underwater—deep enough to avoid the push and pull of the waves, yet shallow enough to perhaps orient themselves to the sun as they traveled between foraging sites. ("Swim speed and movement patterns of gravid leatherback sea turtles [*Dermochelys coriacea*] at Saint Croix, U.S. Virgin Islands," *Journal of Experimental Biology* **205:**3689–97, December 1, 2002)

Leatherback sea turtle, sans harness

THREE'S A CROWD Crossbills and squirrels both feed on the seeds of conifer cones—a dietary triangle that sets the stage for intriguing evolutionary interactions. In the Rocky Mountains, red squirrels harvest most of the cones of lodgepole pines before red crossbills can get at them. According to Craig W. Benkman, a biologist at New Mexico State University (NMSU) in Las Cruces, the cones in the Rockies have few seeds and are relatively wide—evolutionary adaptations that make them less desirable to squirrels. But in areas where squirrels are absent, the cones have focused their defenses on the threat posed by crossbills. The shape of the cones is different, and the scales are thicker—traits that resist the crossbills' attempts to remove the seeds. In turn, the crossbills in the squirrel-less areas have evolved deeper bills, thereby partly countering the cones' defenses.

Now Benkman and Thomas L. Parchman, also at NMSU, have found a similar case of coevolution on the other side of the continent. Squirrels didn't live in Newfoundland until they were introduced there in 1963—too recently for conifers to have evolved in response to the change. Accordingly, the cones of Newfoundland's main conifer, the black spruce, had focused on the threat of the native red crossbill. These cones are larger, with thicker scales than the cones of the tree's counterparts on the mainland, where squirrels have long resided. Fittingly, Newfoundland's crossbills had unusually deep bills.



Crossbills and black spruce cones from the eastern Canadian mainland (left) and Newfoundland (right)

Unfortunately, Parchman and Benkman had to find museum specimens to measure the bill size of Newfoundland's red crossbills. Once the squirrels arrived in Newfoundland in 1963, the local crossbills became rare, if not extinct. Because the black spruce cones were defenseless against the squirrels, the biologists reasoned, the squirrels probably grabbed so many of them that the local crossbills soon had nothing left to eat. ("Diversifying coevolution between crossbills and black spruce on Newfoundland," *Evolution* **56:**1663–72, August 2002)

LETTING GO To escape a predator's grasp, some prey would rather give up a limb than give up on life. Through a process called autotomy, muscles can contract violently along the base of an appendage, breaking off the limb. Thus can sea stars cast off an arm, and various reptiles shed their tails.

Kerstin Wasson, a biologist at the Elkhorn Slough National Estuarine Research Reserve in Watsonville, California, and her colleagues decided to quantify the benefits of autotomy. They put *Petrolisthes* porcelain crabs in the company of larger, predatory crabs and waited until a predator grabbed a porcelain by the claw. Two-thirds of the porcelains jettisoned the claw and escaped alive as the predator munched the detached hors d'oeuvre. The other third fought back, but most of them ended up as a full entrée.

Porcelains have large claws for their body size. Such claws may divert a predator's attention away from the main part of the porcelain's body, Wasson and her colleagues suggest, and keep the predator safely busy for a time. ("Hair-trigger autotomy in porcelain crabs is a highly effective escape strategy," *Behavioral Ecology* **13:**481–86, July 2002)

Stéphan Reebs is a professor of biology at the University of Moncton in New Brunswick, Canada, and the author of Fish Behavior in the Aquarium and in the Wild *(Cornell University Press).*

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Aristotle teaching astronomers, Seljuq dynasty, Turkey, early 13th century

Naming Rights

How to stake a claim in the dictionary of science

By Neil deGrasse Tyson

If you visit the gift shop at the Hayden Planetarium in New York City, you'll find all manner of space-related paraphernalia for sale. Familiar things are in stock—plastic models of the Space Shuttle and the International Space Station, cosmic refrigerator magnets, Fisher space pens. But there are unusual things, too—astronomy Monopoly, Saturn-shaped salt-and-pepper shakers, dehydrated ice cream of the kind originally confected for astronauts. And that's not to mention the weird things, such as Hubble Telescope pencil erasers, Mars rock super-balls, and edible space worms. You'd expect a place like the planetarium to stock such stuff. But something much deeper is going on. The gift shop's offerings bear silent witness to a half century of American scientific discovery.

In the twentieth century, astronomers in the United States discovered galaxies, the expansion of the universe, the nature of supernovas, quasars, black holes, gamma ray bursts, the origin of the elements, the cosmic microwave background, and most of the known planets in orbit around solar systems other than our own. Although the Russians reached one or two places first, the U.S. sent space probes to Mercury, Venus, Jupiter, Saturn, Uranus, and Neptune. U.S. probes have also landed on Mars and on the asteroid Eros. U.S. astronauts have walked on the Moon. And nowadays most Americans take all this for granted, which is practically a working definition of culture: something everyone does or knows about, but no longer actively notices.

While shopping at the supermarket, most Americans aren't surprised to find an entire aisle filled with sugar-loaded, ready-to-eat breakfast cereals. But foreigners notice this kind of thing immediately, just as traveling Americans immediately notice that supermarkets in Italy have vast selections of pasta, and that markets in China and Japan offer astonishing choices of rice. Part of the great pleasure of foreign travel comes from the flip side of not noticing your own culture while you're surrounded by it: you realize what you hadn't noticed about your own country, and you notice what people in other countries don't realize about themselves.

Snobby people from other countries like to make fun of the U.S. for its abbreviated history and its uncouth culture, particularly compared with the millennial legacies of Europe, Africa, and Asia. But a few hundred years from now historians will surely see the twentieth century as the American century—the one in which American discoveries in science and technology rank high among the world's list of treasured achievements.

Obviously the U.S. has not always sat atop the ladder of science. And there's no guarantee or even likelihood that American preeminence will continue. As the capitals of science and technology shift from one nation to another, rising in one era and falling in the next, each culture leaves its imprint on the continuing attempt of our species to understand the universe and our place in it.

Many factors influence how and why a nation will make its mark at a particular time in history. Strong leadership matters. So does access to resources. But something else must be present—something less tangible, but with the power to drive people to focus their emotional, cultural, and intellectual capital on creating islands

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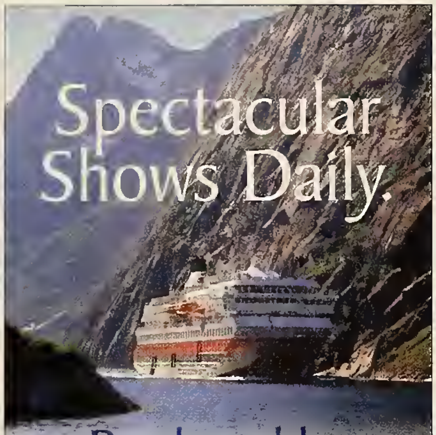

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of excellence in the world. On the blind assumption that things will continue forever as they are, people who live in such dynamic times often take the excellence for granted, leaving the nation's achievements susceptible to abandonment by the very forces that gave rise to them.

Beginning in the 700s and continuing for nearly 400 years—while Europe's Christian zealots were disemboweling heretics—the Abbasid caliphs created a thriving intellectual center of arts, sciences, and medicine for the Islamic world in the city of Baghdad. Muslim astronomers and mathematicians built observatories, designed advanced timekeeping tools, and developed new methods of mathematical analysis and computation. They preserved extant works of science from ancient Greece and translated them into Arabic. They collaborated with Christian and Jewish scholars. Baghdad became a center of enlightenment. Arabic was, for a time, the lingua franca of science.

The influence of these early Islamic contributions to science remains to this day. For example, so widely distributed was the Arabic translation of Ptolemy's magnum opus on the geocentric universe (originally written in Greek in A.D. 150) that even today, in all translations, the work is known by its Arabic title, *Almagest*, or "The Greatest."

> For a time, Arabic was the lingua franca of science, and Baghdad its capital.

The Iraqi mathematician and astronomer Muhammad ibn Musa al-Khwarizmi gave us the words "algorithm" (from his name, al-Khwarizmi) and "algebra" (from the word *al-jabr* in the title of his book on algebraic calculation). And the world's shared system of numerals—0, 1, 2, 3, 4, 5, 6, 7, 8, 9—though Hindi in origin, was neither common nor widespread until Muslim mathematicians exploited it. Furthermore, the Muslims made full and innovative use of the zero, which did not exist among Roman numerals or in any established numeric system. Today, with legitimate reason, the ten symbols are internationally referred to as Arabic numerals.

Portable brass astrolabes were also developed in the Islamic world. Derived from ancient prototypes, they became as much works of art as tools of astronomy. An astrolabe projects the domed heavens onto a flat surface; with its layers of rotating and non-rotating dials, it resembles the busy, ornate face of a grandfather clock. The astrolabe enabled people to measure the positions of the Moon and the stars on the sky, from which they could deduce the time—a useful thing to know, particularly if it's time to pray. The device was so influential as a terrestrial connection to the cosmos that, to this day, nearly two-thirds of the brightest stars in the night sky retain their Arabic names.

The star names typically translate into an anatomical part of the constellation being described. Famous ones on the list (along with their loose translations) include Rigel (*Ar-Rijl*, "foot") and Betelgeuse (*Yad al-Jauza*, "hand of the central one"), the two brightest stars in the constellation Orion; Altair (*At-Ta'ir*, "the flying eagle"), the brightest star in the constellation Aquila; and the variable star Algol (*Al-Ghul*, "the demon"), the second brightest star in the constellation Perseus (the star's name refers to the blinking eye of the bloody severed head of Medusa held aloft by Perseus). In the less-famous category are the two brightest stars of the constellation Libra, though in the heyday of the astrolabe they were identified with the scorpion: Zubenelgenubi (*Az-Zuban al-Janubi*, "southern claw") and Zubeneschamali (*Az-Zuban ash-Shamali*, "northern claw"), currently the longest star names in the sky.

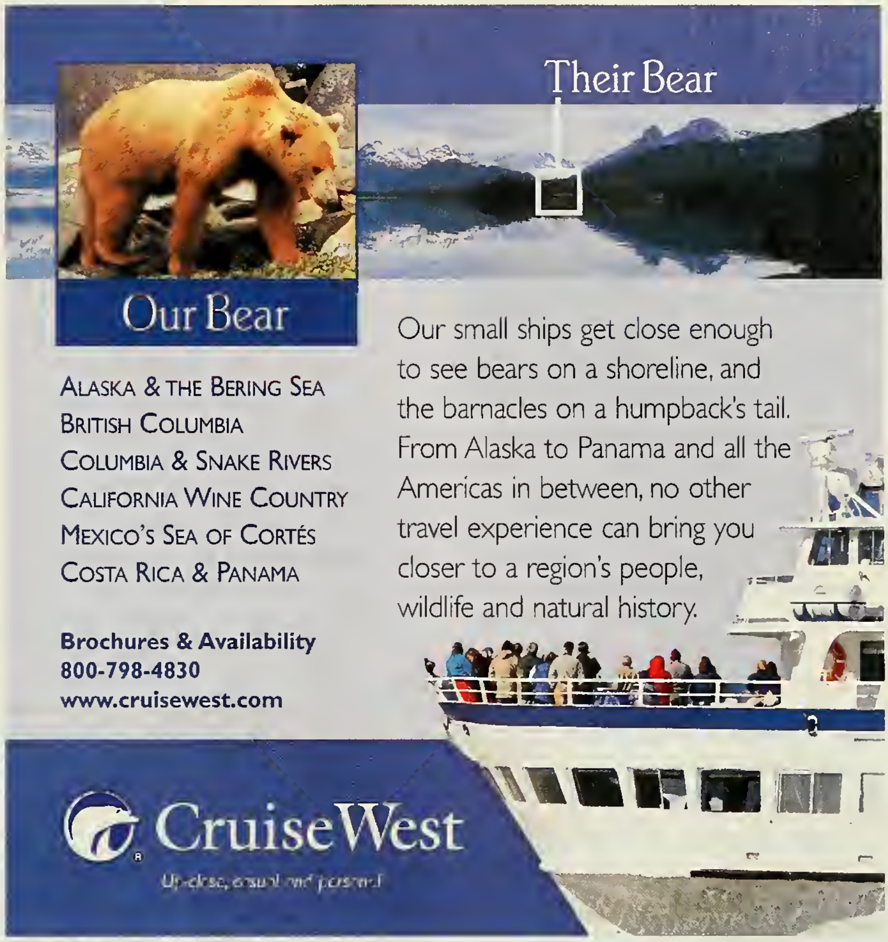
At no time since the eleventh century has the Islamic world regained the scientific influence it enjoyed during the preceding four centuries. The late Pakistani physicist Abdus Salam, the first Muslim ever to win the Nobel Prize, lamented:

> There is no question, but [that] today, of all civilizations on this planet, science is the weakest in the lands of Islam. The dangers of this weakness cannot be overemphasized since honorable survival of a society depends directly on strength in science and technology in the conditions of the present age.

Plenty of other nations have enjoyed periods of scientific fertility. Think of Great Britain and the basis of Earth's system of longitude. The prime meridian is the line that separates geographic east from west on the globe. Defined as zero degrees longitude, it bisects the base of a telescope at an observatory in Greenwich, a London borough on the south bank of the River Thames. The line doesn't pass through New York City, or Moscow, or Beijing. Greenwich was chosen in 1884 by an international consortium of longitude mavens who met in Washington, D.C., for that very purpose.

By the late nineteenth century, astronomers at the Royal Observatory Greenwich—founded in 1675 and based, of course, in Greenwich—had accumulated and catalogued a century's worth of data on the exact positions of thousands of stars. Today we calibrate our watches with atomic clocks, but back then there was no timepiece more reliable than the rotating Earth itself. And there was no better record of the rotating Earth than the stars that passed slowly overhead. And nobody measured the positions of passing stars better than the astronomers at the Royal Observatory Greenwich.

Until the mid-eighteenth century, Great Britain lost many ships at sea



because captains would not know where on Earth they were: the means to determine their longitude with precision did not yet exist. One particularly tragic disaster took place in 1707, when the British fleet, under Admiral Sir Clowdisley Shovell, ran aground into the Scilly Isles, west of Cornwall, losing four ships and 2,000 men. That was finally enough. The British Parliament commissioned a Board of Longitude and offered a fat cash award—£20,000—to the first person who could design an oceanworthy chronometer. The timepiece was destined to be important in both military and commercial ventures. When synchronized with the time at Greenwich, such a chronometer would determine a ship's longitude within half a degree. The captain could just subtract the local time (readily obtained from the observed position of the Sun or stars) from the chronometer's time, and the difference between the two would be a direct measure of his ship's longitude east or west of the prime meridian.

In 1735 Parliament's challenge was met by an English clockmaker, John Harrison. Three decades later, he produced his fourth and final version—an almost palm-size item, less than five inches in diameter. As valuable to the navigator as is a live person standing watch at a ship's bow, Harrison's chronometer gave renewed meaning to the word "watch."

Because of Britain's sustained support for achievements in astronomical and navigational measurement, the Royal Observatory Greenwich landed the prime meridian. This decree fortuitously placed the international date line (180 degrees away from the prime meridian) in the middle of nowhere, on the other side of the globe in the Pacific Ocean. No country would be split into two days, leaving it beside itself on the calendar.

If the English have forever left their mark on the spatial coordinates of the world, the world's system of temporal coordinates—a Sun-based calendar—is the product of an investment in science within the Roman Catholic Church. The incentive was practical: the need to keep the date for Easter in the early spring. So important was this need that Pope Gregory XIII established the Vatican Observatory, staffing it with erudite Jesuit priests who tracked and measured the passage of time with unprecedented accuracy. By decree, the date for Easter had been set to the first Sunday after the first full Moon after the vernal equinox (thereby preventing Maundy Thursday, Good Friday, and Easter Sunday from ever falling on a special day in somebody else's lunar-based calendar). That rule works as long as the first day of spring stays where it belongs, on March 21. But the Julian calendar of Julius Caesar's Rome was sufficiently inaccurate that by the sixteenth century it had accumulated ten extra days, placing the first day of spring on March 11. The quadrennial leap day, a principal feature of the original Julian calendar, had slowly overcorrected the time, pushing Easter earlier and earlier in the year.

An astrolabe of Moorish design, c. 1300

In 1582, when all the studies and analyses were complete, Pope Gregory deleted the offending ten days from the calendar, declaring the day after October 4 to be October 15. The Church also initiated a further adjustment: omitting the leap day every century year that is not evenly divisible by 400, thus correcting for the Julian calendar's overcorrecting leap day itself.

This new "Gregorian calendar" was further refined in the twentieth century to become even more precise, preserving the accuracy of your wall calendar for tens of thousands of years to come. Nobody else had ever kept time with such precision. Enemy states of the Catholic Church (such as Protestant England and its rebellious progeny, the American colonies) were slow to adopt the change, but eventually everyone in the modern world, including cultures that have traditionally relied on Moon-based calendars, has adopted the Gregorian calendar as the standard for international business, finance, and politics.

Ever since the onset of the Industrial Revolution, European contributions to science and technology have become so embedded in Western culture that it may now take a special effort to notice them at all. The Industrial Revolution was a breakthrough in our understanding of energy, enabling engineers to dream up ways to convert it from one form to another. In the end, the revolution would replace human power with machine power, drastically enhancing the productivity of nations and the subsequent distribution of wealth around the world.

The language of energy is rich with the names of scientists who contributed to the effort. James Watt, the Scots inventor who perfected the steam engine in 1765, has the moniker best known outside the circles of engineering and science. Either his last name or its initial gets stamped on the top of practically every lightbulb. A bulb's wattage measures the rate of its energy consumption, which correlates with its brightness. Watt made his famous contribution while repairing a steam engine at the University of Glasgow, which was, at the time, one of the world's most fertile centers for engineering innovation.

The English physicist Michael Faraday discovered electromagnetic induction in 1831, which enabled him to construct the first electric motor. The farad, a measure of a device's capacity to store electric charge, probably doesn't do full justice to his contributions to science.

The German physicist Heinrich Hertz discovered electromagnetic waves in 1888, opening the door to communication via radio; his name survives as the unit of frequency, along with its metric derivatives: kilohertz, megahertz, and gigahertz.

From the Italian physicist Alessandro Volta we have the volt, a unit of electric potential. From the French physicist André-Marie Ampère we have the unit of electric current known as the ampere, or "amp" for short. From the British physicist James Prescott Joule we have the joule, a unit of energy. The list goes on and on.

With the exception of Benjamin Franklin and his tireless experiments with electricity, the U.S. as a nation watched this chapter of human achievement from afar, preoccupied with gaining independence from Britain and exploiting the economies of slave labor.

In the late eighteenth century the Industrial Revolution was in full swing, but so too was the French Revolution. The French used the occasion to shake up more than the royalty; they also introduced the metric system to standardize what was then a world of mismatched measures—confounding science and commerce alike. Members of the French Academy of Sciences led the world in measuring the Earth's shape, proudly determining it to be an oblate spheroid. Building on that knowledge, they defined the meter to be one ten-millionth the distance along the Earth's surface from the North Pole to the equator, passing through—where else?—Paris. This measure of length was standardized as the separation between two marks etched on a special bar of platinum alloyed with iridium. The French devised other decimal standards as well; most have been adopted by all the nations of the world except Liberia, Myanmar, and the U.S. The original artifacts of the metric system are preserved at the International Bureau of Weights and Measures—located, of course, near Paris.

Beginning in the late 1930s the U.S. became a nexus of activity in nuclear physics. Much of the intellectual capital came from the exodus of scientists from Nazi Germany. But the financial capital came from Washington, earmarked for the race against Hitler to build an atomic bomb. The coordinated effort to produce the bomb was known as the Manhattan Project, so named because much of the early research had been done in Manhattan, at Columbia University.

