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SCIENTIFIC AMERICAN PRESENTS

EXTREME ENGINEERING

Volume 10, Number 4, Winter 1999

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The Big, The Small

ABOUT THE COVER: The Citicorp Center, New York City (915 ft). Photograph by Norman McGrath.

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PHOTOGRAPH BY IAN LAMBOT


The Bank of China Tower, Hong Kong (1,209 ft)

The Powerful, The Strong, The Fast

The Tall, The Deep, The Long

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ENGINEERING AT THE

What drives us to reshape our world—to build taller buildings, faster vehicles, smaller computer chips? Is it something innate that pushes us past the limits, helping us to redefine the boundaries of what is possible? The history of civilization is filled with the challenge, the daring—and at times the sheer audacity—of innovative engineering, with each advance enabling countless others. This proud lineage is a testament to our imagination and ingenuity, reaffirming the very qualities that make us human. Here we present our choices for the most noteworthy human achievements. —*The Editors*

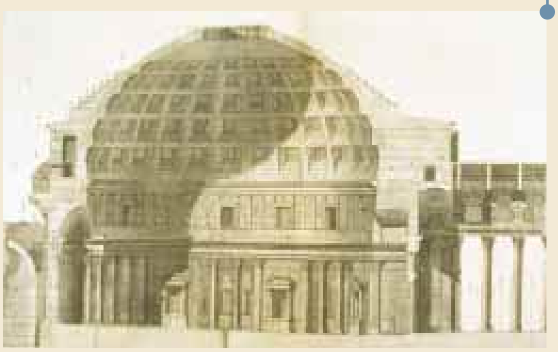
Agriculture appears to have developed simultaneously between 10,000 and 7000 B.C.E. in several parts of the world, as people who had been gathering wild plants began cultivating them (*left:* rock painting from Tassili N'Ajjer, Algeria, circa 6000–2000 B.C.E.). Cereals and legumes were among the earliest plants raised by humans. The domestication of animals most likely started around this time as well.

As early as the third millennium B.C.E., large-scale **irrigation systems** in Egypt and Mesopotamia diverted floodwater for use in agriculture. Around this time, many Mesopotamian farmers also began using a "noria" (*above*)—an animal-driven horizontal wheel that turned a half-submerged vertical wheel equipped with buckets, thereby lifting water into an irrigation channel. The so-called overshot **waterwheel,** developed before the first century B.C.E., reversed the principle of the noria: falling water turned a vertical wheel and produced mechanical energy. The enormous Roman water mill at Arles in southern France incorporated 16 overshot wheels to generate 30 horsepower, enough energy to grind grain for a city of 10,000.

2.6 MILLION YEARS AGO 7000 B.C.E. 5000 B.C.E. 3000 B.C.E. 2000 B.C.E. 200 C.E.

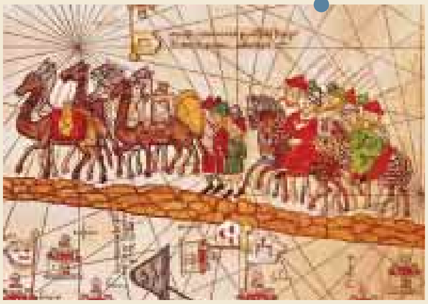
The earliest **stone tools,** discovered in eastern Africa, date to about 2.6 million years ago. Most are simple rock fragments from which *Homo habilis* removed flakes to form an edge. Sharper and more effective tools, such as this 700,000-year-old hand ax found at Olduvai Gorge in Tanzania, began to appear around 1.6 million years ago.

Sometime before 5000 B.C.E., humans first removed a metal—copper—from its ore through the **smelting process.** Humans eventually learned to smelt other metals and to combine different metals to form alloys.



Although **arches** appeared in Egypt and Greece during the middle of the second millennium B.C.E., it wasn't until the Romans adopted them that their full potential was realized. The Roman arches allowed for lighter construction over larger open spaces. Roman builders were also successful in constructing enormous **domes** (actually arches in three dimensions) such as that of the Pantheon (*above*), completed in 124 C.E. The nearly 170-foot diameter of the Pantheon's dome was made possible by using concrete (a lighter alternative to stone, developed in the first century B.C.E.) and by making the walls thicker and heavier near the base.

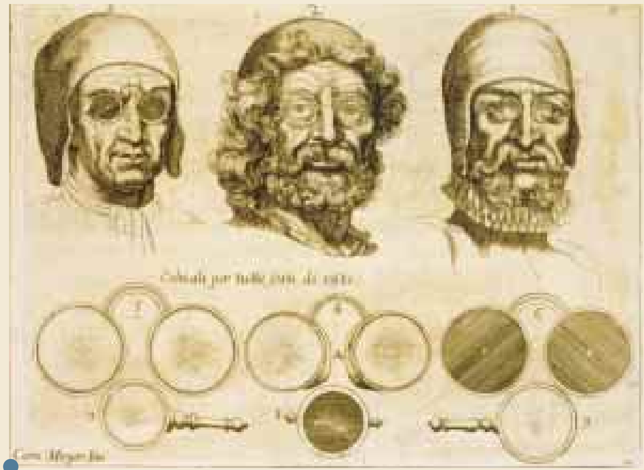
During its zenith around 200 C.E., the **Silk Road** was the longest road in the world, spanning an estimated 7,000 miles, from Xi'an in central China to the western Mediterranean. Venetian explorer Marco Polo utilized the road during his 13th-century C.E. travels (*below*). In addition to its important commercial role as a trade route, the Silk Road was a conduit for the exchange of ideas and technology between the Hellenistic (and later Christian) world and China, India and the Middle East. By the 15th century, with the development of navigational equipment and more reliable ships, the Silk Road had been replaced by nautical trade routes.



EDGE OF THE POSSIBLE

The horse was probably domesticated by nomads in what is now Ukraine around 2700 B.C.E., but not until the invention of the horseshoe, the padded horse collar and the stirrup did the horse become indispensable for warfare, transport and agriculture. The **metal stirrup,** used in China and Mongolia by the fifth century C.E., provided a tremendous military advantage to the horse-riding Mongols who conquered much of Asia during the 13th century.

Lenses existed in China as early as the 10th century C.E., but it was not until the 1300s that spectacles to correct farsightedness appeared in both China and Europe. Lenses to correct nearsightedness were developed in the beginning of the 16th century. Dutch naturalist Antonie van Leeuwenhoek observed bacteria with a single-lens microscope in 1674; Galileo Galilei used two lenses as a telescope in 1610 to discover four of Jupiter's moons. Traditional optical techniques reached their limits with the construction of devices such as the 1897 one-meter-refractor telescope at Yerkes Observatory and the 1948 five-meter-reflector telescope at Palomar Observatory. Only with new technologies, such as those for fabricating and supporting mirrors, have contemporary telescopes superseded the early ones in accuracy and resolution [see "Seven Wonders of Modern Astronomy," on page 42].



J. READER *Science Photo Library/Photo Researchers* (*stone tool*); ERICH LESSING/ART RESOURCE, NY (*rock painting; early gun*); CENTRAL ST. MARTINS COLLEGE OF ART AND DESIGN, LONDON/BRIDGEMAN ART LIBRARY (Pantheon from "Vedute," 1756, by Piranesi); R. ERGENBRIGHT *Corbis* (*waterwheel*); BRITISH LIBRARY, LONDON/BRIDGEMAN ART LIBRARY (Catalan Atlas, 1375) (*Silk Road*); CORBIS/BETTMANN-BARNEY BUSTEIN (*horsemen*); Bakhshālī manuscript (*Hindu numerals*); THE STAPLETON COLLECTION/BRIDGEMAN ART LIBRARY ("Spectacles for All Strengths of Vision," by Cornelis Jansz Meyer) (*lenses*); C. PURCELL *Corbis* (*seal*)

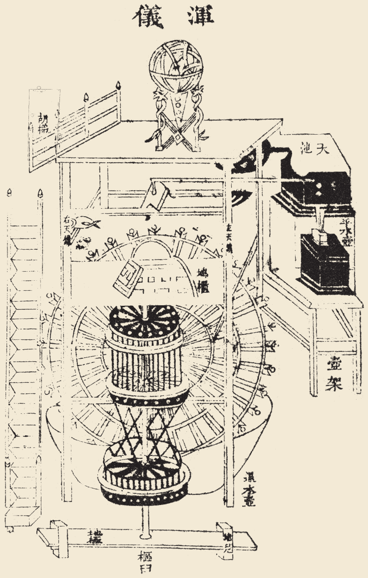
400 C.E. 650 C.E. 300 B.C.E. TO 1600 C.E. 900 C.E. 950 C.E. 1040 C.E.

Built in stages between the third century B.C.E. and the 17th century C.E., the **Great Wall of China** was constructed to repel invaders from the north.

Beginning in the eighth century, woodblocks were used in China to reproduce religious texts in large quantities. This process was revolutionized in 1040 by a process using **movable characters** fixed in wax. Historians are unsure to what degree this technology informed the development of printing in Europe, but by 1448 Johann Gutenberg had created a printing press, based on oil and wine presses, that impressed paper onto movable metal pieces of type.

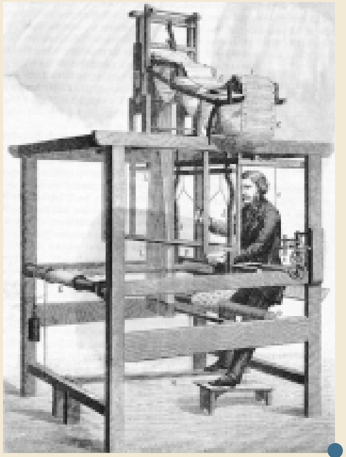
The origins of the familiar **numeral system** can be traced to the work of Hindu astronomers sometime before 650 C.E. The first book to explain clearly the Hindu decimal system, as well as the use of zero as a placeholder, was written during the ninth century C.E. by Muslim mathematician Muhammad ibn Mūsā al-Khwārizmī (whose name is the source of our word "algorithm"). Hindu-Arabic numerals were introduced to Europe by translations of al-Khwārizmī's treatise and were popularized by mathematician Fibonacci in his *Book of the Abacus.* Early numerals, such as these from a Hindu manuscript (*below*), varied greatly from one source to another until printed books standardized them in their modern shapes.

Gunpowder was probably discovered around 950 C.E. by Taoist alchemists, but the incendiary mixture was used almost exclusively in fireworks until it arrived in Europe sometime in the 13th century. Early cannons developed in the 1300s most likely fired only arrows, but by the mid-1400s cannonballs had become the ammunition of choice. The Ottoman Turks relied heavily on cannonballs to batter into Constantinople, just as the French did when fighting the English in the Hundred Years War. Toward the end of the 1400s the gargantuan cannon (which often had to be constructed on site) had been replaced by smaller, more maneuverable cannons.



The first **mechanical clocks** were several Chinese water clocks built starting in the second century C.E. The last and most complex in this series (*above*) was created in 1088 under the direction of astronomer Su Sung. This clock showed the movement of stars and planets, marked hours and quarter-hours with bells and drumbeats, and was the first clock to use an escapement, in which flowing water filled one bucket after another, creating a precise and regular movement.

An early form of **vaccination**—in which patients were inoculated with a mild form of smallpox—was practiced in many Eastern countries before the 18th century. This somewhat risky means of securing immunity was popularized in England during the 1720s by writer and traveler Lady Mary Wortley Montagu, who had observed the practice in the Ottoman Empire. In 1796 English doctor Edward Jenner significantly improved the technique when he found that patients became immune to smallpox when inoculated with cowpox, the bovine form of the disease, which (contrary to this illustration from the period) was not dangerous to humans.



Developed around 1805 by Joseph-Marie Jacquard, the **Jacquard loom** was a culmination of late 18th-century innovations in textile production. The loom was notable not only for its unprecedented mechanical autonomy but also for its use of punched cards to produce patterns automatically. Punched cards had a profound impact on later technologies—namely, computers—that also use **binary encoding.**

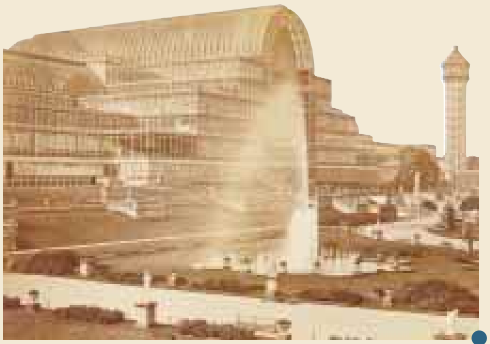
1088 C.E. 1700 1720s 1738 1801 1805

For many years under the feudal system, farmers in Europe operated under an open-field system, in which fields were open to all at certain times of the year for grazing livestock. But during the 1700s and mid-1800s, English farmers saw vast areas of collectively owned land drawn into individual lots demarcated by **fences.** This change, which later spread throughout Europe, allowed farmers to improve their agricultural techniques with new systems of **crop rotation.** It also reflected a general shift from a communally oriented peasantry to a new class of capitalist farmers embedded in a worldwide system of trade.