The wartime investments had huge peacetime benefits for the community of nuclear physicists. From the 1930s through the 1980s, American accelerators were the largest and most productive in the world. These racetracks of physics act as windows into the fundamental structure and dynamics of matter. They create beams of subatomic particles, accelerate them to near the speed of light with a cleverly configured electric field, and smash them into other particles, busting them to smithereens. Sorting through the smithereens, physicists have found evidence for hordes of new particles and even for new laws of physics.

American nuclear physics laboratories are duly famous. Even people who are physics-challenged will recognize the top names: Brookhaven, Fermilab, Lawrence Berkeley, Lawrence Livermore, Los Alamos, Oak Ridge. Physicists at the labs discovered new particles, isolated new elements, informed a nascent theoretical model of particle physics, and collected Nobel Prizes for doing so.

The American footprint in that era of physics is forever inscribed at the upper end of the periodic table: ele-

(Continued on page 74)

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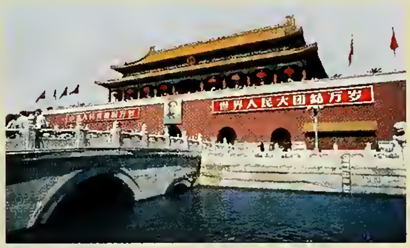

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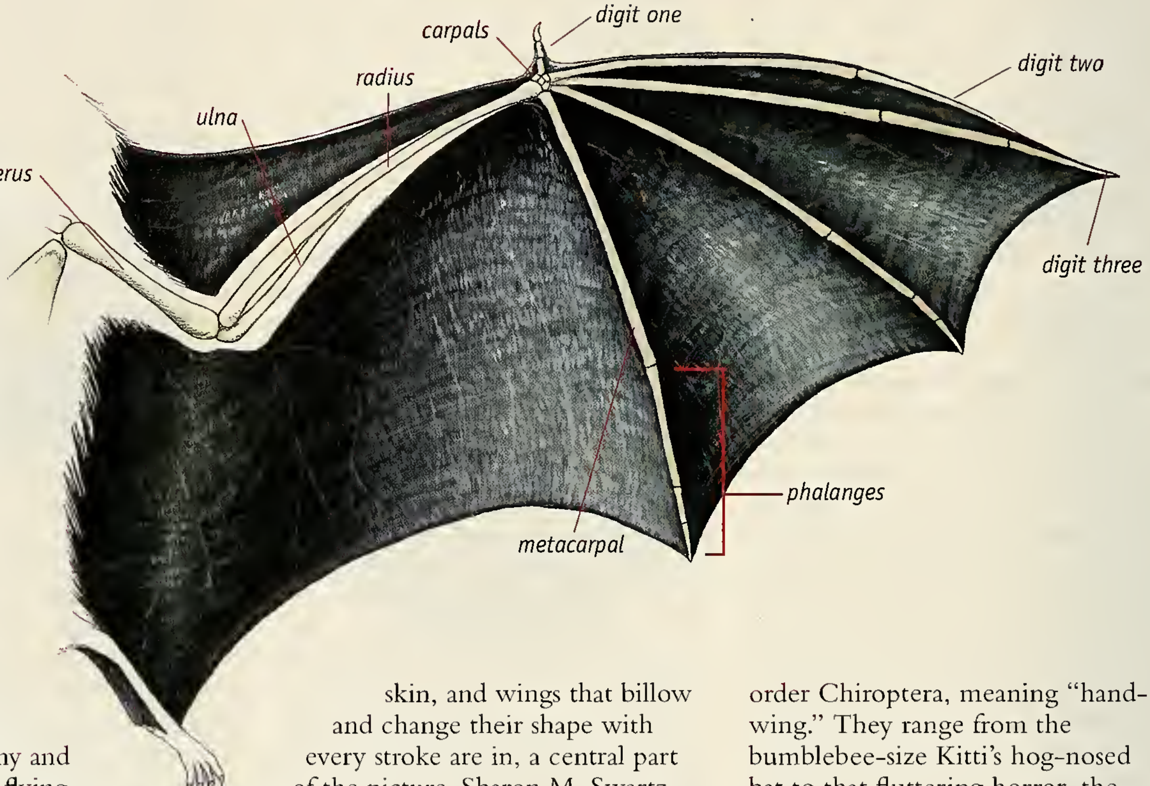
Flap Your Hands

To fly like a bat, you need flexible hand bones and stretchable skin across your fingers.

By Adam Summers ~ Illustrations by Shawn Gould



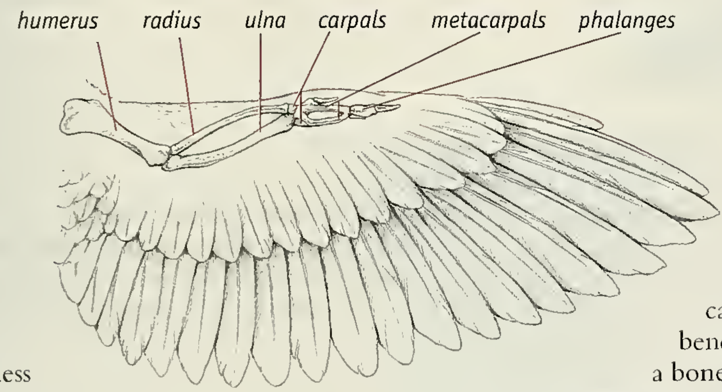
Both the Boeing Company and bats (the furry, flying mammals) are leaders in aeronautical performance and versatility, yet they have strikingly different approaches to getting (and staying) off the ground. The kind of flight most of us have experienced begins with a stiff, strong airfoil, one that undergoes few changes of shape in flight. Built out of aluminum alloys and carbon-fiber composites, rigid wings provide the steady airflow needed to generate lift that is orderly, predictable, and well understood.

Bat flight is an entirely different affair. Rigid, strong, and heavy are out. Thin, whippy bones, stretchy skin, and wings that billow and change their shape with every stroke are in, a central part of the picture. Sharon M. Swartz, a biologist at Brown University in Providence, Rhode Island, and her students Kristin L. Bishop and Maryem-Fama Ismael Aguirre are investigating the fluttering flight of bats with both hands-on tests and computer simulations. They are learning what works, and what doesn't, when fliers must contend with unsteady airflows and with airfoils that continuously deform.

Nearly a quarter of all mammal species are bats, and they are the only winged animals in the class Mammalia. All bats belong to the order Chiroptera, meaning "hand-wing." They range from the bumblebee-size Kitti's hog-nosed bat to that fluttering horror, the vampire bat, to the Malayan flying fox, the largest species.

A bat's wings are not only different from a 747's; they are also quite unlike the wings of a bird. They lack feathers, obviously. And although the humerus, radius, and ulna of birds are quite similar to the humerus and radius of bats (which have only a vestigial ulna), avian hand bones have largely fused [*see illustration on opposite page*]. But bats' carpal bones conjoin at a point about halfway along the leading edge of the wing; the bones of the short, clawed first finger (homologous to our thumb) jut forward. The long second finger forms most of the distal half of the wing's leading edge. The third finger runs closely behind the second, but all the way to the tip of the wing. The fourth and fifth fingers run from the leading edge to the trailing edge of the wing, and stretched across all the fingers is a thin, flexible skin [*see illustration on opposite page*].

Bones don't bend—at least that's the message we get after an orthopedist applies a cast to the results of a misjudgment. But the bones of a bat's fingers have adaptations that promote bending. The digits' cartilage lacks calcium toward the fingertips, making



them less apt than ordinary bone is to splinter under stress. Also, the cross section of the finger bone is not circular, as is the bone in a human finger, but flattened. This shape further encourages flexion (think about how much easier it is to bend a soda straw if you first give it a squeeze to flatten the thing).

Imagine wanting, as Swartz did, to measure how much bat wing bones bend. It's not easy. When bats fly, their wings flail up and down in such a complex path that a three-dimensional reconstruction of the flight would be impossible, even from a movie. Swartz and her colleagues David Carrier of the University of Utah in Salt Lake City and Michael Bennett of the University of Queensland in Brisbane solved the problem about a decade ago by gluing minute metal-foil strain gauges directly to the bones of bats.

The bat they studied was the gray-headed flying fox *(Pteropus poliocephalus),* about the size of a small chihuahua and sporting a nearly four-foot wingspan. It's huge for a bat, but just barely large enough to support the scientists' gauges. In the initial study, Swartz and the others attached gauges to the humerus and radius of the flying foxes; in later work, Swartz attached them to the fingers, between both the first and second and the second and third knuckles (to the proximal and medial phalanges, as an anatomist would say). As the animals flew about inside a long, spacious cage, the bending of a bone would also flex the gauge, thereby changing the electrical resistance in the foil. The tests demonstrated that the wing bones, about the same length as a person's index finger, deformed three-quarters of an inch or more with every beat of the wing.

Swartz went on to develop a computer model of bone deformation during flapping flight. She found that not only are flexible bones vital for bat flight, but so too is the skin that covers the hand-wing. The skin of most mammals can stretch equally in every direction, but bat-wing skin has many times more give along the direction between its body and its wingtip than it does between the leading edge and the trailing one. And when the skin billows out as the bat flies, it is stiff enough to transmit substantial force along the length of the wing and generate lift. In fact, if the skin were any stiffer, the delicate finger bones, despite their flexibility, would probably break.

The computer models, taking into account bones, skin, and the usual motions of flight, suggest that there are some limits to being batty. For one thing, a fruit bat that flies home with a mango in its mouth is pushing the limits of its flight equipment. The model predicts that even though the stresses of unladen flight bend finger bones less than halfway to breaking, the addition of a heavy fruit brings the bones dangerously close to failure. Counterintuitively, the model also predicts that heavier bones would cripple a bat. Its thin wing bones make up just 5 percent of the animal's weight, but if the bones' weight were doubled, the stresses on them would increase to dangerous levels rather than diminish. The wings' very lightness contributes to the safety of flight.

The computer model also makes clear that a bat's aerodynamics are far removed from those of fixed-wing airplanes. Unsteady airflow and flexible airfoils are the province of bat flight, and given the skittish nature of the average air traveler, those features are not likely to cross over to commercial aircraft. But because the complex movements of a bat's bones and skin do not require intricate muscular control, engineers still might try their hand at mimicking the bat's complicated but passive wing—designing a structure whose variable flight surfaces wouldn't require a motor at every joint. Perhaps, just as the wings of houseflies have been co-opted for microflyers, disembodied bat wings will also become an attractive option for flyers of medium scale—if not for Bruce Wayne in Gotham City, then for the designers of small, unmanned reconnaissance vehicles.

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A victim of filariasis cuts into his own leg to extract disease-causing nematodes (nineteenth-century engraving).

The Worm and the Parasite

Some tropical scourges call for a defense against an entire micro-ecosystem.

By T.V. Rajan

In the late 1960s, when I was a student at the All India Institute of Medical Sciences in New Delhi, my classmates and I had a microbiology professor who enjoyed taunting us as we struggled to identify badly preserved, poorly stained slides of parasite larvae and eggs. "You don't know what this is, do you?" he would say, cackling gleefully. "The eye does not see what the mind does not know." In truth, we scientists often don't understand what is staring us in the face. Like everyone else, we see what we see through the lens of a conceptual framework. The history of the treatment of filariasis, and of the research that has been done on the disease, is a perfect example of how a framework can guide, but also limit, our thinking.

The disabling and often disfiguring tropical disease known as lymphatic filariasis is one of the multitude of diseases for which mosquitoes are the vector. Elephantiasis—the grotesque enlargement of a limb, breast, or scrotum, caused by blockage of the lymph vessels—is one of its most conspicuous manifestations. According to the World Health Organization, filariasis afflicts some 120 million people worldwide, and more than a billion may be at risk of contracting it. Surpassed only by malaria as a cause of human suffering from disease, filariasis imposes an enormous burden of illness, lost productivity, and economic hardship on already-poor countries of the global South.

The nematodes that cause this nonlethal but devastating illness are threadlike parasitic worms, primarily of the species *Wuchereria bancrofti* and *Brugia malayi*. As with nearly every infection caused by a parasite, the precise mechanism that gives rise to the clinical disease is unknown. One can say with some confidence that none of the most obvious mechanisms are to blame: not the increasing population of larvae inside the human host; not the substances produced by the larvae, either living or dead; not the constant motion of the adult nematodes.

Transmission begins when a female mosquito siphons off a few microliters of blood from an infected individual. Two weeks later, when the ingested nematode larvae have developed into a stage that is infectious to humans, the larvae enter the insect's head. When she bites again, she transfers the nematode larvae to a second person. But the illness may remain asymptomatic for months or even years, leaving many of its carriers hard to identify.

On the basis of their own experiences in treating lymphatic filariasis, many of my medical mentors in India asserted that certain antibiotics were effective against the acute symptoms of the disease. Yet a quarter century ago (and, to a large extent, today as well) Western physicians pooh-poohed the Indian approach and held firmly to the admittedly logical, though in the end incomplete, position that infections caused by nematodes could not be treated with antibiotics. And here the story begins to take some twists.

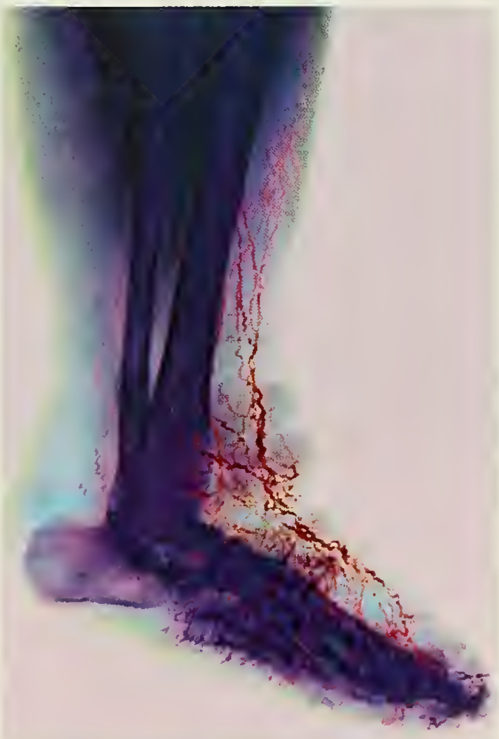
Antibiotics are small molecules made primarily by soil-dwelling microorganisms of the genus *Actinomyces*, which compete with bacteria in the same ecosphere. These molecules can kill the bacteria that *Actinomyces* encounter, but they cannot kill eukaryotic cells—that is, any cell with a true nucleus enclosed by a membrane. Hence most living things made up of eukaryotic cells—and that includes nematodes, people, trees, and virtually anything else nonmicroscopic—are unharmed by antibiotics. So if antibiotics cannot destroy nematodes, how could the Indian physicians have treated a nematode-caused illness by administering them?

Filarial infections, it should be said, have some unusual features. Most people picture a patient with an infectious disease looking feverish, exhausted, and generally sick. Those and other "constitutional symptoms" of infectious illnesses are manifestations of the body's reaction to the invading microorganism; they are not caused by the infectious agent itself. When they detect the presence of alien organisms, the body's white blood cells synthesize proteins that cause a rise in temperature. The response is protective, enhancing the efficacy of the body's defense mechanisms. But one of the cardinal features of many parasitic diseases, particularly infections caused by nematodes, is the near-absence of constitutional symptoms. Nematodes can live in the body without eliciting such responses; even in the face of an active infection, many people do not experience acute symptoms.

Investigators have suggested that the longer two species live together symbiotically, the less chance that either one will disrupt the other's physiology. After all, the parasite needs a living home, not a dead one. Because many nematode infections seem to have coevolved with people over the aeons, most nematodes cause few if any disruptions of human physiology, hence few symptoms of infection. Yet many patients who contract filariasis suffer episodes of high fever, chills, trembling, and rigor. Acute filarial fever, in fact, can often look like an attack of another disease that is rampant in many of the same countries where filariasis is common: malaria.

Here is another oddity: While the nematodes are living out their four- to six-year life spans in their human hosts, they produce vast numbers of larvae that circulate in the blood. When a mosquito transmits some of those infective larvae to a new human host, the larvae migrate almost immediately to the person's lymph vessels. Because the lymphatic system is a critical component of the mammalian immune system, the nematode's choice of home base might seem peculiar: an invader doesn't usually position itself in the midst of a defending army. Yet the nematodes have clearly adapted to that hostile locale all too well.

The central peculiarity of lymphatic filariasis—the apparent usefulness of antibiotics in treating it—should have been resolved a quarter century ago. At that time, several groups of parasitologists interested in the microanatomy of filarial parasites examined the organisms with electron microscopes. One of the investigators, Wieslaw J. Kozek of the University of Puerto Rico School of Medicine in San Juan, noticed something he had not seen in other nematodes, whether parasitic or free-living. Within the vacuoles, or membrane-bound cavities of the nematode's cells, were even smaller organisms, resembling several genera of intracellular bacteria collectively known as rickettsia.



X ray of the swollen lower leg of a patient with elephantiasis. The swelling is coused by blockage of the lymph vessels (red in the false-color image).

Bacteria in this group lack cell walls and cannot survive outside the cells of the organisms they parasitize. Kozek not only concluded that what he had detected were bacterial symbionts; he also noted that the bacteria were more numerous in female nematodes, particularly in the uteri of the worms and in their developing embryos. Here, then, was a possible explanation for the effectiveness of antibiotics against filarial nematodes.

Kozek's findings, however, had the misfortune of being unfashionably morphological. Ever since the emergence of what is widely referred to as quantitative biology, any observation that cannot be expressed as statistical analyses or as DNA sequences has generally been greeted with skepticism, if not outright indifference.

As it happened, a more "quantitative" study was done by another parasitologist at about the same time, and it yielded a complementary, though inadvertent, result. Thomas R. Klei, a parasitologist at Louisiana State University in Baton Rouge, had initiated an experiment with the jird *Meriones unguiculatus*—a docile, gerbil-like desert animal that is susceptible to many of the same parasitic infections that afflict people. After being infected with filariasis, the jirds in Klei's experiment developed an unrelated skin infection that he treated with tetracycline, a broad-spectrum antibiotic. When he and his students examined the jirds at the end of the experiment, they found that the animals treated with tetracycline were free of nematode parasites.

The reigning biological dogma of the time made the finding thoroughly puzzling. After repeating the experiment, with the same result, Klei contacted John W. McCall, a colleague at the University of Georgia in Athens, who had been supplying investigators with the infective larvae of a variety of nematode parasites for several years. It turned out that McCall, too, had noted that filarial parasites did not grow in animals treated with broad-spectrum antibiotics. But McCall told Klei that because he could neither explain nor understand his result, he hadn't published it.

Yet despite this cluster of independent, mutually consistent, and biologically exciting laboratory observations made by Western investigators—and despite the clinical successes achieved by practicing physicians in South Asia—no one picked up the thread until two decades later.

The story resumes in the mid-1990s, when Claudio Bandi of the University of Milan, an expert on bacteria living in insects, sought to determine how commonly other life-forms harbor bacteria within their cells. He was aware of studies done by Kozek and others, noting the presence of bacteria in filarial nematodes. Were these bacteria, Bandi wondered, related to the ones that live in insects? He and his colleagues chose a standard technique for answering such questions: they looked at DNA sequences that code for ribosomal RNA (rDNA). These sequences are present in the cells of all living organisms. Some of the rDNA sequences from heartworms were highly homologous to the rDNA of the arthropod-dwelling bacteria. Undoubtedly, those rDNA sequences had come from the genome of the bacteria that live in the worm, not from the genome of the worm itself.

A second reason for the renewed interest in filarial bacteria was the sequencing of entire genomes of biologically important organisms, such as the laboratory mouse, the worm *Caenorhabditis elegans,* and, of course, *Homo sapiens.* The filarial parasite *B. malayi* was part of the next wave of organisms whose entire genomes were to be sequenced. Even in the early stages of the work on the nematode's genome, Steven A. Williams of Smith College in Northampton, Massachusetts, and Mark Blaxter of the University of Edinburgh in Scotland noted that some of the sequences resembled the ribosomal genes of bacterial cells rather than

Kill off the bacteria living in the worm, and the worm dies too.

those of eukaryotic organisms such as *B. malayi.* But because bacteria such as *Escherichia coli* are ubiquitous in molecular biology laboratories, the investigators initially thought the sequences were just contaminants.