Like the first steam engine, which was designed to pump water from deep mine shafts, the earliest **rails** were used in the mining industry. Early rail carts were usually horse-drawn over wooden rails, until the introduction of iron rails in 1738. English engineer Richard Trevithick's pioneering work in 1803 placed steam engines on rails, and the **locomotive** was born.

In 1801 U.S. inventor James Finley built the first modern **suspension bridge:** a 70-foot-long bridge hung by wrought-iron chains over a river near Uniontown, Pa. When British engineer Thomas Telford designed his suspension bridge over the Menai Straits in Wales, he replaced chains with iron bars. His bridge (*below*), completed in 1826 with a 579-foot central span, still stands, although the bars were replaced by steel cables in 1939. One metal-cable bridge set the standard for stability in all subsequent suspension bridges: John and Washington Roebling's 1883 Brooklyn Bridge, with its record-breaking 1,595-foot span. The late 20th century has seen the development of novel bridge designs (such as cable-stayed bridges) and materials [see "A Bridge to a Composite Future," on page 50].

SCHOOL OF AFRICAN AND ORIENTAL STUDIES, LONDON/BRIDGEMAN ART LIBRARY (Design for a Chinese water clock, by Su Sung); A. McPHAIL *Tony Stone Images* (*fence*); CORBIS (*vaccine; refrigerator*); CULVER PICTURES (*bridge; Crystal Palace*); CORBIS/BETTMANN (*loom*); CORBIS/HISTORICAL PICTURE ARCHIVE (*calotype*); GASLIGHT ADVERTISING ARCHIVES (*car ad*); BT ARCHIVES (*telegraph*)



Designed to house the Great Exhibition of 1851 in London, Joseph Paxton's Crystal Palace (*above*) pioneered the use of **prefabricated parts** and also inspired other engineers to exploit the possibilities of iron and glass. Iron, for instance, was crucial to the structure of the chocolate factory at Noisiel-sur-Marne, built in 1872 by French engineer Jules Saulnier. Prior to this, the walls of a building carried the weight of both the frame and roof; in Saulnier's factory the walls were mere curtains enclosing the iron skeleton that supported the building. The revolution in American cityscapes arrived in the 1880s with William Le Baron Jenney's Home Insurance Company Building in Chicago, often considered the first modern **skyscraper** because of its skeleton frame, which pioneered the use of steel girders in construction [see "The Sky's the Limit," on page 66].

Petroleum seeping from shallow deposits was used in ancient times for purposes as diverse as medicine, weaponry and illumination. It was not until the Industrial Revolution, however, with its great demand for petroleum as both a machine lubricant and a fuel, that attempts to drill for oil began. The modern petroleum industry started in 1859, when U.S. Army Colonel Edwin L. Drake drilled the first successful **oil well** in northwestern Pennsylvania [see "To the Bottom of the Sea," on page 73].

Working in France in 1860, Étienne Lenoir invented a **piston engine** in which a mixture of air and gas derived from coal was ignited by a spark—and thereby introduced the world to the internal-combustion engine. Enhancements in the design over the next few decades so improved the engine that it quickly became an important source of cheap, efficient power, most notably for the automobile. The internal-combustion engine was also crucial to early aviation: the first airplane Wilbur and Orville Wright flew was powered by a 12-horsepower gasoline engine they had built themselves.

1830s

1851

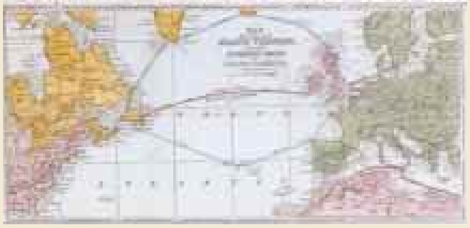
1859

1860

1866

Although several photographic processes were developed in the 1830s, British inventor William Henry Fox Talbot's calotype process is arguably the ancestor of modern **photography.** Unlike other techniques, Talbot's involved negative and positive prints, thus allowing multiple copies of an image to be made (an early calotype image is reproduced above). Photography and its 20th-century progeny, film and videotape, revolutionized the practice of documentation (and deceit). Other more recent imaging techniques such as electron microscopy and magnetic resonance imaging (MRI) extend visual understanding beyond the range of the human eye. And current technology allows us to see—and even move—objects as small as individual atoms [see "Some Assembly Required," on page 24].

After many failed attempts, workers successfully laid a **submarine telegraph cable** across the North Atlantic Ocean in 1866.



In ancient Egypt and India, people produced large blocks of ice with the help of evaporative cooling (the principle that vaporizing water molecules draw heat from their surroundings). Similarly, the **refrigeration machines** built during the mid-1800s cooled air by the rapid expansion of water vapor. French inventor Ferdinand Carré's cooling system of 1859 was the first to incorporate the more heat-absorbent compound ammonia. During the 1870s, refrigerated ships began transporting produce and meat to Europe from places as far away as Australia, inaugurating a new expansion in global trade. Synthetic refrigerants such as freon, discovered in the 1920s and 1930s, made possible the spread of domestic refrigerators and air-conditioners (and, as scientists discovered in the 1980s, the ozone hole).

Chemists developed several semisynthetic polymers during the 19th century, but it was U.S. researcher Leo Baekeland's introduction of Bakelite in 1909 that truly jump-started the **plastics** industry. Unlike earlier plastics, Bakelite could be softened only once by heat before it set, making it ideal for heat-proof containers, such as thermoses (*left*) and various insulated items needed by the new automobile and electrical industries. The synthetic fiber nylon, developed in 1938 by Wallace H. Carothers, was used in the manufacture of toothbrush bristles before its elastic properties were applied to stockings.

Constructed between 1930 and 1936, the **Hoover Dam** was part of an extensive federal project to use water from the Colorado River for irrigation and electrical power. At the time, the 726-foot-high structure was one of the largest dams ever built. A new dam under construction in China will be significantly larger [see "Mighty Monolith," on page 14]. In recent years, however, trends have generally shifted away from allowing the extensive alteration of ecosystems associated with dams; instead emphasis has turned to restoring nature to its pristine state [see "Bringing Back the Barrier," on page 38].

In 1910 Paul Ehrlich and Sahachiro Hata found that arsphenamine, a synthetic substance containing arsenic, was lethal to the microorganism responsible for syphilis. Even with its unpleasant side effects, arsphenamine was the first successful **synthetic drug** to target a disease-causing organism. The idea of developing novel compounds with medicinal properties ushered in the modern pharmaceutical era and its myriad medications, from cancer treatments to antidepressants to the birth-control pill.