It soon became clear, however, that the resemblances were not caused by contamination; Williams and Blaxter continued to extract bacterial rDNA from the nematodes even when the nematode samples were extremely clean. Even more telling, the sequences did not resemble the rDNA of *E. coli.* Instead, they were most homologous to DNA sequences from rickettsia, particularly from members of the genus *Wolbachia.* Combing through the literature to see if they could learn why the sequences were present, Williams, Blaxter, and others encountered the papers of Kozek, Klei, and McCall. Molecular biologists had rediscovered something that had been known to clinicians and morphologists for a quarter century.

Wolbachia bacteria infect at least 20 percent of all known insect species, disrupting their reproductive lives [*see "Invasion of the Gender Benders," by John H. Werren, page 58*]. For instance, the sperm of a male insect infected with *Wolbachia* do not function properly when they fertilize the ova of an uninfected female. But if a female insect is infected with *Wolbachia,* her ova are compatible with the sperm of both infected and uninfected males. Thus females infected with *Wolbachia* have a reproductive edge: they produce more progeny. Furthermore, *Wolbachia* is transmitted from the mother to her progeny, which suggests there will be more infected than uninfected progeny in the next generation. The process has no reproductive benefits for the insects, but it does ensure the rapid spread of the bacteria. Another of *Wolbachia*'s tricks is to turn some insects that were genetic males into sexually functioning females, and that leads to the same end result: an increase in the pool of infected females within the insect population.

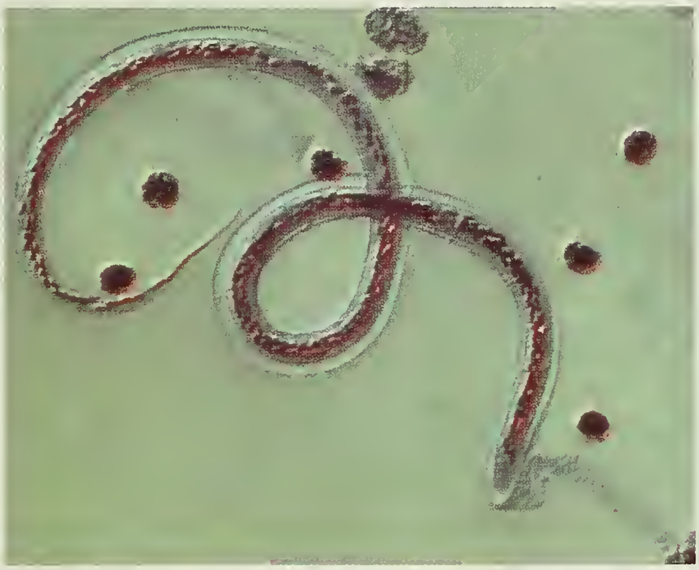
All the symbiotic microorganisms being studied in current research on filariasis are *Wolbachia.* Most insects, however, seem to get along just fine without the bacterium. One insect species may harbor *Wolbachia,* whereas a second species, belonging to the same genus, may remain entirely uninfected. And when the bacteria within an individual insect are killed by antibiotics, the insect shows no obvious deleterious effects. By contrast, every individual filarial worm belonging to a species known to harbor *Wolbachia* has been found to be infected with the bacterium. And, as I suggested earlier, neither the worm nor the bacterium can live without each other. Killing the bacteria (by administering antibiotics) leaves the worms unable to develop, to mate, or to generate progeny.

A complementary finding reinforces the same conclusion. The genomes of the *Wolbachia* species that live within filaria are much smaller than the genomes of the bacteria that inhabit insects. That pattern is common when the relationship between two interacting species becomes fixed and mutually dependent. The smaller organism often jettisons substantial parts of its genome, having come to depend on the larger organism for most of its metabolic requirements.

The rediscovery of the fact that bacteria live within nematodes poses exciting medical possibilities, not only for elephantiasis but also for onchocerciasis, or river blindness, a disease that afflicts millions of people in sub-Saharan Africa. Much of the interest centers on two prescient suggestions made by Kozek and Horacio Figueroa Marroquin in their 1977 paper on *Onchocerca volvulus*, the filarial worm that causes onchocerciasis. First, they suggested that if the worm depends on the bacteria living inside it for some critical metabolic function, one could treat the disease by killing the bacteria. That suggestion has proved to be entirely warranted. Achim Hoerauf and his colleagues at the Bernhard Nocht Institute for Tropical Medicine in Hamburg, Germany, have shown that giving tetracycline to victims of river blindness destroys the *Wolbachia* inside *O. volvulus*. Tests on animals have led to the same result. In addition, a former student of mine, Heidi Smith, who is now a resident in internal medicine at the Dartmouth-Hitchcock Medical Center in Lebanon, New Hampshire, and I have shown that tetracycline prevents the filarial larvae from molting. Hence the antibiotic may be useful as a preventive as well as a treatment.

Kozek and Figueroa Marroquin's second suggestion was that some of the acute inflammation that accompanies filarial infections might be caused by the bacteria living inside the nematodes. Mark J. Taylor, a parasitologist at the Liverpool School of Tropical Medicine in England, and his associates have supported this hypothesis by demonstrating that the inflammation can be attributed to molecules called lipopolysaccharides, which are released by *Wolbachia* bacteria. More recently Eric Pearlman, a microbiologist at Case Western Reserve University in Cleveland, Ohio, and an international group of collaborators demonstrated that the severe eye pathology that occurs in patients with onchocerciasis might be caused by the same molecules.

The presence of *Wolbachia* in insects as well as in filarial nematodes raises an intriguing evolutionary possibility. Perhaps, at some stage long ago, the bacteria were transferred from insects to nematodes, since filarial nematodes reside in insects during some stages of their life cycles. But for reasons that are not yet clear, some filarial nematodes do not contain *Wolbachia*.



A larva (microfilaria) of the parasitic worm Wuchereria bancrofti, *surrounded by white blood cells, magnified 500 diameters.*

Physicians often disregard or even reject certain treatments because they don't "make sense" in the context of mainstream thinking. "The tomato effect: Rejection of highly efficacious therapies," a paper published in the *Journal of the American Medical Association* in 1984, addresses this troubling, though perhaps understandable, phenomenon within the medical community. In the paper, James S. Goodwin of the University of Texas Medical Branch in Galveston and Jean M. Goodwin note that British colonists refused throughout much of the eighteenth and early nineteenth centuries to cultivate tomatoes in North America, on the grounds that the fruit (a member of the nightshade family) was allegedly poisonous. Yet in Italy people had eaten tomatoes for hundreds of years with no ill effects. The Goodwins compare the episode to the rise, fall, and resurrection of such treatments as giving the plant extract colchicine for the pain of gout.

As the title of the Goodwins' paper implies, the treatments they studied were not among the questionable or even useless remedies that untrained or irresponsible "healers" may offer to desperate people. On the contrary, the treatments were provably effective. Clinicians simply avoided them because accepted theories of disease mechanism and drug action offered no explanation for their efficaciousness.

Today, of course, tomatoes are eaten across the globe. Could a similar reversal be in store for antibiotics in treating lymphatic filariasis? It is hard to understand the persistent lack of interest in exploring such a use of antibiotics unless what we have here is an instance of the tomato effect.

I cannot help but conclude that the scientific community is a microcosm of humanity—unable to appreciate the importance of anything until we are ready to do so, not seeing with the eye what we have not accepted with the mind. I wish it were different. I wish we were more truly scholarly, more humble about our limited understanding of the universe, more ready to accept that a number of things work despite our inability to explain why.

T.V. Rajan is a professor and interim chair of the department of pathology at the University of Connecticut Health Center in Farmington.

Genetic Hoofprints

The DNA trail leading back to the origins of today's cattle has taken some surprising turns along the way.

By Daniel G. Bradley

On the move in Niger, northern Africa: Mounted pastoralists travel with their herd of humped, long-horned cattle.

The genes present in the 1.3 billion cattle living on the Earth today represent a stream of inheritance that stretches back 10,000 years. The founding event in the legacy of the domesticated farm animal was the capture of the formidable wild ox, or aurochs. Taming a long-horned beast six feet tall at the shoulder must have been a daunting task, but it was just one of a series of plant and animal domestications that forever changed the way most people live.

But just what is the genetic heritage of domestic cattle? Was more than one kind of aurochs brought under human control, and if so, how many ancestral species does that heritage encompass? How much variation is present in the genome? What experiences does its DNA encode to help the animal deal with heat, cold, hunger, thirst, disease, and all the other stresses of life? Answers to such questions do more than satisfy curiosity. Humanity's dependence on cattle runs deep, and our own well-being is therefore bound up with that of the animal. For example, if the selective breeding that has created a super milker should also inadvertently lead to vulnerability to a particular disease, how deep is the genetic reservoir that could still be called on to fight that vulnerability?

For the past dozen years my colleagues and I at the Smurfit Institute of Trinity College in Dublin have been tracing the genetic origins of modern breeds of cattle. The work has taken us from Great Britain to South Asia to the Sahara, and from modern factory farms to pastoralist societies. Guided by the signposts of DNA, we have virtually traveled back in time along the genetic stream, from the present to the ancient past, to the era when some determined bands of people first tamed an ox.

Before modern techniques of molecular genetics became available, the only meaningful information about how and when domestications took place came from archaeology. The study of those world-changing events, embedded as they are in prehistory, is a tricky business. Yet archaeozoologists have devised a number of ingenious ways of determining, for instance, whether dusty, 8,000-year-old collections of bones are the remains of hunted wild beasts or the former members of a domestic herd. Domestication is likely, for instance, if bone deposits show the animals died at roughly the same age. The conclusion also holds if the bones represent more males than females (herders often slaughter males but keep females to produce offspring) or if the bones indicate changes in structure and a slight decrease in size (features that begin to show up in animals after generations of domesticated life). In the case of cattle, yet another feature of domestic service is diagnostic: the presence of certain kinds of wear and tear in joints or vertebrae, which indicates that the animals were once beasts of burden.

An archaeological site can be designated a domestication center only when excavations indicate that hunting gradually gave way to herding. Archaeologists have documented such a transition in the Fertile Crescent of the Near East. Extending outward from the land bounded by the Tigris and Euphrates Rivers, this region was the center of domestication for an unparalleled number of plant and animal species, including barley, oats, and wheat among the cereal grains, and the "big four" domesticated animals: cattle, goats, pigs, and sheep. But there is evidence that cattle were also brought under domestication farther east, in what are now Pakistan and India.

By tracing the ancestry of living animals, geneticists can verify and amplify archaeological findings, thereby giving a more detailed view of domestication and its history. Blood samples and hair follicles from individual cattle are used to provide samples of certain genes, such as the ones in the mitochondrion, the powerhouse of the cell. The DNA sequences of genes can then be compared. Mutations in DNA sequences accumulate at a pace that remains approximately steady over time. The known mutation rates of common sequences can serve as "molecular clocks," which enable molecular biologists to estimate when ancestral lines branched away from each other. The sequences my colleagues and I have studied indicate that hundreds of thousands of years ago—that is, long before any domestication took place—two distinct kinds of wild cattle emerged, both of which are represented in modern populations.

The characteristics of cattle arising in three ancient centers of domestication are realistically reflected in sacred and decorative arts. From top to bottom: a humpless cow and her calf from the Fertile Crescent, depicted in a Near Eastern ivory; Egyptian wall painting of humpless cattle, from the tomb of Nefertari; and Hindu sculpture of Shiva's sacred bull. Note the humped back of the Indian bull.

Patterns of genetic variation are like ripples in a pond, which persist even after the stone that caused them has sunk from view into the depths. The geneticist can judge from the size and direction of the ripples where and sometimes when a stone was dropped, as well as how big it was. Within the geographical distribution patterns of cattle genes, we have determined that not one but two big stones—corresponding to separate domestications of the two divergent kinds of wild ox—were thrown into the pond 10,000 years ago. The resulting ripples continue to expand and overlap.

Ever since Darwin, opinions had cycled between the one- and the two-stone scenario. Some scholars argued that all domestic cattle had a common origin in a single domestication center in the Fertile Crescent. Others believed, on the basis of archaeological evidence, that the cattle of the Indian subcontinent were separately tamed. Our work has shown that the cattle of Europe, northern Asia, and Africa all have closely related DNA sequences and that they all belong to a group that corresponds most closely to the humpless cattle known as *Bos taurus.* But the genes of the humped, zebu cattle native to India, known as *Bos indicus,* tell a different story. On the bovine family tree, zebu are ten times further removed from the three members of the *B. taurus* group than those three are from one another. The Indian humped cattle belong to a genetically distinct group of their own. So the genetic evidence firmly sides with the archaeological findings: early farmers, in what are now Pakistan and India, did indeed capture and tame their own zebu-like version of the wild ox.

Gene sequences can also be read as a record of how herding may have spread outward from those two domestication centers. Our genetic work had indicated that European cows were related to the ones that were domesticated in the Fertile Crescent. But we wanted to find out whether they also carried a genetic inheritance from the aurochs that still inhabited Europe when cattle were being herded there. (The last remnant population of European aurochs was hunted to extinction in a Polish forest in 1627.)

In 2001, we managed to extract DNA gene sequences from six large aurochs bones discovered in Britain. The bones were between roughly 3,000 and 8,000 years old. The ones of more recent date were from wild oxen that had lived as neighbors of domestic herds then kept in Britain. Our analyses showed that the British aurochs sequences were closer to sequences present in *B. taurus* than to those of *B. indicus,* but they were quite different from any encountered in modern cattle. These wild oxen appear to have made no detectable contribution to the domestic gene pool; they did not interbreed with their domestic contemporaries. The forebears of European cattle, then, were wholesale importations from the Near East. Today a British cow's mitochondrial genes are much more similar to the genes of a cow—ancient or modern—from Syria or Turkey, than to the genes of the wild ox that used to roam the island.

Although we detected no other sources of genetic input in the DNA of modern European cattle, the animals themselves are outwardly much changed since their ancestors migrated from the Fertile Crescent. By selectively breeding for traits such as milk production, physical conformation, and even coat coloration, people have altered the appearance, size, and utility of livestock. After decades of scientific animal breeding, certain traits have been enhanced to an extraordinary degree. Milk production per animal has doubled in the developed world in the past twenty years, largely because of genetic manipulation. Top Holstein-Friesian cattle favored by large-scale dairy farmers can easily produce forty liters of milk a day; in contrast, a West African N'Dama cow may give only four.

Yet selective breeding, by definition, also narrows the genetic base of herds, and it may have side effects as well. Breeding for milk production, for instance, could lead to reproductive problems and increased susceptibility to disease. The predicament is not as extreme as it is in crop species, where the genetic base can be sharply narrowed. But the widespread use of artificial insemination in cattle inevitably implies that the male ancestors of most of the world's elite milking herds are all close relatives. Cattle raised on most European and North American farms today have a pedigree going back only to nineteenth-century founder animals of common breeds, such as Hereford, Holstein-Friesian, and Aberdeen Angus. And though the individual animals from which modern breeds were formed would have varied in appearance, most of the animals that belong to a particular breed today look remarkably uniform. Fortunately, though, there is still some diversity among European breeds, and valuable genetic resources may be tied up in less common breeds, such as the distinctive Scottish Highland and the Portuguese Alentejana cattle.

To find an exuberant variety of breeds, however, one has to look beyond the industrialized West, to regions where cattle have a place not only as commodities in the economy, but in the culture as well. The primacy of the cow is still intact not just in India (where cattle are considered sacred and are more numerous than in any other nation) but also in Africa. In African pastoral societies, milk, meat, and sometimes blood from cattle are major sources of protein; cattle dung provides both fuel and building material; and steers, or castrated bulls, are used as draft animals. Herd ownership can also symbolize status, and individual cattle can serve as large, mobile units of wealth. For example, bridegrooms often present cattle as gifts to the bride's family. Cows also serve religious or ritual functions. The Kapsiki people of northern Cameroon, for instance, keep a cattle breed (also

Although selective breeding for high meat and milk production has marginalized distinctive European breeds, such as the hardy Scottish Highland (right), variety thrives in Africa, where cattle such as the Kuri, of Chad, are prized (left).

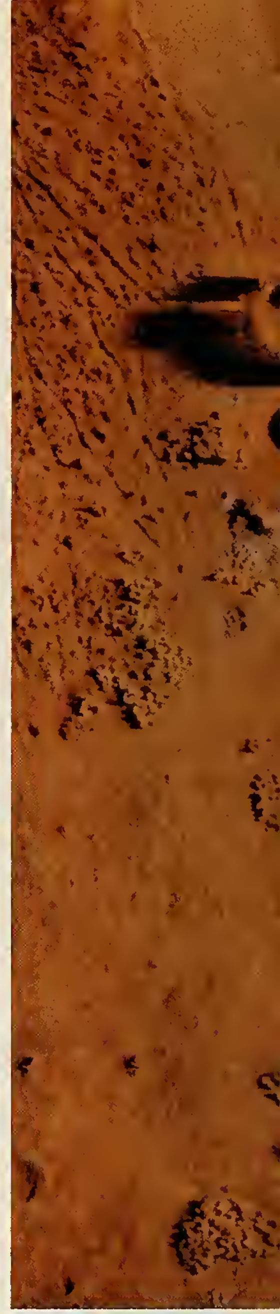
known as Kapsiki) specially for the skins, which are made into burial shrouds.

Such cultural intimacy between the people of Africa and their cattle does not mean that African herders refrain from any selective cattle breeding. But Africans breed their herds without the obsession for uniformity that has emerged in the West. One of the most evident traits that African herders select for is extreme horn size. The enigmatic Kuri cattle, herded near Lake Chad in north Africa, bear horns of enormous length and girth. When these cattle move side by side in the herd, their hollow horns knock together, producing a characteristic resonant sound. The horns are selected for their appearance rather than any utility. Ankole cattle, from the great lakes region of East Africa, are also bred for horn shape and size. Not surprisingly, the animals are prized status symbols.

According to our genetic analyses, African cattle originated neither from Indian humped cattle nor from Near Eastern cattle. Those findings support the separate-origins theory of cattle domestication favored by archaeologists, who had maintained that in Africa, too, cattle domestication was local. Our results confirm that African cattle stem from the domestication of a *B. taurus* type of wild ox that inhabited northern Africa when the Sahara region was much less arid than it is today. It may even be the case that the distinctive pastoral lifestyle of African tribes such as the Masai is of tremendous antiquity, and could pre-date the capture of cattle and development of milking in the Fertile Crescent.

Although the earliest African cattle were of the *B. taurus* type, modern African breeds show multiple influences, traceable through their genetic history. I recently joined the geneticist Olivier Hanotte and his coworkers at the International Livestock Research Institute in Nairobi, Kenya, in a study that was part of a worldwide effort to chart genetic variation in cattle breeds, in the hope of conserving diversity.

Hanotte sampled the genes of fifty indigenous breeds of cattle in twenty-three countries across the length and breadth of Africa. Then, with a technique called principal-component analysis, we were able to peel away the various overlays of genetic variation caused by interbreeding, as they appeared across the continent—rather like peeling the layers of an onion. As each overlay was removed, we exposed a new, previously unseen trend, or pattern of variation. One major trend was the dispersal over millennia of the original *B. taurus*-type cattle from the Sahara region to the forests of West Africa and down to the southern cape. A second, minor genetic trend was a trickle of Near Eastern and European cattle into the continent, where they mixed with native breeds.



The third and most pronounced trend in our genetic data, however, pointed to a great influx into Africa of zebu-type, *B. indicus* cattle from South Asia. A herd in Sudan, for instance, can now carry mitochondrial DNA from the domestication of a northern African wild ox, an event that may have taken place only a hundred miles from Sudan, but more than 7,000 years in the past. The same herd may also include some genes that have leaked southward from the Fertile Crescent in the same period. But strikingly, most of the genes in the Sudanese herd are likely to be of the *B. indicus* type. And the cattle are likely to be humped, like Indian zebu.