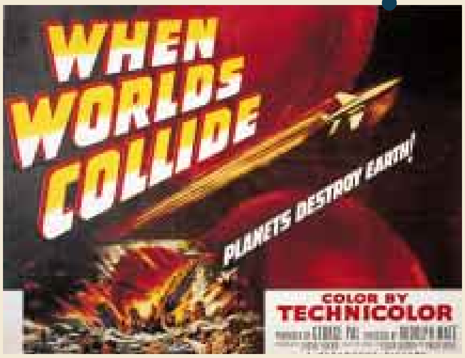
1894 1909 1910 1930 1936 1942

By the end of the 1800s, naturally occurring reserves of nitrogen-based compounds had been so badly depleted by their use as fertilizers that some feared a worldwide famine when supplies ran out. In 1909, however, German chemist Fritz Haber introduced the **Haber process,** which forces the relatively unreactive—but widely available—gases nitrogen and hydrogen to combine to form ammonia, which can then be used in fertilizers.

The **jet engine,** in principle more simple than the earliest steam engines, was patented in 1930 by British aviator Frank Whittle. Work is currently under way on planes that could potentially fly at 20 times the speed of sound [see "Harder Than Rocket Science," on page 62].

In 1894, inspired by the theories of physicist James Clerk Maxwell, Italian physicist Guglielmo Marconi (*above*) began work on a technique to transmit electromagnetic signals through the air over long distances. The first applications of "**wireless telegraphy,**" as it was then known, included sending messages to places that could not be connected by telegraph cables, such as ships. Soon enough, though, the feasibility of communicating information through electromagnetic waves led to a rapid expansion in wireless technology—most notably, radio and television broadcasts. Wireless communications took another leap forward in 1962 with the launch of Telstar, the first communications satellite capable of transmitting telephone and television signals.

Although Russian scientist Konstantin Tsiolkovsky and American inventor Robert Goddard studied rocketry well before World War II, for many years much of the public viewed spaceflight as an implausible dream of science fiction (*below*). The **V-2 rocket,** developed as a weapon in Nazi Germany, became the first rocket to surpass the speed of sound when it was successfully launched in 1942. After World War II, captured V-2s spurred the creation of a variety of rockets: the SS-6 rockets that carried Sputnik and cosmonaut Yuri Gagarin into space, the Saturn rocket that transported the *Apollo 11* crew to the moon, and the intercontinental ballistic missiles of the cold war. More recently, rocket boosters (also descendants of the V-2) have launched the shuttle into space, often carrying components of the International Space Station into orbit [see "Life in Space," on page 32].



In 1984 Kary B. Mullis of Cetus Corporation in Emeryville, Calif., devised the **polymerase chain reaction,** a process that allowed a single strand of DNA to be duplicated billions of times in several hours. PCR made such applications as DNA fingerprinting feasible. (Scientists are now working to put such tests on a single chip [see "A Small World," on page 34].) The technique is now standard in all biotechnology and basic genetic research, such as the ongoing Human Genome Project and various other genome projects [see "Designer Genomes," on page 78]. The current widespread interest in genetic engineering has raised many ethical concerns—most notably after the announcement by Scottish researchers in 1997 of Dolly (*below*), the first sheep cloned from adult cells.

CORBIS/BETTMANN (*Marconi; mushroom cloud*); SCIENCE MUSEUM, LONDON/SCIENCE AND SOCIETY PICTURE LIBRARY (*thermos*); R. CAMERON *Tony Stone Images* (*Hoover Dam*); ARCHIVE PHOTOS (*movie poster*); H. MORGAN *Photo Researchers* (*laser*); N. FEANNY SABA (*Dolly*); APPLE (*Power Mac G4*)

After years of intense work by hundreds of scientists, the first **nuclear bomb** was exploded at the Trinity site near Los Alamos, N.M., on July 16, 1945. The ensuing nuclear age saw the development of more advanced weaponry, as well as nuclear reactors designed to generate electricity. The first nuclear reactor began operation in June 1954 near Moscow; one of the worst technology-related disasters occurred at the Chornobyl nuclear reactor in April 1986 in Ukraine. Since World War II, scientists have also continued research into the structure of the atomic nucleus. Physicists are now building the world's fastest particle accelerator near Geneva; when completed it will enable scientists to probe even deeper into the fundamental properties of the atom [see "Subterranean Speed Record," on page 52].

1945 1960 1966 1984 1994 1999

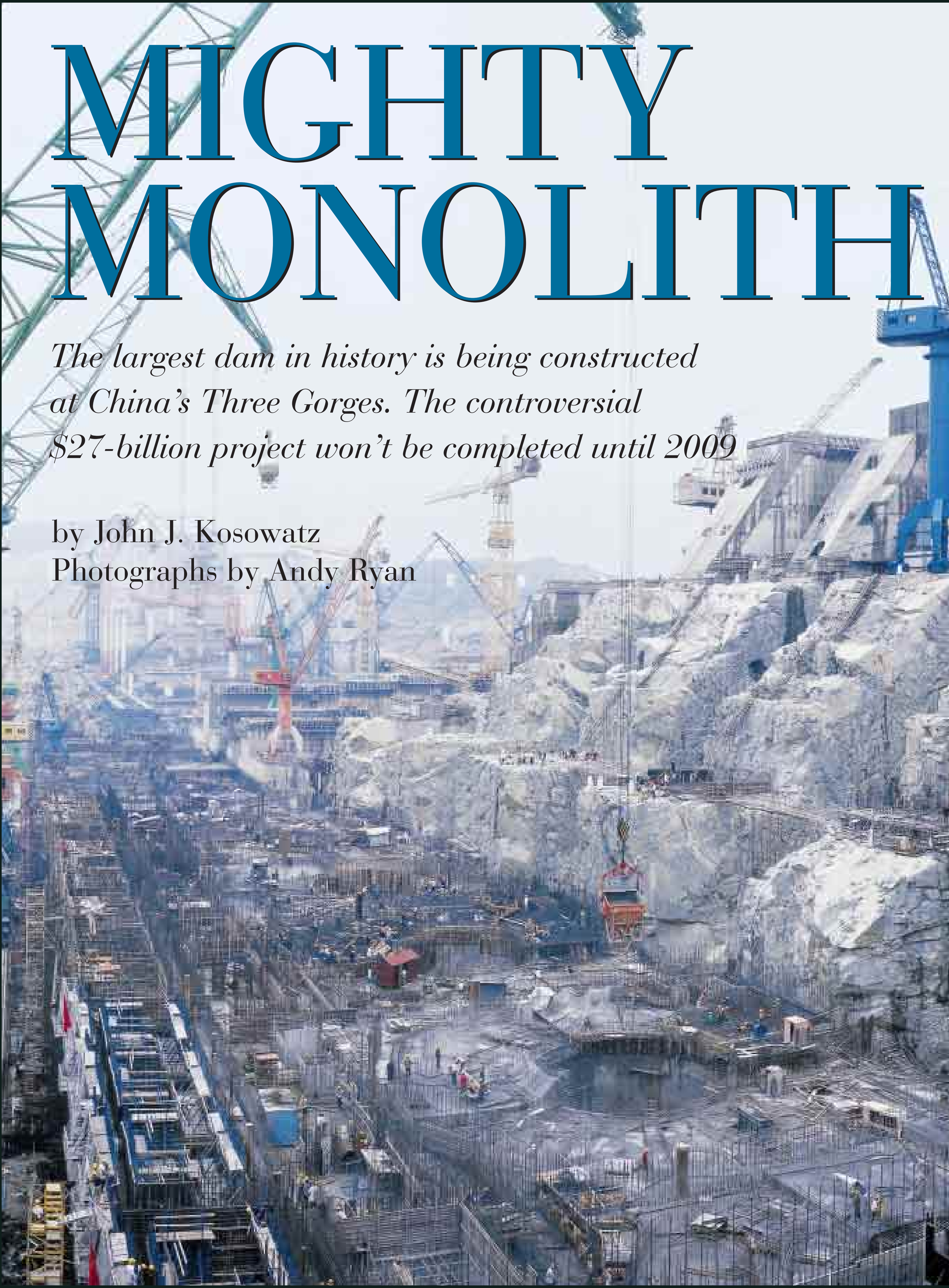
The first working **laser** was built in 1960 by physicist Theodore Maiman of Hughes Research Laboratories in Malibu, Calif.