When we overlaid the gene types on a map of Africa, we discovered that the numbers of *B. indicus* genes peaked on the east coast. The clusters suggest that zebu were first imported into Africa in large numbers by sea, rather than via an overland route such as one crossing the isthmus of Suez. Perhaps the humped cattle were brought first to Arabia, then on to East Africa. We also determined that the most purely *B. indicus* of African breeds live on the island of Madagascar, a finding that also supports the idea that the Asian cattle came to Africa by sea. The trade between Africa and India seems to have been ancient and reciprocal. African cereals such as sorghum and finger millet appear in India as early as the second millennium B.C., about the same time *B. indicus* may have first appeared in Africa.

Since their arrival in Africa, Indian cattle genes have thrived and through interbreeding, have spread throughout the continent. Zebu are generally well adapted to hot and dry environments, a

Masai homes clustered around a carral in East Africa show that cattle are literally at the center of village life.

boon in African regions that are becoming increasingly arid. And in the late nineteenth century, when the cattle disease rinderpest became epidemic and decimated *B. taurus* herds, zebu genes conferred some resistance.

In an age when most cattle in the developed world have a slim family tree, humanity should treasure, and perhaps will come to be thankful for, the rich weave of ancestry that persists on the plains of Africa. Pastoral societies also preserve the cultural importance of this largest of domesticated species. In Western societies, this cultural element has mostly disappeared from people's everyday lives. Cattle retain their significance only behind the fenced-in properties of agribusinesses and the well-guarded entrances to commodity-trading floors.

Here in my home, Ireland, the economy was dominated for millennia by cattle farming. The system stretched back to the time of the herders who built the stone-walled fields of Céide, in the west of the island, fields that have lain buried under peat bogs for 5,000 years. The Irish word for a road, *bothar,* means a path wide enough to accommodate a cow. And in the wider cultural setting cattle have literally been the alpha, if not the omega, of the Western world. After all, the first letter of the alphabet you are now reading had its genesis as a symbolic representation of an ox. □

In the Indian city of Bhuj, forty miles from the epicenter of a recent earthquake, stands the half-ruined city palace, or darbargarh, *of the maharajas of the district of Kachchh.*

Shaken to the Core

Mid-continental earthquakes can be even more damaging than the ones at the boundaries of tectonic plates. The great Indian earthquake of 2001 is a benchmark for geologists seeking to understand how they happen.

By Susan Hough and Roger Bilham

In the westernmost corner of India, south of a huge salt marsh known as the Rann of Kachchh, lies the old walled city of Bhuj, administrative headquarters of the district of Kachchh. To a Westerner, even a traveler equipped with a Lonely Planet guidebook, the area seems remote. A single train arrives in Bhuj each day; rarely does a tourist disembark. Yet, like most of India, the city and surrounding region are densely populated and rich in architectural heritage.

Deep cracks in a wall, caused by the earthquake's severe shaking, flank the partrait of a nineteenth-century ruler of Kachchh.

Two years ago these human and architectural riches became, in an instant, the preconditions for tragedy. On January 26, 2001, a magnitude 7.6 earthquake struck India about forty miles northwest of Bhuj. The quake was the first major temblor to take place on land, and away from a tectonic plate boundary, since the invention of the modern seismometer in the 1880s. It killed more than 18,000 people and wrecked hundreds of thousands of buildings across the Indian state of Gujarat.

Less than a year and a half later a much smaller, magnitude 5.1 mid-continental earthquake hit New York State just south of the Canadian border. This one, the Au Sable Forks quake of April 2002, did little damage, but its unfamiliar rumblings were felt all over the northeastern United States. A temblor that size in Los Angeles would barely be noticed in earthquake-jaded San Diego, a hundred miles away.

Gujarat and New York are on virtually opposite sides of the globe, but in geological terms they have much in common. Unlike California or Alaska, neither Gujarat nor New York is situated atop a seismically active boundary between the Earth's great tectonic plates—rigid blocks of the planet's brittle outer layer that can measure thousands of miles across but are often less than a hundred miles thick. Given such a substantial platform, one would not expect either state to undergo many earthquakes—certainly not as many as take place in the regions situated above active plate boundaries.

But the earthquakes that do strike places like Gujarat and New York have a particularly long reach. In regions along plate boundaries—coastal California and Alaska, but also the Himalaya and the Andes—the crust is a jumble of once-distinct terrains. Over geologic time, as tectonic plates have ground past each other, rocks have been cracked, ruptured, and folded, thereby mixing and mangling ancient terrains. Earthquake waves cannot propagate efficiently in such a complex, fractured setting. In regions that lie within plates, however, the underlying crust is older, less fractured, and less complicated, and the waves reverberate over much greater distances from an earthquake's epicenter.

The Bhuj temblor strongly shook the ground as far as 300 miles from its epicenter in the district of Kachchh. High-rises toppled in Ahmadabad, a large industrial city almost 200 miles away. In the hardest-hit towns and villages, people and buildings alike were thrown down violently. Writing to BBC News Online, a resident of one devastated town described the scene as she and her father stood on the balcony of her apartment block, watching everything around them shaking and crumbling. "We were in the jaws of death waiting for it to gulp us," she wrote. "Any small jerk could have caused the building to collapse."

Bhuj was truly a shock heard round the world, a wake-up call both for its horrific immediate effects and for its even more frightening implications. Earthquake damage reflects not only the magnitude of a main shock but also a region's population density and the vulnerability of its buildings, roads, and other structures. As recently as October 2002 a magnitude 5.9 earthquake in the southern Italian village of San Giuliano di Puglia took twenty-nine lives; three days later a magnitude 7.9 quake in Alaska claimed none.

It is sobering to contemplate what might take place when the next major earthquake hits the Himalayan region. The combination of potentially great magnitude, efficient earthquake wave propagation, crowded cities, and fragile buildings could threaten the lives of tens of millions of people. For comparison, consider the effects of the magnitude 7.8 shock that took place in the industrial city of Tangshan, China, in 1976. Tangshan has the unhappy distinction of being the only large city to have suffered a direct hit from a major earthquake in the past hundred years; the death toll there may have been as high as 750,000, though the official tally is closer to 250,000. A future large Himalayan earthquake could cause an immediate six-figure death toll in India and Pakistan—not to speak of the likelihood of widespread epidemics, the obliteration of costly and essential infrastructure, and the possible release of radiation from nuclear power plants.

The Bhuj earthquake offers lessons for other regions as well. Modern seismic monitoring and analysis have established it as the standard against which to compare anecdotal descriptions of other large mid-continental quakes in the historical record. Among the most important such earthquakes, at least for North Americans, were three powerful shocks that struck the southeastern corner of Missouri, near the town of New Madrid, in 1811 and 1812. The New Madrid earthquakes were strong enough to temporarily reverse the course of the Mississippi River and cause damage as far away as coastal South Carolina [*see "The Aftershocks That Weren't," by Susan Elizabeth Hough, March 2001*].

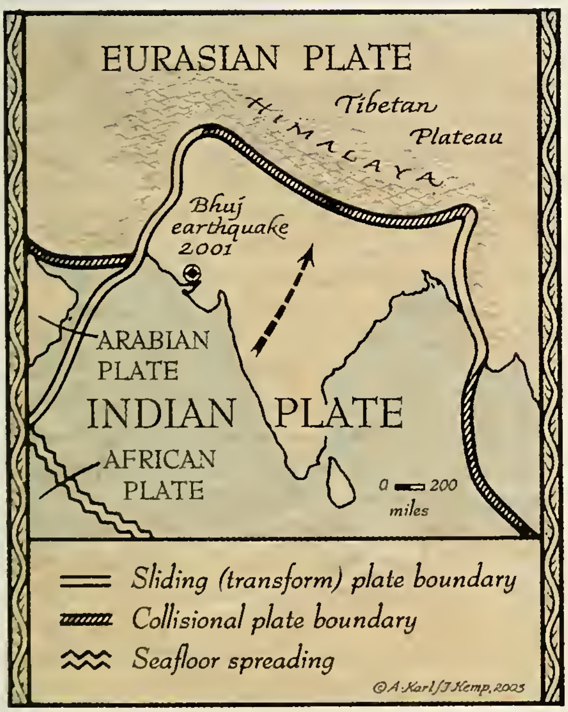
To probe the full implications of what happened in western Gujarat in 2001, geologists are seeking to understand as much as possible about the region's earlier geologic history. The ancient port of Debal, on the Indus River delta, was destroyed in A.D. 893 by an earthquake, and another temblor is thought to have submerged the nearby city of Samaji in 1668. In 1819 an enormous, magnitude 7.8 earthquake known as the Allah Bund (Dam of God) hit Kachchh. Less than two centuries later came Bhuj. And between the Allah Bund and Bhuj events there were six earthquakes in Gujarat greater than magnitude 6. Moreover, recent excavations of mutilated skeletons, which seem to have been buried suddenly under a jumble of strata, have led some scholars to conclude that the highly organized Harappan civilization of the Indus Valley, which flourished in the fourth and third millennia B.C., may also have suffered earthquake devastation.

The Allah Bund and Bhuj earthquakes were of roughly the same strength, and they generated strikingly similar patterns of damage. Captain James MacMurdo, the first colonial administrator of Kachchh, experienced the 1819 event firsthand; his reports echo vividly across the centuries: "Many of the villages . . . are reduced to heaps of rubbish," he wrote. From Bhuj he relayed accounts of "a violent undulating motion, so that it was with difficulty [that people] could keep [their] legs."

The two earthquakes are now thought to have ruptured closely neighboring faults, cracking through the earth's crust. Like the Bhuj quake, the Allah Bund largely reduced the two closest towns, Bhuj and Anjar, to rubble. It also created a broad, towering ridge—a natural dam—across the nearby (and now dry) Puran River. Downstream from the ridge the land sank, leaving an enormous depression that flooded with seawater. A fort that had stood on the riverbank south of where the ridge formed became a ruin surrounded by seawater for fifteen miles in every direction. (Today the structure is invisible, buried beneath a crust of salt.) Survivors inside the fort were ferried to the shores of the new lake; by the time they reached that relative safety, local residents were pulling both the living and the dead from the remains of their villages. Not only did the ridge dam the flow of freshwater from the north: it also put an end to trade along the Puran River.

Many buildings in the center of Bhuj had stone walls and concrete roofs, a combination that proved particularly vulnerable to damage from shaking.

To anticipate and help prepare for future earthquakes, earth scientists rely heavily on data from past events. Mostly they analyze data from seismometers deployed around the globe, as well as data from the two dozen satellites that make up the Global Positioning System (GPS). The satellites can give positions so accurately that geologists can monitor the long-term deformation, or warping, of the earth's crust with extraordinary accuracy: the glacially slow motions of tectonic plates can be measured and tracked to within the thickness of a fingernail.



Various kinds of tectonic boundaries of the Indian plate reflect its current northeastward motion (arrow). Moving at 1.7 inches a year (relative to the Eurasian plate), the Indian plate is pushing up the Himalaya and creating the high Tibetan plateau.

Of course, no such data are available either for the Allah Bund or for any of the other large mid-continental earthquakes in recorded history, including the New Madrid quakes in North America. Many important seismic events simply took place too long ago to have left behind evidence from which earth scientists can extrapolate.

Yet even without seismic recordings, one can sometimes infer the subsurface character of an earthquake from the wrinkles it creates at the surface. Much of what is known about the source of the largest New Madrid shock has been inferred from descriptions of a small region of uplift that created a waterfall on the Mississippi River. In the same way, the Allah Bund ridge has provided clues about the mechanism and size of that earthquake.

The New Madrid and Allah Bund quakes were strikingly similar in ways other than the surface uplift they produced. Sizable mid-continental earthquakes tend to strike in ancient, fault-riddled zones of relatively weak rock, which arise where landmasses begin to part. (One of the most conspicuous contemporary examples of an ongoing parting is the splitting of the African plate along the East African Rift System, which is creating the deep lakes that run from Lake Albert to Lake Tanganyika.) Numerous subsidiary cracks develop in the crust, widening along with the main rift over geologic time. Some of the cracks link up, ultimately forming deep lakes and new oceans; others languish, but they can be reactivated by new tectonic forces millions of years later.

Both the Allah Bund and the New Madrid earthquakes resulted from ruptures along steeply inclined cracks, or thrust faults. Such ruptures make it possible for a block of crust to ramp up over adjacent rock. That slippage between blocks of crust temporarily relieves the stresses that led to the ruptures in the first place, but the slippage also creates new points of stress. In fact, every large earthquake leads to a substantial redistribution of the stresses in its immediate locale, raising the specter of future redistributions, and future shocks, on adjoining faults.

Unfortunately, such a broad-brush picture offers little insight into the where and when of the next earthquake: the geological understanding of stress redistribution is still in its infancy. Any hope of making useful forecasts will require more data from large earthquakes. For example, even after nearly two centuries of study, geologists cannot say when the next large earthquake will strike the New Madrid area. And if events in that area follow the pattern of events in western Gujarat, the next great central U.S. earthquake might take place, not in New Madrid, but in the southwestern corner of Tennessee—close to the city of Memphis—or perhaps near the southwestern corner of Indiana, where a magnitude 5.0 quake struck in June 2002.

An earthquake as powerful as the one that struck western Gujarat in 2001 rings the earth like a bell, and geologists respond to the seismic signal as if it were a fire alarm.

An earthquake as powerful as the one that hit western Gujarat in 2001 rings the earth like a bell. The waves it generates cannot be felt by people living in other regions of the world, but seismic sensors virtually anywhere on the globe can detect them. For geologists, the seismic signal of a big earthquake is like a fire alarm, instantly causing concern and impelling a quick response.

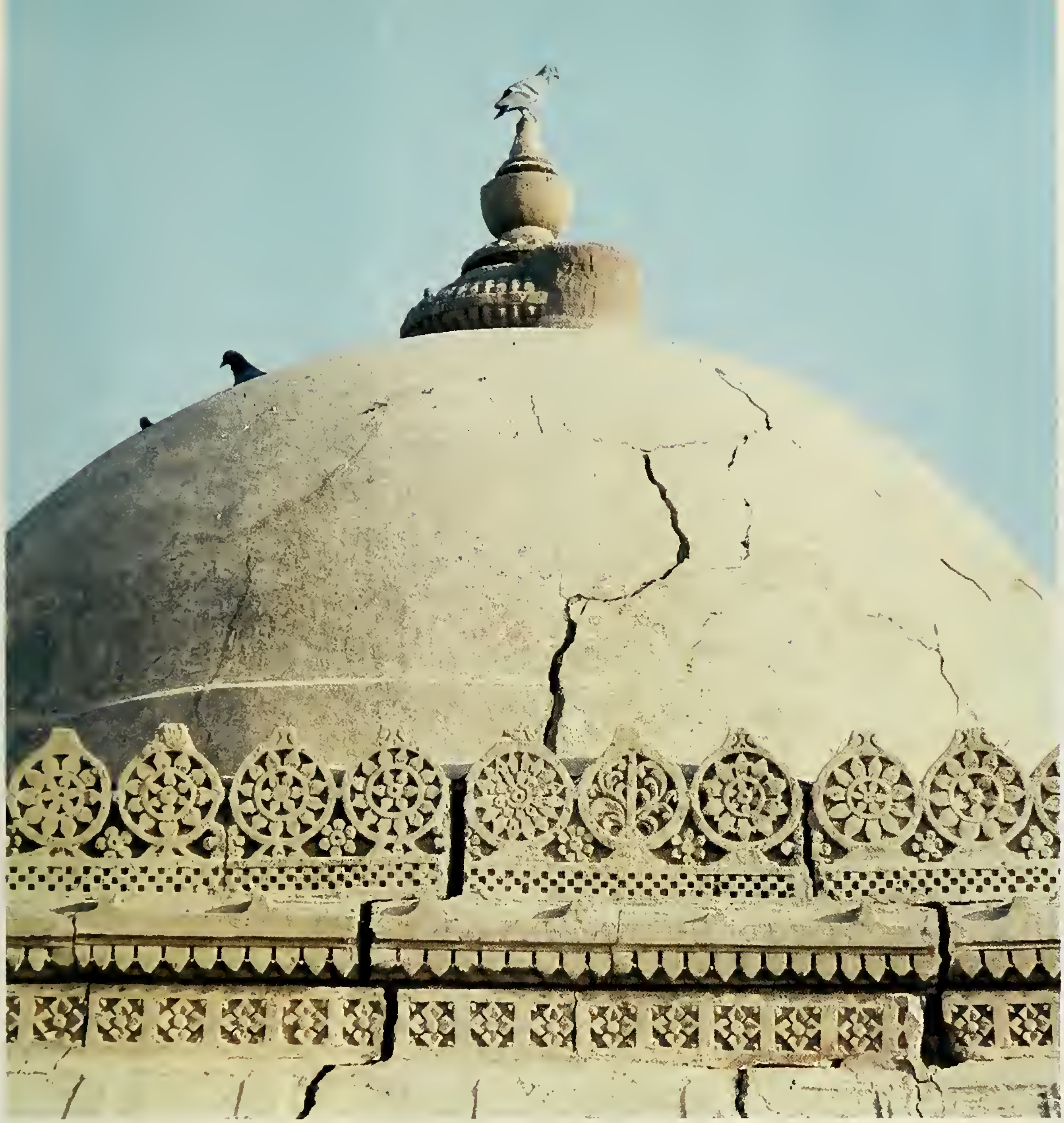
Geologists rushed to Kachchh, expecting to map the surface pattern of faulting. Large earthquakes generally cause a visible giant crack or a displacement of the surface rocks and soil. But the investigators in Kachchh found only a few minor cracks and bulges, all of which were attributable to the effects of violent shaking rather than to deeper breakage along a fault. In spite of the temblor's substantial size, the slippage along the fault stopped propagating well before it reached the earth's surface. Geologists found nothing to map except relatively modest secondary ground disruptions.

But there are other ways to reconstruct the details of movement along a deep fault, a study worth pursuing on both academic and practical grounds. Earthquakes of the same magnitude—quakes that release the same amount of energy overall—do not always generate fault ruptures of the same size, and differences in the size of a rupture lead to differences in the shaking of the ground. The longer the rupture, the lower the dominant frequency of its vibrations. The same principle determines the pitch of an organ pipe or a string on a double bass: the larger the pipe, or the longer the unstopped string, the lower the note. Even though a musical instrument is enclosed in air and a rupture is enclosed in rock, both transmit sound waves through their respective mediums.

As it happens, buildings are generally most vulnerable to shaking within a fairly narrow range of frequencies; they absorb vibrational energy primarily at their own resonant frequencies, just as a plucked string does. The kinds of structures most common throughout Gujarat—masonry buildings typically one story high and almost never higher than ten stories—are affected primarily by vibrations of between one and ten cycles a second. That is a fairly high frequency for a large earthquake. Recent investigations reveal that earthquakes of magnitude 7 or greater that have relatively small ruptures will shake particularly violently at frequencies between one and ten cycles a second. The severe damage caused by the Bhuj earthquake, coupled with its magnitude, suggested that the quake had an unusually small rupture area.

Without a surface rupture to measure and assess, seismologists could turn to three other kinds of data: the distribution of aftershocks; the "strong motion" seismic recordings from the vicinity of the event; and deformations, or warping, of the surface. Data on aftershocks and on strong motion from a main shock come from records made by seismic equipment deployed before an earthquake takes place. Deformation data are most valuable if the region was surveyed before the quake.

Following the Bhuj shock, seismologists faced frustration at nearly every turn. Few modern seismometers were in place in Gujarat at the time of the quake. In spite of its history of earthquakes, the region was thought to be less vulnerable to damage than are areas in which large or frequent quakes have hit more recently. One such area is the 1,500-



The heavy dome of a funerary monument, or chhatri, *outside the walls of the old city of Bhuj still rests on its supporting columns, despite having rocked back and forth during the earthquake's violent shaking.*

mile arc of the Himalaya, which lies along the boundary of two colliding tectonic plates. (The Himalaya, the world's highest mountain range, is still being squeezed upward by immense pressures as the northeastward-moving Indian subcontinent collides with the rest of Asia.) Lacking recordings of the Bhuj earthquake's strong motion, investigators had no detailed seismic evidence of the patterns of motion along the fault. Moreover, the positions of the quake's aftershocks could not be pinpointed until teams of seismologists were able to analyze data gathered with portable instruments during the weeks and months following the main shock.

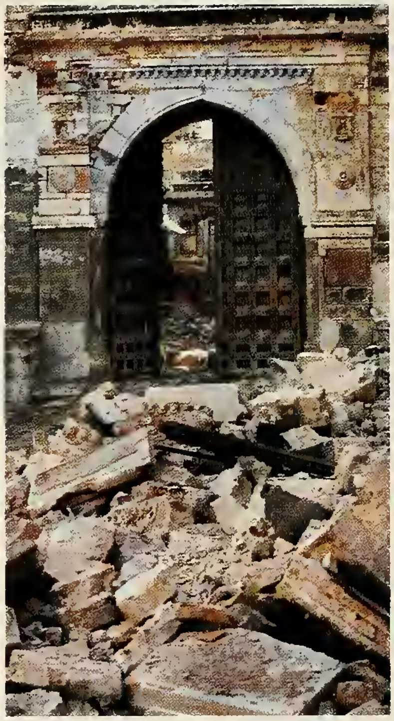
What saved the day for the investigators was a detailed survey of Gujarat—part of the Great Trigonometrical Survey of India—that was completed in the mid-nineteenth century. Thousands of engraved stone markers, placed deep within pillars, had been installed on hilltops during the heyday of the British Raj to enable accurate mapping of the region. The recorded positions of the markers established a baseline for geologists, who could then measure how much the markers had shifted after the quake. So when Indian, Pakistani, and U.S. teams of earth scientists sped to the region in early 2001, they brought along both high-tech GPS surveying units and quaint Victorian descriptions of the survey points' positions.

Although simple in principle, the field investigations were quite complicated in practice. Some of the markers had been destroyed by the violent shaking of the pillars surrounding them; many others had been lost to scavengers and small children during the preceding century and a half. Nevertheless, the scientists located a dozen of the old markers; several had shifted more than three and a half feet. An analysis of the altered positions confirmed that, deep in the crust, a fault some twenty-five miles long had slipped, on average, about twenty feet—a massive amount. The rupture of the fault had terminated more than three miles below ground.

Months later, after studying their seismometer data to infer the locations of aftershocks, seismologists also concluded that the rupture area was deep and surprisingly compact. The combination of a relatively short rupture and a large amount of slippage, as in the Bhuj quake, leads to unusually strong stresses at the edges of the rupture. Those stresses can stretch or compress rock well beyond its breaking point. Indeed, a flurry of aftershocks took place around the underground Bhuj rupture. The positions of the aftershocks seemed to confirm that the stresses had been great enough to cause extensive cracking and fragmentation of the crust surrounding the parts of the fault that had moved during the main quake.

In the end, modern data gave earth scientists a fairly good view of the underground processes that led to the earthquake. But assessing the severity of shaking at the surface was an entirely different kind of challenge, and it was the shaking, after all, that had caused the damage. Some disruptions at the surface—sand blows, for instance, which are literally fountains of sand that erupt at the surface like geysers—were widespread, and geologists were able to document them. But such effects yield at best only indirect information.

Because of the almost complete lack of direct, immediate seismographic data on the Bhuj earthquake itself, earth scientists turned instead to a time-honored source of information: personal anecdotes describing damage and other effects. By collecting accounts in the field as well as compiling the descriptions published in the media and on the Web, investigators were able to map the shaking during the event. The effects ranged from the near-total collapse of villages to barely perceptible shaking felt by residents of India's east coast.



A finely crafted doorway in the Bhuj darbargarh's *Ranivas Palace, built in the seventeenth and eighteenth centuries, remains largely intact.*

Such accounts, properly weighed and interpreted, can yield an estimate of an earthquake's intensity—the severity of shaking at a particular location—typically stated as a Roman numeral between I and XII. Near the Bhuj main shock the inferred intensities reached IX to X, strong enough to cause catastrophic damage to masonry structures.

These investigations helped establish the Bhuj earthquake as a yardstick and made it possible to assign more accurate magnitudes to the largest quakes at New Madrid: between 7.2 and 7.5, almost as large as the earthquake that devastated western Turkey in 1999.

The historical record of earthquakes in Gujarat is also prima facie evidence that a cluster of major shocks can occur in areas removed from active plate boundaries. The devastation in Bhuj provides clear evidence that such shocks can cause enormous damage.

If the lessons of Bhuj are sobering for North America, they are staggering for India and Pakistan. Home to 1.2 billion people, the two countries—though riven by social, political, and religious upheavals both internal and external—jointly face the imminent deadly hazard of a great Himalayan earthquake. The ongoing collision between the Indian and Eurasian plates creates enormous stresses throughout India, which account for the shocks away from the plate boundaries. And the sustained uplift of the Himalaya themselves is accompanied by great earthquakes that represent a common enemy of countries along and near the mountains' arc. Recent calculations indicate that several earthquakes as large as magnitude 8 are due along fully half the length of the Himalaya.

Humanity has never had to face potential earthquake devastation of this nature and scale. Multiple urban targets of great size and vulnerability have never before existed in areas where strong seismic shaking is common. As a result, what was impossible even half a century ago is now not only possible but, in some places, probable. As horrific as it was, the Bhuj earthquake was really only a warning shock. Its legacy will depend on the extent to which the world heeds the warning. □

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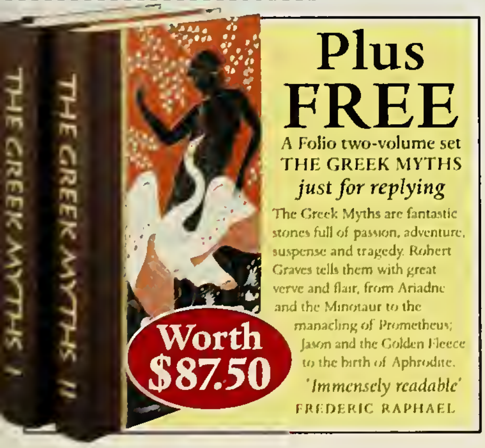

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Biosphere III

A ninety-year-old inadvertent experiment in tropical biodiversity is unfolding on several islands created by the construction of the Panama Canal.

Photographs by Christian Ziegler
Story by Egbert Giles Leigh Jr. and Christian Ziegler

How does a tropical forest manage to stay green despite an onslaught of leaf-eating sloths, monkeys, porcupines, and iguanas, not to mention a plethora of leaf-chewing and sap-sucking insects? Most flowering plants defend their leaves with toxins that deter all but the most specialized pests. Animals that the plants recruit as seed dispersers and pollinators enable some of the young plants to escape notice until they are large enough to survive the depredations of specialist pests. The animals also ensure that mature plants are cross-pollinated even if other members of the species are not close by.

In the Jurassic period, 150 million years ago, a few square miles of tropical forest harbored relatively few species of plants: conifers, cycads, seed ferns, and the like. Dependent on cross-pollination by wind, members of a species had to grow near each other, and so the pests, too, spread easily from one plant to another. Plants therefore had to invest heavily in pest resistance, leaving fewer resources for quick growth. Fifty million years later, aided by animal pollinators, a baroque diversity of faster-growing, flowering plants entered the tropical forest. After the dinosaurs died out, they became dominant.

Damming a tropical river, however, creates a reservoir that reduces forest to island fragments. Small islets cannot support resident pollinators and seed dispersers, and many of those essential reproductive helpers will not cross the water to visit. On such islets, a Jurassic world returns, where plant diversity plummets and animals help themselves to plants without helping them in any way.

What happens on a large fragment? Barro Colorado, in central Panama, is a six-square-mile island that was cut off from the mainland when the Chagres River was dammed in 1912 to form part of the Panama Canal. Since then, the island has been losing species. At least seven mammals have disappeared, including the herds of white-lipped peccaries. Various insect-eating birds that nested or foraged on the ground have vanished. The large ocellated antbird is also absent: it can only catch insects flushed by army ants, and one year the ants did not swarm in large enough numbers to support it. Biologists owe such details to a field station built on the island soon after it was declared a biological reserve in 1923. Since 1966, when the station became part of the Smithsonian Tropical Research Institute, the island has become one of the world's best-studied tropical forests.

Barro Colorado is large enough to show how a tropical forest supports a diversity of plants and animals. Nearby islets of less than three acres, however, support no resident mammals at all. They have no agoutis to store seeds by burying them, so seeds of many tree species are ravaged by insects, and these tree species are dying out. Although Barro Colorado still holds many secrets, it has made clear that forest fragmentation has intricate repercussions.

A wasp lingers after emerging from one of the white cocoons attached to the mottled surface of a sphinx moth caterpillar. In a tropical forest, "the enemy of my enemy is my friend." Plants muster various defenses of their own to ward off insect herbivores, but they also benefit from a pest's natural enemies. Among these allies are wasps whose larvae live in and on the larvae or adults of other insects, sapping their strength before eventually killing them. The white cocoons here belong to such a parasitoid, a wasp in the family Braconidae. Some parasitoids are themselves subject to such attack, by hyperparasitoids. The emerged wasp is actually one that has parasitized the wasp larva in one of the cocoons. ("Great fleas have little fleas upon their backs to bite 'em / And little fleas have lesser fleas, and so ad infinitum.")

A cicada has just emerged from its larval skin after spending years underground as a larva sucking xylem sap from roots. This kind of sap is a diluted food, and so a cicada larva grows slowly. When it finally crawls out of the ground one night, it climbs a plant, hooks onto it, and metamorphoses into an adult. The mature cicada continues to live off sap while pursuing its brief adult life seeking a mate. (An insistent noise, rather like the sound of a high-pitched buzz saw, that pervades the forest is the male advertising its presence.) Insects that suck plant juices, such as cicadas, leafhoppers, and aphids, slow plant growth every bit as much as leaf-chewers do, but they leave no visible evidence of their depredations.

Seemingly covered in moss, a walking stick (Autolyca *sp.) is a master of camouflage. Stick insects are among the many leaf-eaters that plants must contend with. A tropical forest such as Barro Colorado not only includes many kinds of trees, but the various species are also well mixed over the landscape. The most logical explanation for the intermingling is that the insects that specialize in consuming a particular species are likely to kill any young plants growing close to their parents or to others of their kind. A tree species can maintain a scattered population by relying on friendly insects and other animals to pollinate their flowers and spread their seeds across long distances.*

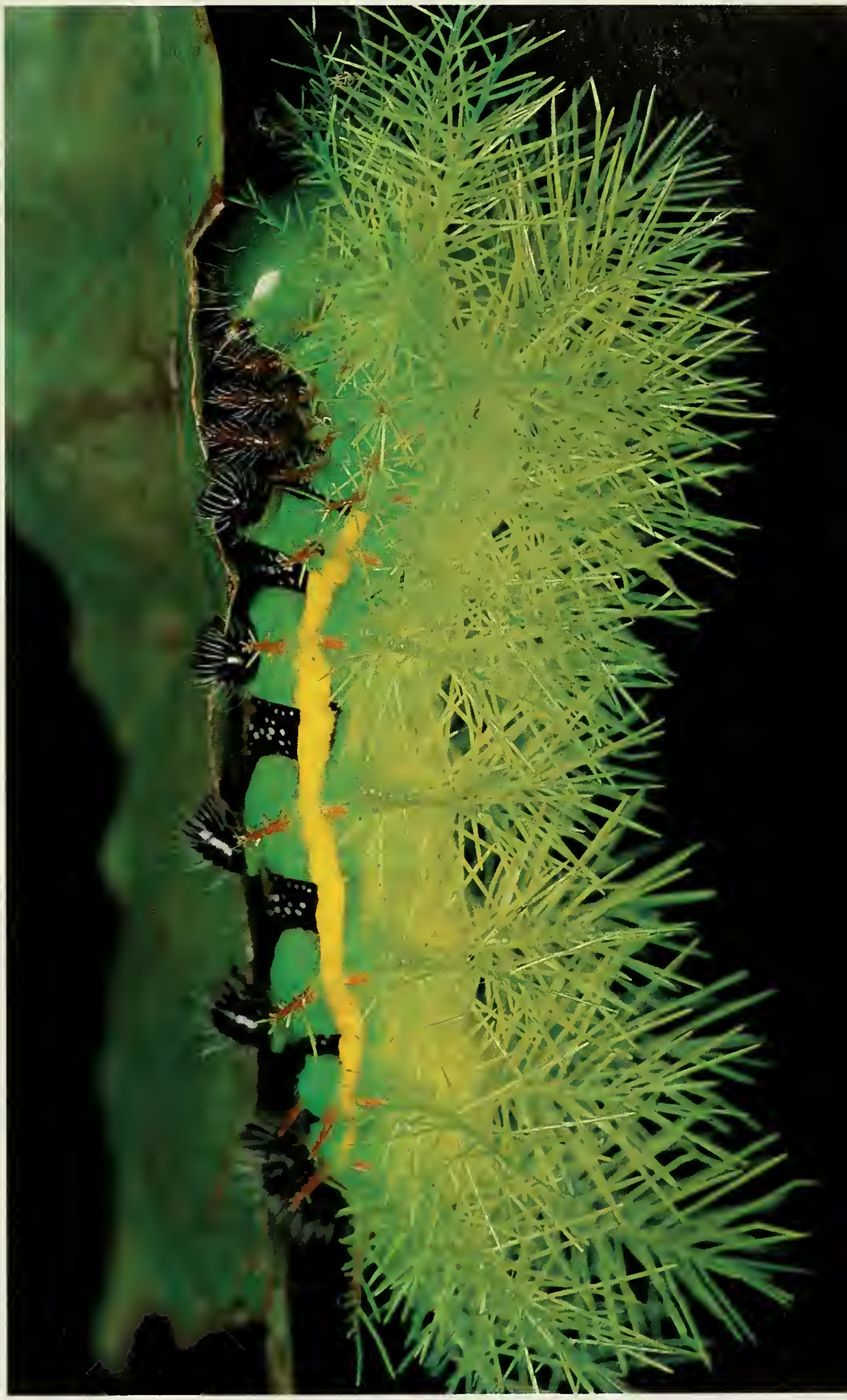
Many plants, including this Croton billbergianus *tree, have nectaries on the bases of their young leaves that attract ants (a nectary is visible here near the ant's head). The ants can scare off some potential herbivores. In the case of this* Croton, *however, some resident* Thisbe irenea *caterpillars have induced the ants to leave them in peace. The caterpillars curry favor by drinking the plant's nectar and turning it into a liquid the ants prefer. Accordingly, the ants let the caterpillars devour the leaves at will and even defend the caterpillars against some of their enemies. The caterpillars have structures on their bodies that attract ants with sound, and when danger threatens, they can even summon their defenders by releasing chemicals that mimic the alarm signals of ants. Another plant whose nectaries attract ants is the swollen-thorn acacia* (Acacia melanoceras), *a tree with bulbous hollow thorns where the ants can nest. An acacia's resident ants—members of the species* Pseudomyrmex satanicus, *justly named for its obnoxious stings—chew off the tips of encroaching vines, repel herbivores, and maintain a clearing around their plant's base.*

A fig fruit starts out as a flower head, then turns itself outside in to form a ball, or syconium, that is lined on the inside with flowers. The wasp pictured here specializes in laying its eggs in the syconium from the outside, with its long ovipositor, and leaves the pollinating of the flowers to another species of wasp. Each species of fig tree—in Barro Colorado there are eighteen—has its own species of pollinating wasp. Pollinators enter the syconium through a hole at one end and lay eggs in about half the flowers. The larvae grow inside the developing fig seeds, no more than one to a seed. When the adult wasps emerge from their seeds, they mate among themselves inside the fruit. The males then chew a hole in the syconium's wall, and the fertilized females—dusting themselves with the pollen that the flowers are only now producing—fly off in search of new trees in which to lay their eggs.

To feed its pollinators, each fig species must always have some trees with fruit ready to pollinate, whether or not the season is propitious for fig seedlings. Moreover, the trees must ensure that the fruits don't overheat in the sun and kill the wasps inside. Species that produce relatively large figs, which cannot shed heat to the surrounding air as readily as small figs can, provide a steady stream of water to their fruits throughout the day, which cools through evaporation. The trees rely on other animals to eat their ripe fruit and disperse the many seeds that have been spared by the wasps. Trees with red fruit are served mainly by birds, which are attracted to the color red. Species with green fruit depend mainly on fruit-eating bats, which they attract during the night with a distinctive scent.

Fig trees are often "keystone species"—disproportionately important to the maintenance of other species—in tropical forests of the Americas and Asia. Fig trees do not invest heavily in defenses against the herbivores; instead they grow fast, produce an abundance of nutritious foliage and fruit, die relatively young, and rot quickly when dead.

The poisonous green spines of this caterpillar, from the moth family Limacodidae, discourage potential predators such as birds. Caterpillars are a diverse and abundant group of leaf eaters. Many feed on only one genus or species of plant, collectively enhancing tree diversity by preventing any one species from crowding out the others. A casual visitor to a tropical forest may not spot the caterpillars feasting on the vegetation, but only an upward glance is required to see their handiwork: tree leaves that have holes and ragged edges or that have been reduced to a delicate network of veins. One might also experience what sounds and feels like a gentle rain—but it is the falling of the frass, or feces, of leaf-eating caterpillars overhead.



Adapted from *A Magic Web: The Tropical Forest of Barro Colorado Island*, Photographs by Christian Ziegler, text by Egbert Giles Leigh, Jr. (Oxford and New York: Oxford University Press, 2002). ©2002 by Oxford University Press, Inc. Photographs ©2002 by Christian Ziegler

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A Culex pipiens *mosquito, newly emerged from its pupal skin: Males of the species, if infected by* Wolbachia *bacteria, produce sperm that is incompatible with the eggs of uninfected females. Other* Culex *species have protozoan infections that are transmitted through the eggs and kill the male larvae but not the female ones.*

Invasion of the Gender Benders

By manipulating sex and reproduction in their hosts, many parasites improve their own odds of survival and may shape the evolution of sex itself.

By John H. Werren

Sex is fraught. Every teenager can attest to the havoc it wreaks—and to its unique power to change a life. Of course, that's one of life's lessons that survive far beyond the teenage years—and far beyond the human condition. To anyone who explores the ramifications of sex in other species, its permutations seem bottomless. In recent years, the study of evolution, of parasites, and even of disease has often led back to sex. Particularly fascinating are the ways in which some parasites manipulate sex and reproduction in their hosts—stories of exploitation and subterfuge that have amazed and astonished even life scientists long jaded by tales of biological intrigue.

Take the case of *Nosema granulosis,* a protozoan that often resides within the cells of *Gammarus duebeni,* a small shrimp that lives in intertidal pools along the coasts of Europe. When an infected mother shrimp reproduces, the protozoans hitch a ride in the cytoplasm of her eggs and thereby infect her offspring. But if the protozoans infect a male shrimp, they cannot readily infect his offspring by hitching a ride in his sperm, because sperm contain so little cytoplasm. As a result, *N. granulosis* is transmitted solely by female hosts, not by the males.

So what happens when the protozoan ends up in a baby male shrimp? That would seem to be the end of the line. What's a protozoan to do? To bypass this dead end, *N. granulosis* takes over the sex-determining mechanism of the shrimp and converts the male into a female. That bit of genetic magic assures the protozoan's passage to future generations—though how it accomplishes this, no one knows.