In November 1994 Britain was physically joined to the European continent when commercial rail traffic began flowing through the **Channel Tunnel.** It had been considered impossible to tunnel under a river until 1842, when British engineer Marc Isambard Brunel used the first protective shield—an iron casing that could be pushed through soft ground by screw jacks—to complete a 1,200-foot tunnel under the Thames River. Today's shields are essentially the same as those designed by British civil engineer James Henry Greathead, who introduced a more efficient shield in 1869. [For details on a 1990s combination bridge and underwater tunnel, see "Bridging Borders in Scandinavia," on page 82.]

The principle of connecting terminals to mainframe computers had been well established by the early 1960s, but the first true **computer network** was created in 1966. Using special Western Union cables that allowed simultaneous service in both directions, Tom Marill of the Massachusetts Institute of Technology's Lincoln Laboratory temporarily connected M.I.T.'s TX-2 mainframe computer to a mainframe in Santa Monica, Calif. Although this first connection was disappointingly slow, the potential of networks to overcome geographical distances separating researchers and computers was great. The network developed in the late 1960s by the U.S. Department of Defense has evolved into today's Internet.

In 1999 the largest commercial **software** ever created—Windows 2000—enters the final stages of testing [see "Building Gargantuan Software," on page 28]. The digital computers that can run Windows as their operating system trace their origins to Charles Babbage's idea, which dates to the 1830s, for what he called an analytical engine. In addition to processing and storing memory, Babbage's computer (never built) would have solved problems using conditional branching, a central component of all modern software. The enormous ENIAC, completed in 1946, was the first all-purpose, all-electronic digital computer. The vacuum tubes used by early computers, including ENIAC, began to be supplanted by transistors in 1959. Continual improvements in computer technology have resulted in supercomputers and even personal computers that are many orders of magnitude faster than ENIAC [see "Blitzing Bits," on page 56].

EUGENE RAIKHEL, a former staff member at Scientific American *who is now a freelance writer and researcher based in New York City, compiled this timeline.*



MIGHTY MONOLITH

The largest dam in history is being constructed at China's Three Gorges. The controversial $27-billion project won't be completed until 2009

by John J. Kosowatz
Photographs by Andy Ryan

Three Gorges Dam, summer of 1999

The setting could hardly be more dramatic: a long stretch of the Yangtze River slicing through the fabled Three Gorges, a breathtaking region steeped in history and culture, with relics and records to the dawn of Chinese civilization. Against this stunning backdrop, the world's biggest, most expensive—and most controversial—construction project is under way.

When completed in 2009, the Three Gorges Dam will be a concrete monolith of mind-boggling proportions: 60 stories high and 1.4 miles (2.3 kilometers) long. The record-shattering $27-billion project will block the Yangtze to impound a narrow, ribbonlike reservoir longer than Lake Superior. Twenty-six monstrous turbines will generate 18,200 megawatts, roughly the output of 18 nuclear power plants.

The megastructure may mark the end of an era that began during the Great Depression at Hoover Dam in the U.S. Today many prime sites for large dams have already been developed or are protected, and rising concerns over the environmental and social impact of such structures, combined with their tremendous monetary cost, effectively scuttle development.

China has bucked the trend, shrugging off stiff domestic and worldwide criticism. With the country's most famous and controversial project at stake, Beijing has put engineers and managers on notice. The challenge now is to keep to a schedule so ambitious that workers must break every known record for concrete construction.

JOHN J. KOSOWATZ is assistant managing editor of Engineering News-Record *in New York City.*