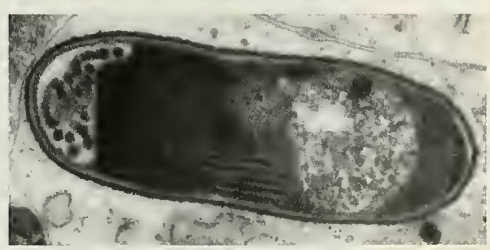
Naturally, if the protozoans were to become too common in host populations, they could drive the shrimp to extinction by causing a scarcity of males. Fortunately for the survival of both species, the protozoans are not transmitted to all the eggs of an infected mother; in the wild, in fact, they typically infect fewer than a fifth of the baby shrimp.

Parasites that manipulate the sex of their hosts are called reproductive parasites—and they are not as rare as one might like to think. Some, such as *N. granulosis,* convert males into females, but a widespread and diverse array of microorganisms simply kill the sons of their hosts; the daughters, which transmit the microorganisms, are allowed to live.

The protozoan *Amblyospora californica,* for instance, is transmitted through the eggs of infected female mosquitoes, but it kills the developing male larvae. Once again, that would seem to be a dead end for the protozoans in the males, but all is not lost. The protozoans in the males develop into specialized spores that cannot infect other mosquitoes but can infect small aquatic crustaceans called copepods. When a female copepod ingests the remains of a male mosquito larva killed by the protozoans, the copepod also ingests the spores. The protozoans then infect the female copepod and turn her ovaries into a "protozoan factory," generating the kind of spores that *can* infect mosquito larvae. When the mosquito larvae are filter feeding, they take in the spores from the water, and so complete the cycle. Thus the parasite has the best of both worlds: it exploits its female mosquitoes for transmission via eggs, and the male mosquitoes for infectious passage to new hosts. Pretty clever for an organism without a brain.

Other male-killers include various bacteria that make themselves at home in fruit flies, wasps, butterflies, and beetles. In those insects, though, the only way the microorganisms make it into the next generation of hosts is through the eggs of infected mothers. No sex-change operation on a male insect is possible; no suitable "third-party" species like the copepod is available to provide the parasites in males with an alternative host. For parasites that end up in a male, the options are limited. Killing the male insect has zero cost to the parasite, but what is the benefit?

In some cases it appears that killing off male hosts enhances the survival of the hosts' infected sisters. After all, without the males to compete with, the infected female insects have more resources for themselves. That alone, of course, doesn't help the parasites in the male insects. Unlike the *A. californica* protozoans, they gain nothing directly, because they die along with their hosts. They do gain indirectly, however, because the death of the male insects benefits the parasites' "family." All the parasites passed along by the infected mother insect are genetically identical to one another (that is, they are a clone). The parasites



Shrimp of the species Gammarus duebeni, *top, often harbor protozoans that are transmitted through the shrimp's eggs. In a step that ensures their own transmission, the protozoans can change a male host into a female. Bottom: The protozoan species in question,* Nosema granulosis.

Some populations of the white-barred Acraea, *above, are infected by* Wolbachia *bacteria that kill off most of the males. The female butterflies then assemble in courting areas, which attract the few remaining males.*

that happen to infect a daughter insect benefit from the additional resources available to her. So, by killing males the extended clone of parasites increases within host populations. For infected insect mothers, however, the infection is a disaster, because all of their sons are killed.

When male-killers become widespread, they can even affect the mating system of their hosts. Francis M. Jiggins, a biologist at the University of Cambridge, has detected male-killing microorganisms in high proportions of the individuals in some populations of African butterflies, and the highly skewed sex ratios that result lead to changes in the mating system. In *Acraea* butterflies males normally congregate at food plants, and matings take place there when the females arrive to lay their eggs. But in some populations of the white-barred *Acraea,* so many females are infected with male-killing bacteria (more than 95 percent in some cases) that males are extremely scarce. In those populations, females assemble in courting areas called leks to attract the few males that are flying about. These lucky males procure many matings, but there is still not enough sperm to go around, and many females remain uninseminated. Female leks are extremely rare in nature; in most species that form leks, it is the males that aggregate to attract the females. But under the pressure of male-killing bacteria, the white-barred *Acraea* appears to have evolved an unusual but adaptive mating system.

Biologists have just begun to document the diversity of male-killing bacteria in nature, and it is likely that a large percentage of invertebrate species play host to them. Vertebrates may also harbor male-killers, though none have yet been found. People need not worry, though: given the intense study of our own species, if we carried male-killing microorganisms, they would certainly have been discovered by now.

The white-barred *Acraea* is an extreme case; male-killers rarely infect a fraction of a population large enough to force a change in the mating system of a host species. Yet some biologists speculate that even a relatively small proportion of infected individuals (say, 5 percent) pushes the sex-determining genes of a host species to change in ways that enable it to escape or to suppress the male-killing effects. The cat-and-mouse game between male-killers and their hosts may be one of the motors contributing to the great diversity of sex-determining mechanisms that occur in nature.

The undisputed virtuosos of reproductive parasites are bacteria of the genus *Wolbachia,* which, like many of their brethren, are transmitted in the cytoplasm of eggs. These bacteria also infect across species boundaries, which has made them unusually widespread in invertebrates. *Wolbachia* bacteria infect many insects, arachnids (mites and spiders), crustaceans, and parasitic nematodes. At least 20 percent of all insect species harbor them, and the proportion could be as high as 70 percent—biologists are still trying to determine the number. Because most animal species are invertebrates, the abundance of *Wolbachia*'s hosts makes the genus among the most common parasitic bacteria on the planet. Analysis of its DNA indicates that the bacteria have lived in insects for at least 50 million years, and in invertebrates for at least 100 million. Only ten years ago *Wolbachia* was regarded as an obscure little group of bacteria, but the genus has come up in the world, at least in the eyes of biologists.

Its broad distribution is one of the major mysteries of *Wolbachia:* how can one genus of bacteria infect so many kinds of hosts? Some investigators speculate that species that are ecologically associated in some way (predators and prey, for instance, or competitors feeding on the same food resource) may occasionally exchange *Wolbachia.* But convincing evidence has not yet surfaced to back up the speculation.

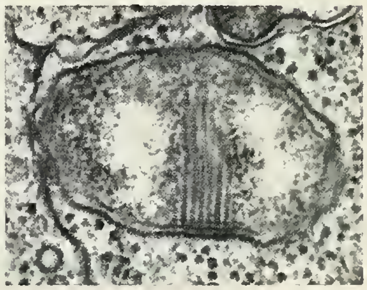
Wolbachia bacteria are masters at manipulating the reproductive and cell biology of invertebrates. Like other reproductive parasites, some members of the genus kill the male insects they infect, whereas others turn males into sexually functioning females. Some even induce parthenogenesis in their hosts—a mode of reproduction in which eggs develop into females without fertilization, thereby dispensing with males and their sperm. Parasitic parthenogenesis has been noted in more than three dozen species of insects, mainly wasps. The bacteria accomplish this trick by manipulating the basic processes of the cell in such a way that the single set of chromosomes in the egg is duplicated, and the unfertilized egg develops into a female.

When the bacteria in parthenogenetic insects are killed with common antibiotics such as tetracycline, the insects usually revert to sexual reproduction. Sometimes, however, the insect species have been parthenogenetic for so long that when the *Wolbachia* bacteria are eliminated, the insects can no longer reproduce sexually. In the small parasitic wasp *Encarsia formosa,* antibiotics lead to the production of males, but the males cannot mate: the genes needed for male courtship have been lost.

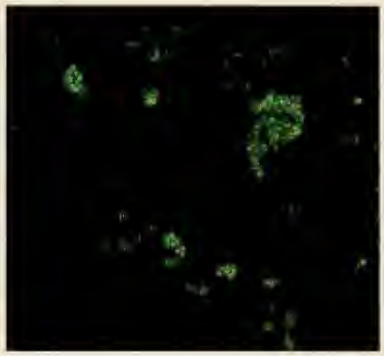
Parasites that are passed on through the eggs of their host species face a potential dead end if they find themselves in a son of their former host.

Other wasp species have similar stories to tell. In some, the females no longer respond to courtship; in others, the males no longer produce functional sperm. Given enough time, mutations accumulate in the genes for sexual characteristics, and the species can no longer revert to sexual reproduction. Their reproduction becomes completely dependent on the bacteria that live inside their cells.

But perhaps the most intriguing effect of *Wolbachia* is the ability of some strains to induce an incompatibility between host sperm and eggs, a process that may even implicate the microorganisms in the evolutionary divergence of insect species. The discovery of these capabilities has a long history. *Wolbachia* bacteria were



Above: A kind of bacterium living in this Encarsia *wasp causes it to reproduce parthenogenetically—that is, the wasp's eggs develop into females without the need for fertilization. Top right: The as-yet-unnamed bacterium, a relative of soil bacteria of the genus* Cytophaga.



A Brevipalpus phoenicis *mite, left, can be infected with the* Cytophaga-*like bacteria, above, which enable the mite to reproduce parthenogenetically. Other mite species carry* Wolbachia *bacteria that induce incompatibility between sperm and egg.*

first observed in the 1920s, when the pathologists Arthur Hertig and S. Burt Wolbach, working at Harvard Medical School, found them inside the eggs of *Culex* mosquitoes. Hertig later named the bacterial genus in honor of his colleague and mentor. In the 1950s the German biologist Hannes Laven discovered that when males from some strains of the mosquito *C. pipiens* were crossed with females of another strain, the offspring died as embryos. Laven subsequently showed that the effect was inherited through the mother's lineage. As he viewed it, the cytoplasm in the eggs of certain strains of insects was incompatible with the sperm from certain other strains. Laven was apparently unaware, however, that bacteria had earlier been discovered in the eggs of the insects.

It wasn't until the early 1970s that two other investigators, Janice H. Yen and A. Ralph Barr of the University of California, Los Angeles, made the connection. They showed that Laven's "cytoplasmic incompatibility" was caused by the bacteria. Antibiotic treatments that eliminated the bacteria also changed the compatibility relationships between males and females.

The basic pattern is that eggs from uninfected females are incompatible with sperm from infected males. The *Wolbachia* present in the testes of males biochemically "encrypt" the developing sperm, probably by altering proteins that bind to the sperm DNA. The same strain of *Wolbachia* must then be present in the egg to "decode" the encrypted sperm. Otherwise the chromosomes from the sperm are not properly processed in the fertilized egg, and the embryo dies. The actual mechanisms are still a mystery, but it is already clear to investigators that there are many different kinds of *Wolbachia*, which differ in their encryption systems.

The diversity of the encryption mechanisms raises the possibility that *Wolbachia* could play a role in the evolution of new insect species. If different populations of a species, or closely related species, are infected with different strains of *Wolbachia*, the bacteria could prevent the insects' gene pools from mixing. Just such a circumstance may have arisen in jewel wasps, a genus *(Nasonia)* of small parasitic wasps that kill fly pupae. There are three closely related species of jewel wasps, but each is infected with its own distinct *Wolbachia*. The bacteria render any matings between the different wasp species incompatible, thereby preventing the development of hybrids.

Biologists have also discovered that *Wolbachia* plays an essential developmental role in some host species. For example, if *Wolbachia* bacteria in the wasp *Asobara tabida* are eliminated with antibiotics, the female wasps fail to develop ovaries and so become sterile. Filarial nematodes—parasitic "worms" that cause such diseases as river blindness and elephantiasis in people and heartworm in dogs—also need the bacteria if their embryos are to develop properly. Antibiotic treatment of adult worms kills the embryos, rendering the adults sterile. This discovery has increased interest in the possibility that nematode diseases can be controlled with antibiotics [*see "The Worm and the Parasite," by T. V. Rajan, page 32*].

To study the details of *Wolbachia*'s capabilities, biologists have experimentally transferred the bacteria from one insect species to another. The method is similar to the microinjection techniques developed for in vitro fertilization: a needle containing the bacteria from one insect is injected into the egg of a different, uninfected species. Not surprisingly, perhaps, the "foreign" *Wolbachia* bacteria can have different effects in their new hosts. For example, in the adzuki bean borer moth *(Ostrinia scapulalis)*, *Wolbachia* turns a male host into a female. When the same bacteria are injected into the common flour moth *Ephestia kuehniella*, however, they simply kill the males.

Alerted to the newly recognized importance of *Wolbachia* in manipulating invertebrate reproduction, investigators are now discovering an en-

Fifty million years from now, Wolbachia *bacteria may, like the mitochondria before them, have evolved into a new kind of cell organelle.*

tire pantheon of sex-manipulating microorganisms that are transmitted from females to their offspring through eggs. A recent finding is a relative (as yet unnamed) of soil bacteria in the genus *Cytophaga.* Biologists have shown that the unnamed bacterium induces parthenogenesis in hosts as varied as wasps and mites, and is likely to be widespread.

Others await discovery. The genus *Rickettsia,* which is a member of the same family as *Wolbachia,* includes a number of disease-causing bacteria spread by arthropods, such as the microorganisms responsible for Rocky Mountain spotted fever and typhus. Recently, *Rickettsia* bacteria that are transmitted through eggs and cause male-killing have been identified. I anticipate that once additional discoveries are made, it will be clear that most members of the genus are engaged in distorting sex in arthropods, and that causing disease in vertebrates is a relatively uncommon trait. The widespread occurrence of reproductive parasites illustrates a basic principle: whenever a microorganism is inherited through the eggs of its host, it will be selected for its capacity to manipulate the host's reproduction in ways that enhance the microorganism's transmission.

An even more remarkable story than that of *Wolbachia* and other reproductive parasites belongs to the "microbes" present in nearly all plants and animals—the mitochondria. Flourishing in the cytoplasm of nearly all nucleated cells, mitochondria are specialized organelles, with their own DNA. They are the cell's power stations, generating energy for cellular metabolism. There is now overwhelming evidence that mitochondria evolved from a symbiotic bacterium during the early evolution of nucleated cells. In fact, on the basis of similarities in their DNA, biologists now think mitochondria and *Wolbachia* may be distant relatives.

The small parasitic wasp Trichogramma kaykai *deposits its eggs within the eggs of butterflies. Inside the ovaries of this wasp are* Wolbachia *bacteria that induce parthenogenetic development of the wasp eggs.*

Like *Wolbachia,* mitochondria are inherited through the cytoplasm, and therefore from mothers but not from fathers. And, like *Wolbachia,* mitochondria that skew the sex ratio of their "host" organisms toward females can be favored by natural selection. Biologists have demonstrated that in many plants, such as corn and rye, mitochondrial variants cause an abortion of the male parts of the plant, the pollen-producing anthers. The effect is known as cytoplasmic male sterility, and it leads to an increased production of seeds, which transmit the mitochondria. A contest ensues: plant genes evolve that suppress the renegade mitochondria, and new mitochondrial variants arise that can escape the new control.

As far as anyone knows, animal mitochondria do not play such games. The reason may be simply that animal mitochondria have much smaller genomes than their counterparts in plants, and therefore may not be able to draw from as rich a grab bag of genetic trickery. Fortunately for animals and plants, most of the time mitochondria are quite well behaved.

The comparison with mitochondria raises one final, tantalizing question about bacteria of the genus *Wolbachia.* Given their ubiquity, their adopted homes within the cells of other organisms, and their heritability through the eggs of their hosts, why haven't they evolved into organelles like the mitochondria before them? Perhaps it's only a matter of time before they do. If bacteriologists take a peek in, say, 50 million years, they might well find that *Wolbachia* bacteria have been tamed by some invertebrate group and have evolved into a new kind of cell organelle. What service that organelle might perform is anyone's guess. □

Tuff Crowd

Formations of volcanic rock dominate a landscape in southeastern Arizona.

By Robert H. Mohlenbrock

About 27 million years ago, in what is now the southeastern corner of Arizona, a volcano spewed out vast amounts of hot ash and pumice that fused into a 2,000-foot layer of rock known as rhyolitic tuff. Subsequent erosion has transformed the landscape into an incomparable collection of spires, chimneys, and balanced rocks. Located about thirty-five miles southeast of Willcox, Arizona, Chiricahua National Monument was established in 1924 to protect these formations. The botanist and author Janice Emily Bowers has described them imaginatively yet accurately: "chess pieces—pawns and castles, knights and bishops, kings and queens, all crowded together at one end of the chessboard."

When my wife Beverly and I pulled up to the entrance station of the monument, a cheerful and enthusiastic ranger asked if we had ever visited before. "About thirty years ago," I replied. "Well, nothing has changed much," the ranger told us. And she was right. The stone pillars and balanced rocks looked the same, of course, but that wasn't all. A raccoon-like coati scurried across the road and into the adjacent woodland, just as one did thirty years before. A Mexican jay was drinking from a catch basin at a public water fountain, just as Beverly remembered one doing three decades ago. And the thick-billed parrot, the only parrot whose native range once extended north of the Mexican border, was still nowhere to be seen (the species was extirpated from this locale in 1922, and predators have foiled attempts to reintroduce it). But I did notice that the trees lining the road had grown somewhat taller.

We followed the main park road, which winds about eight miles through Bonita Canyon and on up to Massai Point. The canyon is forested mainly with pines and junipers, but other trees grow along the streambed that the road follows for much of the way. (Water flows through the stream most predictably during the months

Rack formations and trees, viewed west from Massai Paint

For visitor information, contact:
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of July and August, when a shift in wind direction brings "monsoon" rains.) At the end of the drive we got a superb view of the rocks and pinnacles below.

On the way back we stopped in Bonita Canyon to hike the Natural Bridge Trail, which heads north for half a mile or so, then turns westward out of the canyon and enters an upland woods. About 120 acres here have been designated Picket Park. The ground cover, particularly on ridges that get the full brunt of the sun, is mostly chaparral, a community of drought-tolerant plants, often with leathery leaves that inhibit evaporation. Oak woodland predominates below the ridges, on rough, south-facing slopes where heavy exposure to the sun combines with steep terrain broken by columns, cliffs, and ledges.

Continuing our hike through Picket Park, we reached a zone where mixed conifer forest, with stands of rare Apache pine and Chihuahua pine, grows amid the rock formations. Finally we came to a pine and oak woodland nestled in a narrow, steep-walled canyon. At the canyon bottom is an impressive stand of Arizona cypress. From there the trail would have taken us south to a rock formation called Natural Bridge, but we decided it was time to turn back.

First-time visitors should be sure to follow the trail to Heart of Rocks for a close-up view of some of Chiricahua National Monument's most popular rock formations, with names such as Duck on a Rock and Punch and Judy [*see photograph on this page*]. Big Balanced Rock is perhaps the most famous (and most photographed) of all.

HABITATS

Streamside forest Along the streams and washes are Arizona sycamore, Fremont cottonwood, Arizona walnut, velvet ash, and Arizona cypress. Flowering herbs and shrubs include horsetail, seep willow, desert broom, threadleaf ragwort, desert willow, hummingbird trumpet, chokecherry, Apache plume, western white honeysuckle, mutton grass, and skunk-bush.

Chaparral Principal woody plants are alligator juniper, Emory oak, Mexican pinyon pine, Arizona cypress, and the shrubby Toumey oak, deerbrush, and mountain mahogany. Wildflowers, grasses, and flowering shrubs include woolly Indian paintbrush, bristlehead, rabbitbrush, turpentine bush, yellow hawkweed, threenerve goldenrod, dwarf desert peony, American threefold, pinyon ricegrass, century plant, Palmer's agave, and small palmleaf thoroughwort.

Oak woodland The primary woody plants are dwarfed and gnarly and include Toumey oak, silverleaf oak, Arizona white oak, netleaf oak, Emory oak, Mexican pinyon pine, and alligator juniper. Wildflowers and shrubs include longstalk greenthread (whose flowers resemble a dandelion head), Wright's beebrush, antelope sage, evergreen sumac, sotol, century plant, bear grass, ocotillo, cliff fendlerbush, turpentine bush, evergreen rock fern, and beggartick three-awn (a grass).