The Furious Flow of Concrete

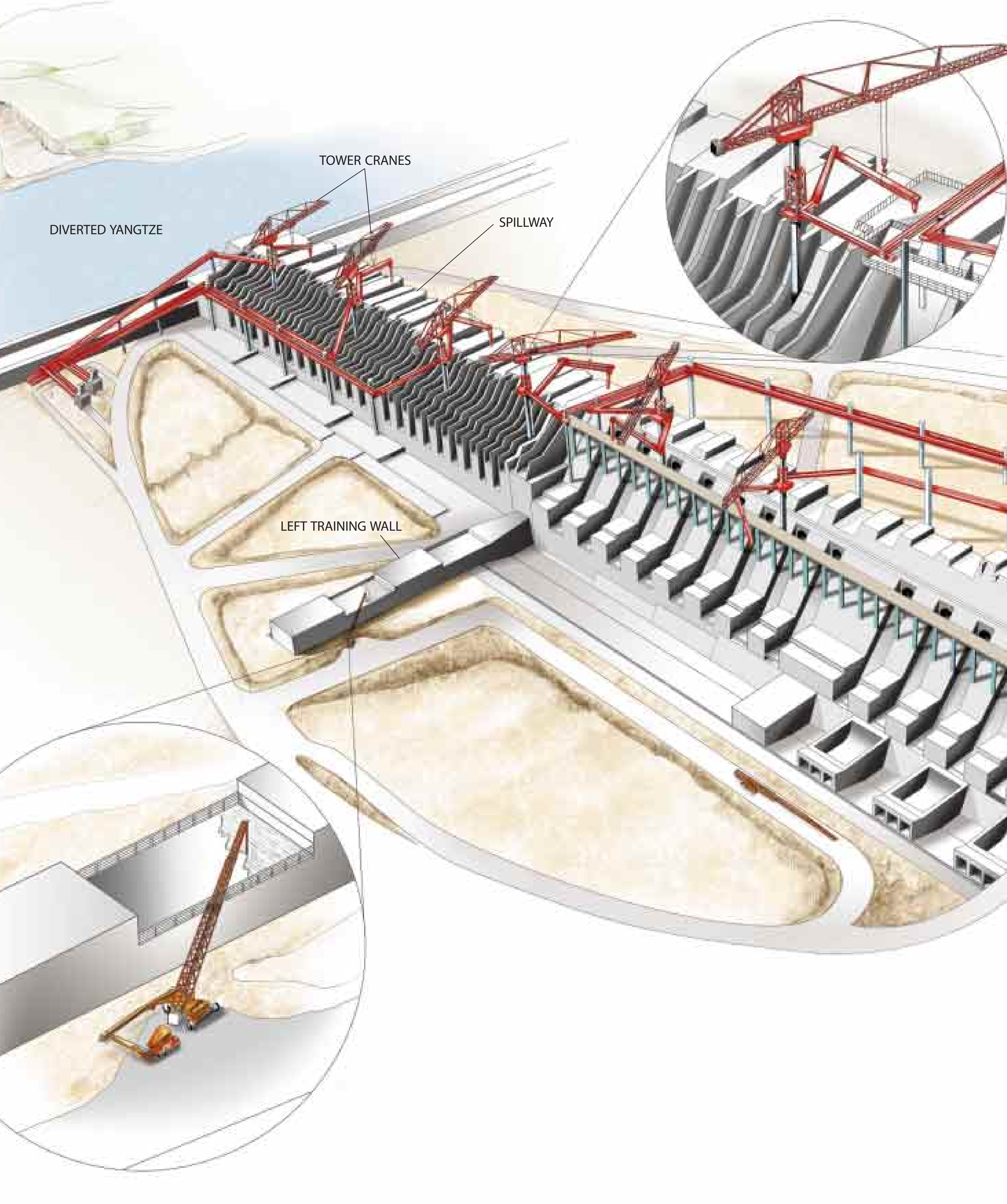
Over the next several years, some 25,000 workers will be swarming over the 3,700-acre (15-square-kilometer) construction site to complete the second of three phases of the Three Gorges Dam [*see illustration on page 20*]. This critical stage presents perhaps the megaproject's biggest challenge: keeping to an aggressive schedule while constructing the dam's spillway and left intake structure, which will house 14 giant turbines (*below*). To meet deadlines, workers must pour concrete at a staggering pace (some 520,000 cubic yards [400,000 cubic meters] per month), requiring an extensive and complex system for transporting the material from the mixing plants.

The equipment, from U.S. supplier Rotec Industries, consists of about five miles of movable and rotating conveyors. As the dam grows taller, progressing to its eventual height of 607 feet, six tower cranes specially fitted with jacking systems will raise the conveyors. The illustration at the right shows how the site should look in about a year. In addition to their lifting capacity, the tower cranes (*inset at right top*) have swinging telescopic conveyors that are designed to pour concrete at the impressive rate of more than 600 cubic yards per hour. A mobile crane (*inset at right bottom*) will deliver concrete from a large hauler to construct the dam's left training wall.

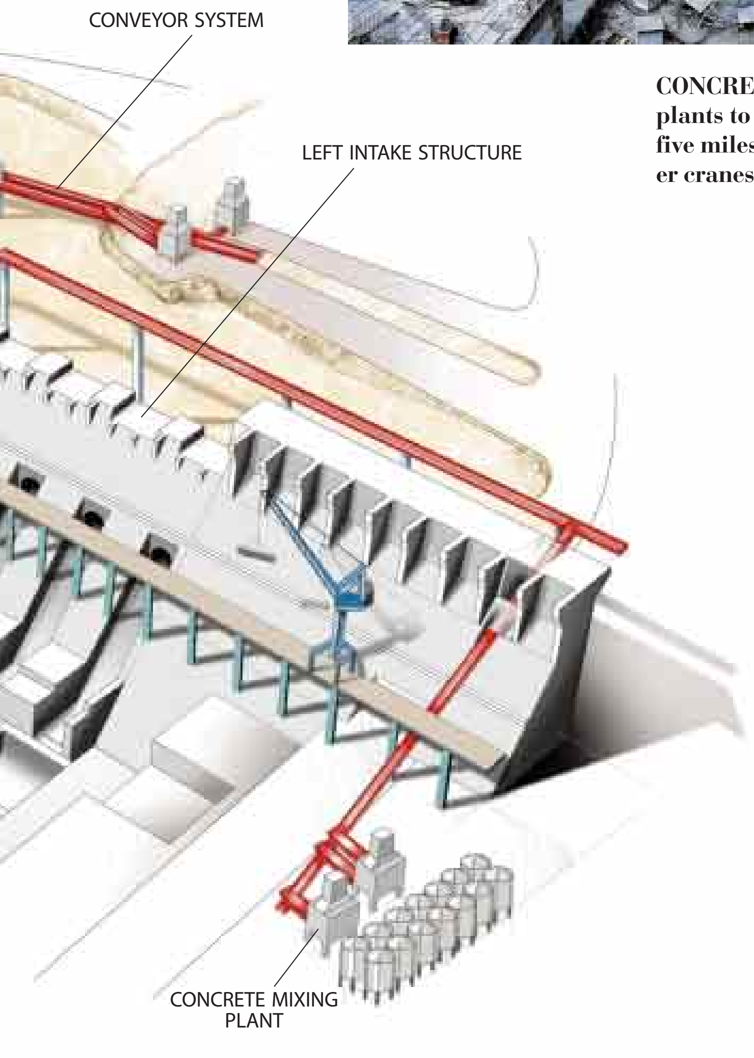
Transporting enormous quantities of concrete is one thing; curing it is another. Because concrete generates considerable heat as it sets, large volumes can become exceedingly hot, damaging the material's structural strength. Recently, amid a national crackdown on shoddy construction practices in China, French and U.S. quality experts were hired to monitor the placement of the concrete, which must be kept at a cool 45 degrees Fahrenheit (seven degrees Celsius) as it hardens.