Mixed conifer forest Ponderosa pine, Douglas fir, and Arizona cypress are the dominant trees above layers of Apache pine, Chihuahua pine, pinyon pine, silverleaf oak, Emory oak, Arizona white oak, alligator juniper, Arizona madrone, and pointleaf manzanita. Among the wildflowers, flowering shrubs, and grasses are Chiricahua Mountain columbine, desert blazingstar, Santa Rita Mountain aster, plains blackfoot, southwestern cosmos, purple locoweed, Alpine false spring parsley, false Solomon's seal, showy goldeneye, cardinal catchfly, Huachuca Mountain geranium, satin bunchgrass, Wright's silktassel, and bear grass.


Punch and Judy

Pine and oak woodland usually occurs in canyon bottoms, which provide enough moisture for the growth of Arizona cypress, Arizona white oak, alligator juniper, netleaf oak, and silverleaf oak. Wildflowers and flowering shrubs include antelope horns, pineneedle beardtongue, dwarf false pennyroyal, Chihuahuan brickellbush, Missouri goldenrod, roving sailor, cliff fendlerbush, mutton grass, and Ross' sedge.

Robert H. Mohlenbrock is professor emeritus of plant biology at Southern Illinois University in Carbondale.

Tightening Our Kuiper Belt

From the edge of the solar system come hints of a disrupted youth.

By Charles Liu

More and more often, some new astronomical discovery is thrusting Pluto and its home, the Kuiper Belt, into the public eye. Most of the attention focuses on Pluto's status as one of our solar system's major planets. Should it retain that status, even though astronomers know Pluto really is just a ball of ice and rock, smaller than our Moon?

A few months ago the flames were fanned again, when Michael E. Brown and Chadwick A. Trujillo, both astronomers at Caltech, announced the discovery of a large new Kuiper Belt object (or KBO) that they dubbed Quaoar (after the creation force of the Tonga tribe who lived in the Los Angeles area). No one was calling Quaoar a major planet; it's only 800 miles wide. Yet Pluto—about 1,400 miles in diameter—isn't that much bigger than Quaoar, and Quaoar's orbit looks much more like the orbits of the other eight major planets than Pluto's does. Pluto-bashers everywhere hailed Quaoar as further proof that the runt of the traditional nine planets should be reclassified as just another KBO, albeit a large one.

But all the hoopla missed the scientific point. For many of us astronomers, it's not Pluto, Quaoar, or any other individual KBO that matters; it's the Kuiper Belt itself that counts. And if you take the Pluto-Quaoar episode as an occasion for a closer look at the Kuiper Belt, you get into some pretty intriguing scientific questions. For example, R. Lynne Allen of the University of British Columbia in Vancouver and her collaborators recently published findings that, though useless to the argument about what to call Pluto, suggest that the Kuiper Belt is a surprisingly sharp edge cinching our solar system five billion miles out from the Sun, and that it holds some clues to our solar system's early history.

Eva Lee, *Eyesites,* 2000

Named after the Dutch American astronomer Gerard Kuiper, one of the first people to posit its existence, the Kuiper Belt is a doughnut-shaped zone of space, populated by comets and comet-like bodies, which lies beyond the orbit of Neptune. KBOs are small—most are less than 100 miles across—and made up almost entirely of ice and rock. They're remnants of the solar system's early history, relatively unaltered by four and a half billion years of stellar and planetary evolution.

Someday astronomers will get the chance to study KBOs up close, and the objects will provide an unparalleled glimpse into the chemical and physical conditions of the early solar system. But the scientific value of the Kuiper Belt as a whole is even greater than the sum of the information in every icy dirt ball. The reason is that in the past decade or so, astronomers have discovered disks of dusty gas as large as 100 billion miles in diameter orbiting a number of stars much younger than, but otherwise quite similar to, our Sun. According to current astrophysical models, planets originate in these disks, and our solar system represents one possible outcome of the evolution of such a disk. The Kuiper Belt is probably what remains of the Sun's original disk, so its shape, size, and thickness serve as critical benchmarks for understanding how planetary systems form, grow, and age.

Neptune's orbit, a nearly circular ellipse some three billion miles away from the Sun, traces the Kuiper Belt's inner edge. The belt's outer edge is far less certain, though. Of more than 600 KBOs discovered to date, none of those with nearly circular orbits is more than roughly five billion miles from the Sun. That suggests the Kuiper Belt's outer boundary could well lie there. But the outer boundaries of the disks orbiting the younger stars I mentioned are as much as

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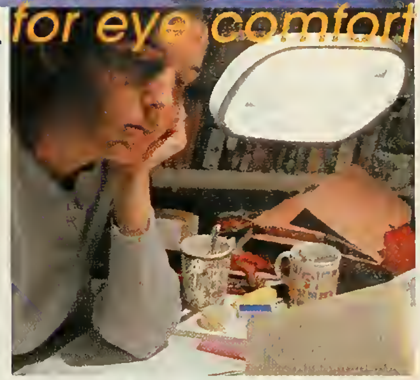

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twenty times farther away from their central stars. If the Kuiper Belt is what's left of such a disk around our Sun, why is it so small?

To resolve this discrepancy, astronomers have proposed a composite shape for the Kuiper Belt, with an inner part that bulges like a bagel, and an outer part that's thin like a dinner plate. According to that model, the belt extends a long way out, but the hypothetical KBOs that would allegedly make up the outer part of the belt haven't been discovered because they're confined to a narrow band—about the width of an outstretched pinkie—across the sky.

Enter Lynne Allen. To test the predictions of the model, she trained the four-meter telescope at the Kitt Peak National Observatory in Arizona on portions of the band of sky where the model suggested she would find the outer Kuiper Belt. Sure enough, she found dozens of new KBOs there to be sure, but none of them were more than five billion miles away. By Allen's calculations, the observations strongly suggest that the KBO distribution has a sharp boundary at that distance, and that a thin outer Kuiper Belt simply does not exist.

So the question remains: why is the Sun's Kuiper Belt so much smaller than the disks of other stars? One possibility is that, billions of years ago, our solar system suffered a major disturbance—perhaps a near-collision with a passing star—that chopped the outer regions off the Sun's circumstellar disk. If so, such a cropping would have directly affected the development of our entire planetary system. For one thing, a larger disk might have caused many more comet collisions early in Earth's history. If the passing-star scenario can be confirmed, it may show that the development of life on Earth was linked to a chance but crucial event in the history of the Kuiper Belt.

Charles Liu is an astrophysicist at the Hayden Planetarium and a research scientist at Barnard College in New York City.

THE SKY IN FEBRUARY

By Joe Rao

Swift **Mercury** shines low along the east-southeastern horizon about an hour before sunrise in the first week of February. The planet, as bright as magnitude −0.1, reaches its greatest western elongation from the Sun on the 4th, 25 degrees from the Sun's glare. For the rest of the month Mercury falls back toward the Sun and, as early as midmonth, is hopelessly lost in the morning twilight.

Brilliant **Venus** graces the dawn low in the southeast, though not quite so brightly as it did in January. The planet fades from magnitude −4.3 to −4.1 and sinks about 5 degrees lower into the sunrise. It has also entered its uninteresting season for telescopic observers; it looks like a small, featureless, gibbous Moon for the rest of the year. But Venus is still immensely brighter than any other point of light. Early risers in the first half of the month can enjoy watching the "teapot" of Sagittarius gliding below Venus in the starry background, then moving above and to the right of the planet as the weeks go by. On the morning of the 27th a waning crescent Moon appears on the southeastern horizon, well below and to the right of Venus.

Mars rises between 2:30 and 3:00 A.M. local time throughout the month, and is well up in the south-southeast by dawn. Shining at magnitude 1.3, the planet passes 5 degrees north of the first-magnitude star Antares on February 1, as it moves through the constellation Ophiuchus. Although Mars remains rather inconspicuous, its luminosity continually increases as the Earth's smaller, faster orbit brings the two planets closer. Mars reaches opposition in August, when it will be just 34,646,418 miles from the Earth, but in mid-February it's still 154 million miles away. Seen through a telescope, it presents a minute disk. A fat crescent Moon will be hovering well below and a bit to the left of Mars on the morning of the 25th.

Silvery white **Jupiter**, low in the east this month as the sky darkens at sundown, dazzles the eye at magnitude −2.6. Jupiter is at opposition to the Sun on February 2; it rises at sunset, stands highest in the south at midnight, and sets at dawn. At dusk on the 15th, Jupiter climbs the east-northeastern sky alongside the Moon, which is just one day from full.

Saturn, in the eastern part of the constellation Taurus, is high toward the south in the early evening hours. It sets in the west at around 4 A.M. at the beginning of the month and about two hours earlier by month's end. At magnitude −0.2, Saturn carries on its grand show for viewers with telescopes, as the great ring system continues to tilt steeply toward Earth. Late on the night of February 11, the Moon appears to pass less than 3 degrees to the north of Saturn.

The **Moon** is new on February 1 at 5:48 A.M. It reaches first quarter on the 9th at 6:11 A.M., full on the 16th at 6:51 P.M., and last quarter on the 23rd at 11:46 A.M.

Unless otherwise noted, all times are given in Eastern Standard Time.

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REVIEW

The Curious Energy of the Void

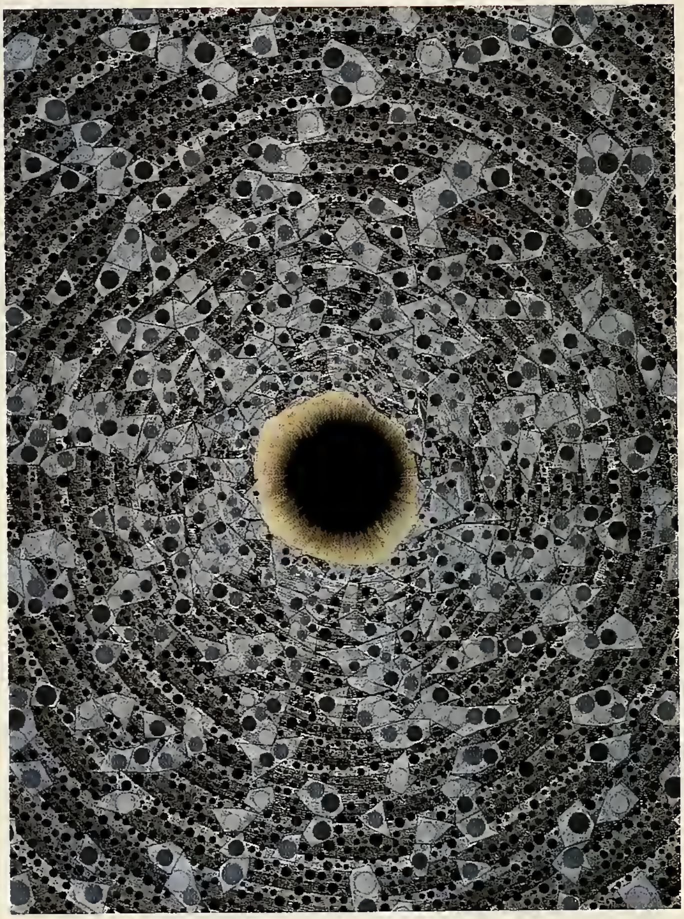
Dark energy is making the universe bigger and bigger, faster and faster.

By Donald Goldsmith

In February 1998 new observations of exploding stars in distant galaxies stood the world of cosmology on its ear. The expansion of the universe, far from slowing down, as earlier theories had implied it should, turned out to be speeding up. Objects in the universe are moving apart from one another at progressively greater speeds. The new findings foretell a future in which the cosmos becomes an unimaginably vast, cold, dead, and barren expanse of near-nothingness.

How did astronomers reach such a startling conclusion?

In 1916 Einstein, shortly after completing the formulation of his theory of general relativity, discovered that the solutions to a key equation within the theory implied that the universe must always be either expanding or contracting. Einstein's pencil-and-paper discovery took him by surprise, because astronomers of the era had no evidence to suggest that the universe either expands or contracts. To fix what he then took to be an error, he restated his key equation with an additional, constant term—which quickly became known as the cosmological constant. If the constant had precisely the right value, Einstein wrote in 1917, the universe could exist in a state of perfect, static balance.



Andrea Way, *The Holy Tree*, 1997

The Extravagant Universe: Exploding Stars, Dark Energy, and the Accelerating Cosmos
by Robert P. Kirshner
Princeton University Press, 2002; $29.95

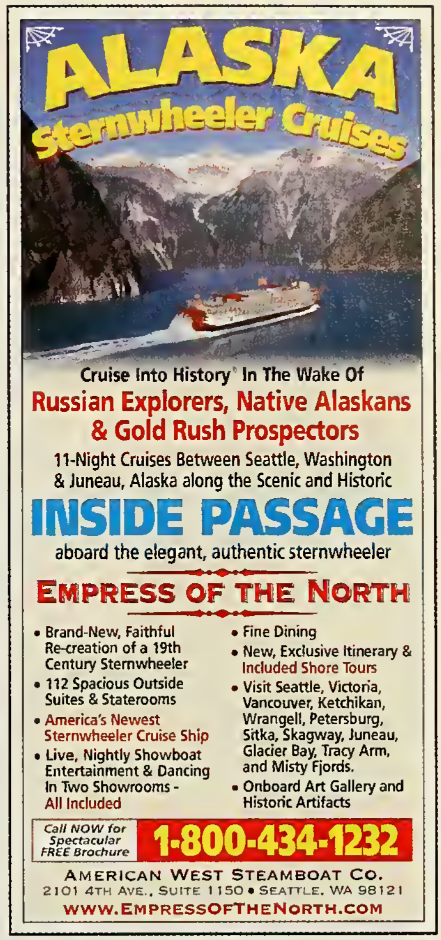
But the Russian mathematician Alexander Friedmann soon demonstrated that such a static universe must be balanced, as it were, on a knife edge: the slightest tremor would topple it over in one direction or the other, into a state of either expansion or contraction. Another, even more serious objection to Einstein's solution appeared in 1929, when Edwin Hubble discovered that the cosmos is indeed expanding. On distance scales as large as the ones between clusters of galaxies, all objects are moving away from all other objects at speeds that increase in proportion to the distances between them. (Cosmologists imagine the expanding universe most simply as the three-dimensional analogue of the skin of a balloon. As the balloon expands, every point on the skin of the balloon moves away from all others, yet no one point is motionless.) Einstein soon pronounced the cosmological constant a dead letter, calling it his "greatest blunder."

The results announced in 1998 effectively resurrected Einstein's "blunder." Those observations included two kinds of measurements: first, the distances to certain kinds of supernovas, or exploding stars, that astronomers discovered in distant galaxies; and second, the speeds with which those galaxies are receding from us. But when astronomers tried to describe the relation between those distances and speeds, they found they had to restore Einstein's full equation from 1917, including a nonzero cosmological constant.

The value that the 1998 observations imply for the cosmological constant is not equal to the value Einstein adopted to keep the universe static—after all, the two kinds of universe could hardly be more different. But the fact that the recent observations require a nonzero value for the constant carries a tremendous implication: Every cubic centimeter of what seems to be empty space instead teems with hidden energy, which astronomers now call dark energy. As the universe expands from its origins in the big bang, more space continuously comes into being, and so the total amount of dark energy also increases proportionately. The ever-growing amount of dark energy progressively accelerates the universal expansion. Although gravity acts in the opposite sense, tending to slow the expansion because all matter in the universe attracts all other matter, the expansionist tendency of the dark energy has now become dominant. The cosmos has entered a phase of accelerating expansion.

Such a striking result should be accepted with caution. Astronomers have spent years determining the distances and velocities of remote galaxies. Although the galaxies' velocities can be found relatively easily by measuring the shift in the colors of their light, finding their distances has proved much more difficult. In fact, astronomers could make only fairly crude estimates of the distance to any faraway galaxy—until they identified a marvelous type of exploding star called a type Ia supernova (or SN Ia for short).

Like the light from other exploding stars, the apparent brightness of a type Ia supernova grows for a few days, reaches a peak, and then fades away



over several months' time. But unlike other supernovas, all type Ia supernovas at their brightest generate nearly the same amount of energy per second. Thus they furnish astronomers with "standard candles," objects that are almost identical in their intrinsic luminosities. If observers can identify two such supernovas in different galaxies, measuring how bright they appear at their peak outputs is enough to calculate their relative distances. For example, if one SN Ia appears four times as bright as another, the fainter supernova must be twice as distant as the brighter one (by simple geometry, the brightness decreases with the square of the distance).

This method works only if astronomers can identify exploding stars as members of the SN Ia class and can control for the fact that, even within that class, some variation does exist. Beginning in 1995, two competing groups of astronomers have been obtaining brightness measurements of type Ia supernovas to analyze the expansion of the universe.

At first the findings of the two groups contradicted each other, leading to suspicions within each group that the data from the other group were flawed. The cause of science could hardly ask for more favorable circumstances. There is probably no better way to check the accuracy of one group's results than to pit that group against another, particularly if the second group suspects the first of promulgating grievous errors. In this case, happily, the results converged. As improved techniques began to eliminate the differences in the observational data, both groups concluded that their measurements could be explained only if the universe has a nonzero cosmological constant.

Robert Kirshner, a supernova expert at Harvard, has written an excellent insider's account of the race to discover the fate of the cosmos. In *The Extravagant Universe* Kirshner skillfully weaves the details of his career—which brought him to the leadership of one of the SN Ia observer groups—into the larger cosmic story. Along the way he pauses to describe a host of astronomical phenomena, from the life cycles of stars to the effect of the cosmological constant on the universe's expansion.

Kirshner shows an impressively deft touch with complex explanations, and he doesn't hesitate to bridge gaps in the reader's knowledge with an apt metaphor. For example, one of the constraints on the synthesis of every element heavier than helium is that no atomic nucleus only slightly heavier than helium is stable in nature. As a result, no natural process can make the heavier elements by adding protons or neutrons one by one to a helium nucleus. How then do stars succeed in doing so? As Kirshner puts it, they "skip across that gap, as improbably as crossing a stream by stepping on a salmon, to fuse three helium nuclei into a single carbon nucleus." The image may not exactly explain the phenomenon, but it remains satisfyingly in mind.

The Extravagant Universe presents an intriguing history of how supernova observers discovered the accelerating universe. But the full story of the acceleration has another crucial aspect. In 1999 and 2000, radio astronomers announced that entirely independent observations—made by radio telescopes studying the faint glow from the early universe known as the cosmic microwave background (CMB)—likewise imply a nonzero cosmological constant. Hence they, too, imply an accelerating universe.

The new data are arguably even more fundamental than the observations of distant supernovas. Not only do they reveal an accelerating universe; they also record how the amount of radiation generated by the universe in the earliest years of its expansion varies in different directions in space. By measuring those variations astronomers can determine how strongly space is curved. The amount of curvature depends on the sum of

PHOTOGRAPHY & ART

Dodo: A Brief History, *by Errol Fuller (Universe Publishing, 2002; $22.50)*
No extinct animal is less extinct as a cultural icon than the dodo. Missing from the Earth since the late seventeenth century, the flightless bird from Mauritius lives on in historical accounts, literary sources, and popular myths, many gathered together in Fuller's sumptuous book. They fill in admirably for the dearth of evidence about the real thing.

the dark energy and the energy locked up in all the matter in the universe—the second of which, at least in theory, is equivalent to the energy given by Einstein's famous formula $E = mc^2$. Hence measuring the variations in the cosmic microwave background can help determine the amount of dark energy in the universe.

The supernova observations, in contrast, give the difference between the amount of dark energy, which accelerates the expansion of the universe, and the amount of matter, whose mutual gravitational attraction slows it down. In the best of all worlds, combining the results from the radio and the supernova observations will give an accurate measurement not only of the amount of dark energy but also of the amount of matter—most of which, as it happens, is made up of a completely unknown form called dark matter.

Kirshner deals only in passing with the CMB observations, yet those data are highly relevant to the story because they have sharply increased astronomers' confidence that the cosmic expansion is accelerating. A further exploration of that story, however, would require another book. *The Extravagant Universe* delivers the promise of its subtitle extremely well, and should serve as the definitive insider's story of how Kirshner led his motley group of astronomers to glory in their search to find the fate of the universe. Nothing now remains for cosmology—except to explain why the universe has turned out the way it has. That's a big challenge for our new century, but, given the remarkable successes so far, it may prove to be well within our grasp.