ILLUSTRATION BY DANIELS & DANIELS

FEEDING THE TURBINES: Huge water intakes (*left*) will divert water from the Yangtze River to one of 26 gigantic turbines. At full capacity the dam will generate 18,200 megawatts, making it the biggest hydropower producer in the world. The intakes are placed about halfway up the dam's eventual 60-story height (*below*).


TOWER CRANES
DIVERTED YANGTZE
SPILLWAY
LEFT TRAINING WALL

CONCRETE DELIVERY: Transporting concrete from the mixing plants to the dam requires a complex and extensive system of about five miles of fast conveyors (*above*). This equipment is raised by tower cranes as work progresses and the dam grows continuously taller.



GIGANTIC LOCK: Matching the dam in scale, an enormous five-step lock (*right*) is being carved from granite on the river's left bank. The chambers of the lock will be lined with concrete, and when completed it will lift 3,300-ton ships 285 feet, making it the largest such system in the world.

One Dam, Three Phases,

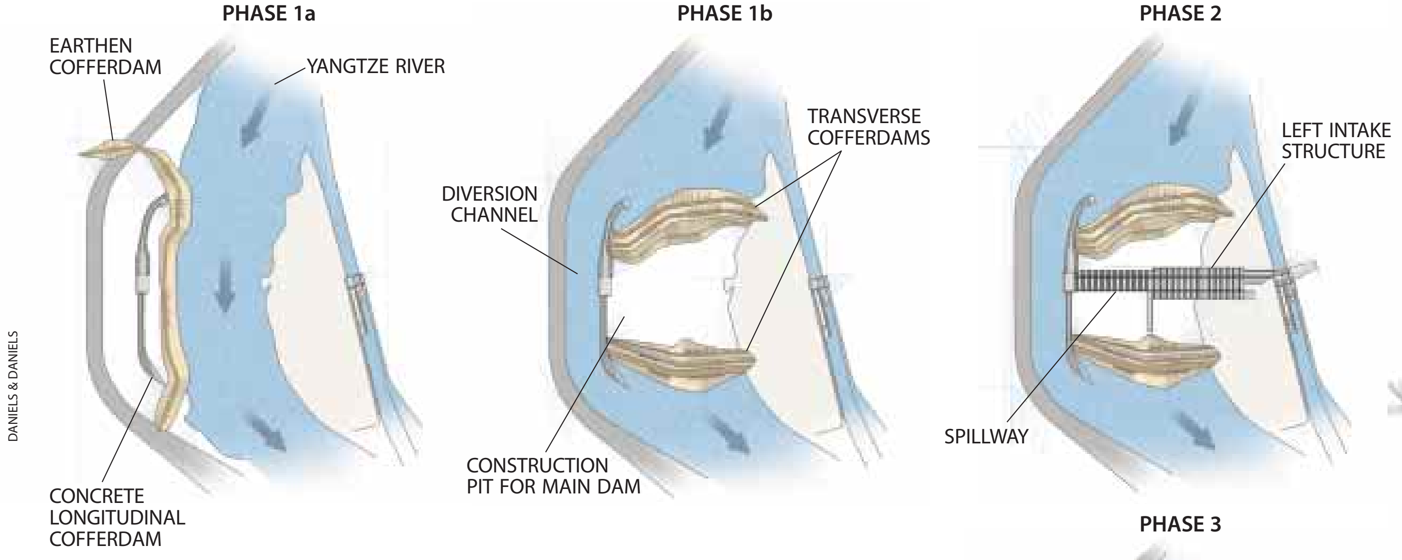
Perhaps no dam in history has been studied to the extent of the multibillion-dollar structure currently rising across the middle reaches of the Yangtze River. Preliminary site investigations for the Three Gorges Dam began in the 1920s, with support from China's prewar government. Later none other than communist leader Mao Tse-tung would champion the project, and from 1958 the first of many detailed geologic studies enabled the present design to take shape. After considering more than a dozen possible sites, engineers selected a wide stretch at Sandouping near the head of Xiling (the easternmost of the Three Gorges) because of the location's abundant granite, deemed ideal for the dam's foundation.

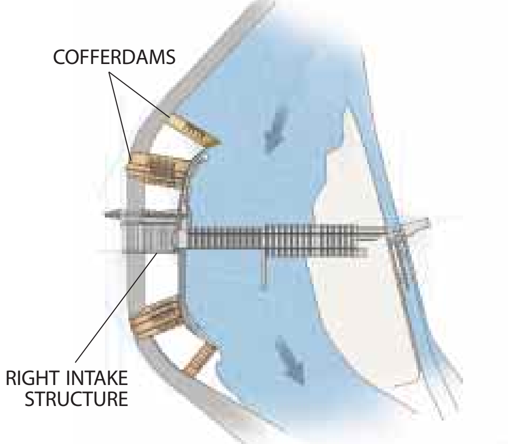
To facilitate transporting thousands of workers to the construction site, the government built a four-lane highway from Yichang, the nearest city of significant size. By any standard, the $110-million road, which cuts through the mountains that frame Xiling, was itself a considerable undertaking: 40 percent of its total length of 17 miles consists of bridges and tunnels, including a twin bore that is more than two miles long. Additionally, a 2,950-foot suspension bridge, the longest in China outside of Hong Kong, was built at Sandouping for access to the project's right bank.

At the dam site, massive earthmoving dominated the first of three major phases, which commenced in 1994. An important goal was the diversion of the Yangtze to enable the later construction of the main dam. First, a large, temporary earthen cofferdam was built along the right bank (*below*). This barrier protected workers from the river as they poured the concrete for a permanent cofferdam. The large longitudinal structure (4,000 feet long and 460 feet high) now defines the Yangtze diversion channel and will eventually be tied into the main dam.

Next, workers built transverse cofferdams both upstream and downstream to clear and protect an area that would become the construction pit for erecting the main dam. The pit was dug to a depth of 260 feet, allowing the foundation work to begin. Numerous holes (with a total length of more than 60 miles) are currently being drilled into the ground and filled with pressurized grout. This "grout curtain" will help protect the main

DANIELS & DANIELS





MOVE A RIVER, BUILD A DAM: In phase 1a, workers constructed an earthen cofferdam that protected them from the Yangtze so that they could pour concrete for a permanent structure. This longitudinal cofferdam helped to divert the river in phase 1b, in which additional transverse cofferdams were built to isolate and protect a construction pit. Phase 2 could then commence, with the pouring of concrete for the spillway and left intake structure of the main dam. In several years, phase 3 will begin with the closing of the diversion channel, which will allow workers to build the right intake structure of the main dam. The illustration at the far right shows the project at its completion, scheduled for 2009.