Donald Goldsmith, an astronomer and science writer, won the 1995 Annenberg prize, given by the American Astronomical Society for outstanding contributions in popularizing astronomy. His most recent books on cosmology are Einstein's Greatest Blunder? *(Harvard University Press) and* The Runaway Universe *(Perseus Books).*

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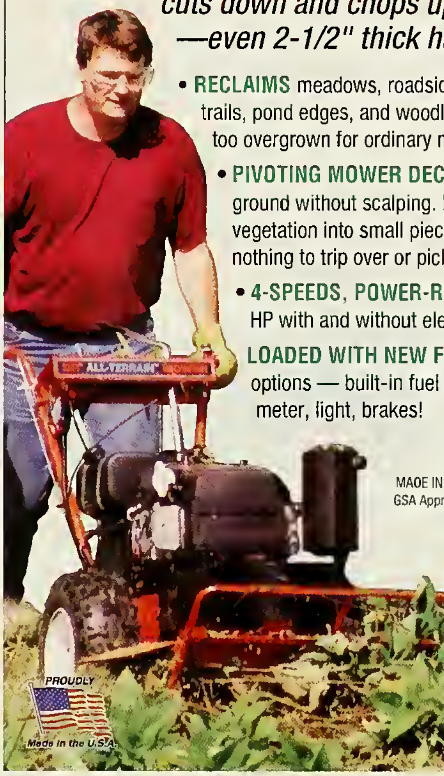

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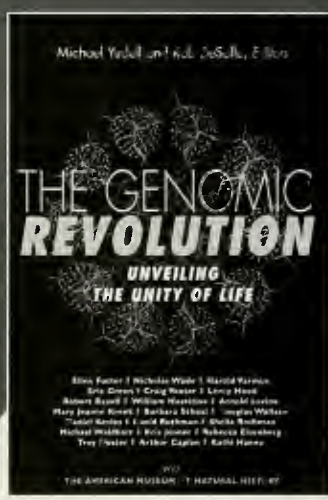

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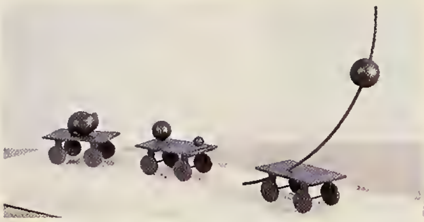
Scaling Down

By Robert Anderson

It's a pretty safe bet that you're never going to travel more than a few thousand miles from home—how could you, without becoming an astronaut and leaving the Earth itself? So how can you hope to get an intuitive grasp of the size of the solar system? Given the distances, measured in millions and billions of miles, my guess is it's nearly impossible. You might as well try to conjure a visceral sense of geologic time—surely a quixotic exercise, when you think about the seconds ticking by as life evolves from jellyfish to human.

But still, you can try. And if you have any interest in astronomy, the wow factor is well worth the effort of thinking about how the solar system would scale down to a more manageable size. Now the Exploratorium in San Francisco has introduced a Web site (www.exploratorium.edu/ronh/solar_system/index.html) that will blast you off to a great start. You type in how big you want your model sun to be, and the site does the rest, calculating the size of each planet and its distance from the Sun. I typed in 9.5 inches for my model, the diameter of a basketball, and was surprised to learn that the Earth would be the size of a peppercorn, eighty-five feet from the Sun, and Pluto would be almost two-thirds of a mile away. The Web site also calculates such things as the distance to Alpha Centauri—after the Sun, the nearest bright star. On my chosen scale its distance would be 4,351 miles. Much beyond that, though, and the model quickly becomes almost as unmeaningfully large as the real thing.



Richard E. Prince, *The Wand'ring Planets*, 2002

If you want to find out about large-scale solar system models, check out the links at the bottom of the Exploratorium Web page. My favorite, the most ambitious project in North America but still a work in progress (unless more funding can be found), has been laid out across 200 miles of central Kansas (www.fhsu.edu/solarsystem/). The planets are roughly aligned along Interstate 70, running east from the city of Hays, where the enormous dome of the Sternberg Museum of Natural History stands in for the Sun. A project much closer to completion can be found in northern Maine (www.umpi.maine.edu/info/nmms/solar/index.htm), where three-dimensional scale models of the planets adorn forty miles of U.S. Route 1, from Presque Isle to Houlton.

Robert Anderson is a freelance science writer living in Los Angeles.

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UNIVERSE

(Continued from page 29)

ment number 95 is americium; number 98 is californium; number 103 is lawrencium, for Ernest O. Lawrence, the American physicist who invented the first particle accelerator.

Ever-larger accelerators reach ever-higher energies, probing the fast-receding boundary between what is known and what is unknown about the universe. The big bang theory of cosmology asserts that the universe was once a very small and very hot soup of energetic subatomic particles. With a super-duper particle smasher, physicists might be able to simulate the earliest moments of the cosmos. In the 1980s, when U.S. physicists proposed just such an accelerator (eventually dubbed the Superconducting Super Collider), Congress was ready to fund it. Plans were drawn up. Construction began. A circular tunnel fifty-four miles around was dug in Texas. Physicists were eager to peer across the next cosmic frontier. But in 1993, when cost overruns looked intractable, a fiscally frustrated Congress permanently withdrew funds for the $11 billion project. It probably never occurred to our elected representatives that by canceling the Super Collider they surrendered the U.S. primacy in experimental particle physics.

If you want to see the next frontier, hop a plane to Europe, which seized the opportunity to build the world's largest particle accelerator and stake a claim of its own on the landscape of cosmic knowledge. Known as the Large Hadron Collider, the accelerator will be run by the European Laboratory for Particle Physics (better known by an acronym that no longer fits its name: CERN). Although some American physicists are collaborators, the U.S. as a nation will watch the effort from the sidelines.

Astrophysicist Neil deGrasse Tyson is the Frederick P. Rose Director of the Hayden Planetarium in New York City and a visiting research scientist at Princeton University.

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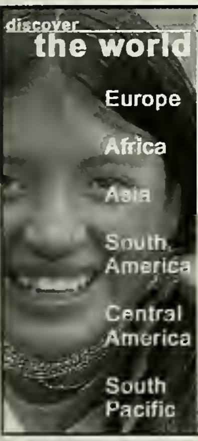

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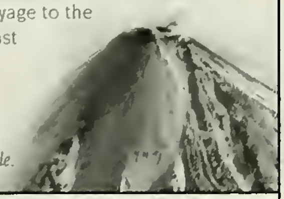

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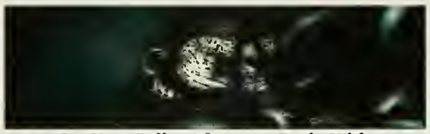

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AstroBulletin Showcases Cutting-Edge Research at the South Pole

RANDY LANDSBERG

Vivian Trakinski and Jason Lelchuk celebrate their arrival at the South Pole, which is designated by the marker in the foreground.

For decades, cosmology, the study of the origin and evolution of the universe, garnered little support within the scientific community because few believed there was enough direct evidence to support such inquiry. Today, however, it is generally agreed among both astronomers and physicists that the universe was created some 10 to 20 billion years ago in an explosion dubbed the "Big Bang."

But how can we know about an event that took place so long ago? The cosmic microwave background (CMB)—called a "background" because it is detectable from every direction across the sky—is a whisper of microwave radiation, a vast curtain of energy. By identifying and observing the CMB, scientists are able to draw conclusions about the distant history of our universe, as far back as its creation. The pervasiveness and uniformity of the radiation throughout the universe suggests that it remains from a time when the universe was significantly hotter and denser than it is now, supporting the notion of a Big Bang–type origin.

Scientists from the University of Chicago's Center for Astrophysical Research in Antarctica (CARA) are studying the CMB at the Amundsen-Scott South Pole Station. Taking advantage of Antarctica's long winters, dry conditions, and endless sky, they are making what are arguably the most detailed measurements ever of the CMB, thereby building a body of data that will increase our understanding of the origin and evolution of the universe.

In December 2001, Vivian Trakinski and Jason Lelchuk, members of the Museum's Science Bulletins production team, journeyed to the South Pole to visit the scientific team working there. Their short film, *Cosmic Microwave Background: The New Cosmology,* takes viewers to this forbidding place and shows how scientists are unraveling the story of the universe.

Produced as part of the Rose Center's AstroBulletin program, *Cosmic Microwave Background: The New Cosmology* will be screened at the Museum during regular Museum hours through June 2003 in the Black Hole Theater of the Frederick Phineas & Sandra Priest Rose Center for Earth and Space's Dorothy and Lewis B. Cullman Hall of the Universe. More information about the CMB will be featured on AstroBulletin kiosks in the Cullman Hall of the Universe.

The AstroBulletin employs high-definition video, computer animations, and images from satellites, observatories, NASA, and the Hubble Space Telescope to dramatize cosmic events, explain astronomical concepts, and report recent discoveries in the field of astrophysics. *Cosmic Microwave Background: The New Cosmology* and other elements of the AstroBulletin are made available to museums, science centers, planetariums, and other public spaces nationwide and around the world.

The AstroBulletin is generously supported by Toyota Motor North America, Inc. Significant educational and programming support is provided by the National Aeronautics and Space Administration (NASA).


D. FINNIN AMNH

AN INTERVIEW
with Ian Tattersall

Co-curator of *The First Europeans: Treasures from the Hills of Atapuerca*

Ian Tattersall is Curator in the Division of Anthropology and author of many books on human evolution including, most recently, The Monkey in the Mirror: Essays on the Science of What Makes Us Human.

Q: What is the significance of this exhibition?

This is the first time outside Spain that this extraordinary material that documents the very earliest attempt by human beings to occupy Europe has been on display.

There are two sites at Atapuerca. One is literally a hole in the ground that's filled with human bones that are thought to be about 400,000 years old. This is the Sima de los Huesos site, or the Pit of the Bones.

There is another site, only half a mile away, called Gran Dolina [where] an enormous sequence of archaeological deposits was exposed. Low down in that sequence were found human bones that are about 800,000 years old, twice as old as the other hominids at the Sima. It's just pure coincidence that these two extraordinary sites are so close to each other.

Q: How does this material fit in with the human fossil record?

We tend to think of human evolution as having been a kind of a single-minded slog from primitiveness to perfection. And it really was not like that at all. It was instead a matter of new species going out into the environment and competing with other life forms, and succeeding or failing and going extinct.

This material that we'll have on display is some of the best evidence that we have for this pattern in human evolution. I think that the earliest material we're going to have on display [from Gran Dolina] was the product of a failed attempt by an early human species to colonize Europe. And the later material is closely related to the Neanderthals who were a species that lost out when *Homo sapiens* finally entered Europe. So here are two separate attempts to be a European, as it were.

Q: You mentioned the Sima de los Huesos, or Pit of the Bones. Why is this site so unusual and intriguing?

Human fossils are not that common and this particular site is the most astonishing concentration of human fossils that has been found anywhere in the world.

Hellish conditions, by the way. Absolutely hellish, horrible, cramped, at the bottom of this shaft in the ground. You have to walk 700 yards into a cave through dark passages in the pitch dark and over a rough floor. And then you have to descend 50 feet vertically down a shaft in the dark 'til you come to a slope that leads down even further into the cavity where these bones collected.

Q: What do these hominids teach us about ourselves or about what it means to be human?

What it mainly teaches us is what a special phenomenon *Homo sapiens* is. There's something qualitatively different about *Homo sapiens* compared to any previous hominid species. I think it's important to understand that we weren't gradually burnished by evolution to do what we do superbly well. We are more like an accidental product that happens to have all these new cognitive capacities and we're still exploring the ways in which they can be used.

Q: You use both the terms "humans" and "hominids." What's the distinction?

There is no universally agreed definition for what "human" means. The word was invented before people knew anything about the apes, let alone before anybody had any concept that we had close extinct relatives. So "human" is a very elusive term. And we do all tend to use it a little loosely—I certainly tend to use it rather loosely. I don't think that it matters, just as long as we realize that what is human is contextual, is something that we sort of intuitively recognize rather than rigorously define. In the strictest sense none of the Atapuerca people were human; but there is something that we can recognize as humanity in all of them.


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THE FIRST EUROPEANS:
Treasures from the Hills of Atapuerca

Through April 13, 2003

The First Europeans will reveal the mysteries of ancient humans in western Europe through exquisitely preserved hominid and animal fossils—some up to one million years old—found in the hills of Atapuerca in the Spanish region of Castilla y León. This remarkable exhibition provides Americans their first-ever glimpse of these "first Europeans," and explores what their existence teaches us about what it means to be human today.

Co-organized by the American Museum of Natural History and Junta de Castilla y León

MUSEUM EVENTS

EXHIBITIONS

Einstein
Through August 10, 2003
Gallery 4, fourth floor
This exhibition profiles this extraordinary scientific genius, whose achievements were so substantial and groundbreaking that his name is virtually synonymous with science in the public mind.

Organized by the American Museum of Natural History, New York; The Hebrew University of Jerusalem; and the Skirball Cultural Center, Los Angeles. Einstein *is made possible through the generous support of Jack and Susan Rudin and the Skirball Foundation, and of the Corporate Tour Sponsor, TIAA-CREF.*

The Butterfly Conservatory: Tropical Butterflies Alive in Winter
Through May 26, 2003
The butterflies are back! This popular exhibition includes more than 500 live, free-flying tropical butterflies in an enclosed tropical habitat where visitors can mingle with them.

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R. MICKENS/AMNH

Remains of a Rainbow: Rare Plants and Animals of Hawaii
Through March 2, 2003
Color and black-and-white photographs of Hawaii's endangered species.

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Under Antarctic Ice
Through March 2, 2003
Spectacular large-format photographs by one of the world's leading underwater photographers, Norbert Wu.

This exhibition is made possible by the generosity of the Arthur Ross Foundation. Developed by Norbert Wu Productions and produced by the Pacific Grove Museum of Natural History.

PERFORMANCES

Einstein and Love
Friday, 2/14, 7:30–9:00 p.m.
Join the "Physics Chanteuse" for a Valentine's Day show that pays tribute to the life and loves of Einstein while exploring physics and more.

Cosmic Cabaret
Sunday, 2/16, 2:00–3:00 p.m.
This vaudeville act for a family audience weaves music and magic with the latest research and theories in physics.

WORKSHOP

Hands-On Einstein
Saturday, 2/8
11:30 a.m.–1:00 p.m. (adults)
2:00–3:30 p.m. (teens, ages 14–17)
Explore the basic physical and mathematical properties of gravity and space-time.

EINSTEIN FOR EVERYONE

The Sun and Its Energy
Saturday, 2/1, or Sunday, 2/23
1:30–3:00 p.m.
Learn about the Sun and how much we depend on it. (Ages 7–9)

An Expedition into Space-Time
Sunday, 2/2, 10:30 a.m.–12:00 noon
Observe a cosmic ray, play with a laser, and learn about black holes. (Ages 7–9)

Adventures in Light!
Sunday, 2/2, or Saturday, 2/22
1:30–3:00 p.m.
You're never too young to start playing with light! (Ages 4–6, each child with one adult)

CHILDREN'S ASTRONOMY PROGRAMS

Journey through the Solar System
Three Wednesdays, 2/5–19
4:15–5:45 p.m. (Ages 10–13)

Space Explorers
Telescope Star Party
Tuesday, 2/11, 4:30–5:45 p.m.
(Ages 12 and up)

A Taste of Things to Come!

To whet your appetite for the exhibition *Chocolate,* opening at the Museum on June 14, the Museum Shop introduces a full selection of Godiva chocolates, just in time for Valentine's Day. Visit the Main Shop and also pick up a copy of the exhibition's delicious companion book, *Chocolate: The Nature of Indulgence.*

GLOBAL WEEKENDS

Black History Month
Movement '63: The Pinnacle of the Civil Rights Struggle in America
Saturday, 2/1–22, 1:00–5:00 p.m.
Films, discussions, and performances of spoken word, poetry, dance, and music honor this explosive period in American history.

HAYDEN PLANETARIUM PROGRAMS

The Train Station at the End of the Universe
Sunday, 2/9, 12:00–3:00 p.m.
Grand Central Terminal, with its breathtaking starry ceiling, will serve as the backdrop for this discussion of selected concepts in astronomy. Wear comfortable walking shoes.

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Grand Central Terminal

Celestial Highlights
Tuesday, 2/25, 6:30–7:30 p.m.
This monthly tour of the heavens offers a view of the constantly changing night sky.

Courses
Using a Telescope
Four Mondays, 2/3–3/3, 6:30–8:30 p.m.
This course covers the basic functioning of telescopes as well as locating celestial objects and using charts and other aids for observation.

The Science of the Rose Center
Five Tuesdays, 2/4–3/4, 6:30–8:30 p.m.
Join five of the scientists who developed the Rose Center's content on an in-depth exploration of the planets, stars, galaxies, and the universe.

SPACE SHOWS

The Search for Life: Are We Alone?
Narrated by Harrison Ford. Every half hour Sunday–Thursday and Saturday, 10:30 a.m.–4:30 p.m.; Friday, 10:30 a.m.–7:30 p.m.

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Homing Instinct

By Jeff Fair

By the time I hired on to survey the common loon population of northern New Hampshire, back in 1978, bald eagles were long gone as a nesting species. Shot as predators, trapped for the taxidermy trade, left homeless as, one by one, their ancient nesting trees were sawed out from under them, and then poisoned inadvertently to the brink of extermination by insecticide, our national symbol had little reason to stick around. The last pair of bald eagles in New Hampshire had nested near the top of a huge old white pine tree near the western shore of Lake Umbagog. They laid their final clutch of eggs in 1949, then disappeared.

Years passed. Sometime in the late 1960s that last eagle nest, long-empty and derelict, tumbled out of its tree and crashed to the ground.

More years passed. Occasionally an eagle appeared near Lake Umbagog. Observations became more frequent. By 1981 I was spotting bald eagles during many of my surveys around the lakeshore, their white heads and tails glowing like spotlights against the dark alder and fir. Sometimes one would perch in the old "eagle tree."

In 1987 a raptor biologist working on Lake Umbagog observed a bald eagle with a yellow tag in its wing. The tag identified the bird as a male abducted in 1984 from a nest in Alaska and released in New York State as part of the eastern recovery effort. He seemed quite willing to resettle here: by 1988 he was seen regularly in the company of an adult female. That was the summer I heard voices from a tree.

I was in my canoe near the shoreline of a quiet backwater, more than a mile from the lake and the eagle tree, searching for the nest of a pair of loons I had been tracking all summer. Suddenly I heard the English language issuing forth from the top of a tall pine nearby. I paddled over to investigate. The tree became very quiet. After a few minutes, a human form descended the tree trunk. I observed that she was none too happy at being discovered.

Somewhat reluctantly she explained that a small team from the Audubon Society was constructing a nest replica to entice the new eagle pair. The tree seemed a safer site for a new eagle nest than the exposed top of a tree on the lakeside, where the team feared duck hunters might shoot the eagles, or (far more likely, I thought) bird-watchers might love them to distraction. Regardless, the initiative under way above us was an act of wildlife management, highly classified, and I was sworn to secrecy.

I never did find the loon nest, but late that summer we saw the eagles carrying sticks, and we knew something was happening. By the following spring they had finished installing a huge and ungainly pile of branches near the top of a tall white pine—not the tree that had been chosen for them, but the very same tree where the last active eagle nesters had made their home in 1949.

Three-week-old eagle chicks in the "eagle tree" nest on Lake Umbagog

How did a young eagle, hatched a continent away and belonging to a species that had not nested in these parts in four decades, come to choose the eagle tree? We may never know the answer. It is enough for now to observe, in a time of population modeling and species management, that these patterns of resilience, of hope itself, are carried within the individual: a young eagle, an ancient pine, perhaps even a dutiful field biologist, kneeling in his canoe.

Jeff Fair has visited New Hampshire's Lake Umbagog every year since 1978 to count loons and listen for voices in the trees.

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