Decades in the Making

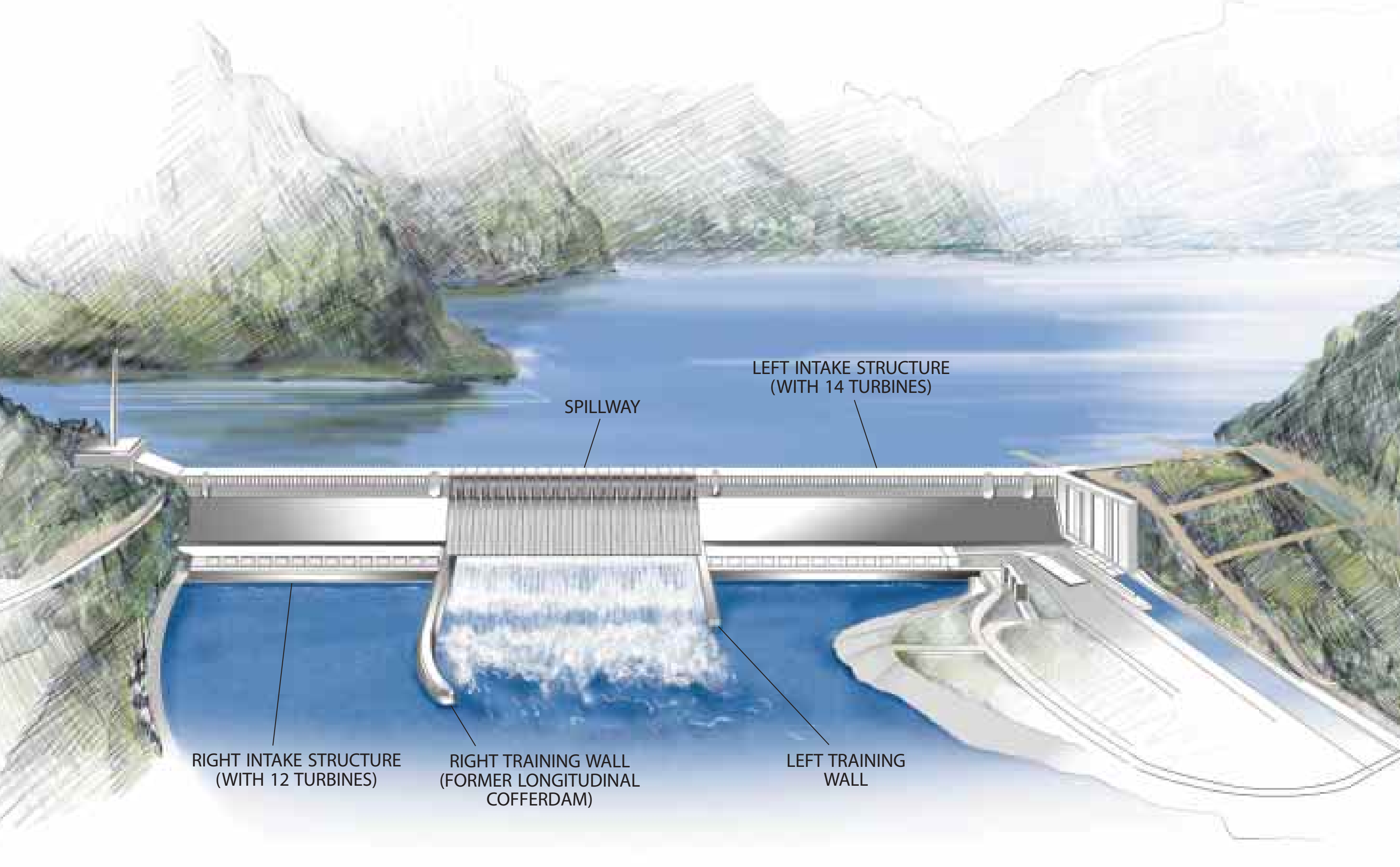
dam from uplift by preventing water from seeping underneath the structure. (For the same purpose, 870,000 square feet of concrete walls were sunk below the transverse cofferdams.)

All told, diverting the Yangtze required about 60 dredges and a huge equipment fleet (oversize trucks, bulldozers and shovels) to place 13 million cubic yards of material. Some of that matter came from excavation of the project's gigantic five-step lock on the left bank (*not shown in these illustrations*). To carve space for the multiple chambers of the lock, workers had to blast with precision more than 75 million cubic yards of hard rock. Because the lock will not be completed for years, a smaller temporary lock and a ship lift were completed along the left bank for moving traffic upriver. (Travel downriver occurs along the diversion channel.)

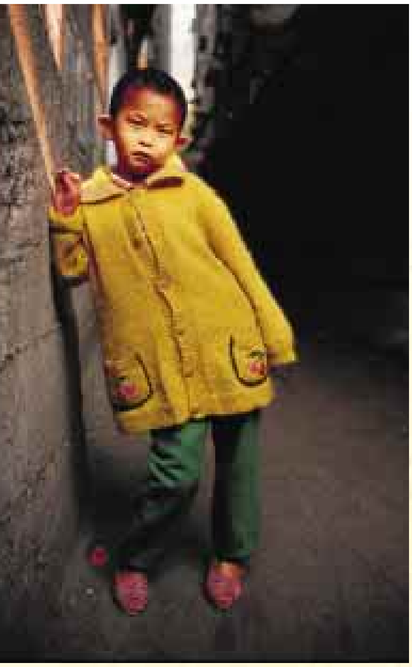
Speed in completing the river diversion and transverse cofferdams was critical. Fearing that the unpredictable Yangtze might flood the site, government officials pushed contractors to finish within one dry season. In November 1997 the river was diverted (before an audience that included President Jiang Zemin), and the transverse cofferdams were completed five months later. The work was essentially finished when the heavy rains arrived in the summer of 1998. The resulting floodwaters caused severe damage along the middle and lower reaches of the river, but at the construction site the cofferdams easily handled the peak flow of 80,000 cubic yards per second.

In the current activity of phase 2, concrete is being poured for the spillway and left intake structure of the main dam. The schedule calls for the first two turbine generators to be producing power—and critical revenue—by 2002, followed by the remainder of the bank in 2003. Phase 2 will also mark the completion of the five-step lock, which will lift ships 285 feet, making it the largest such system in the world.

Years from now, in the third and final phase of the project, laborers will close the diversion channel by building several earthen cofferdams. Construction will then progress on the right intake structure of the main dam, including the powerhouse that will contain the remaining 12 turbines. If all goes according to schedule, the Three Gorges Dam will be completed in 2009 (*below*), marking decades since the preliminary site studies.



An Uncertain Future

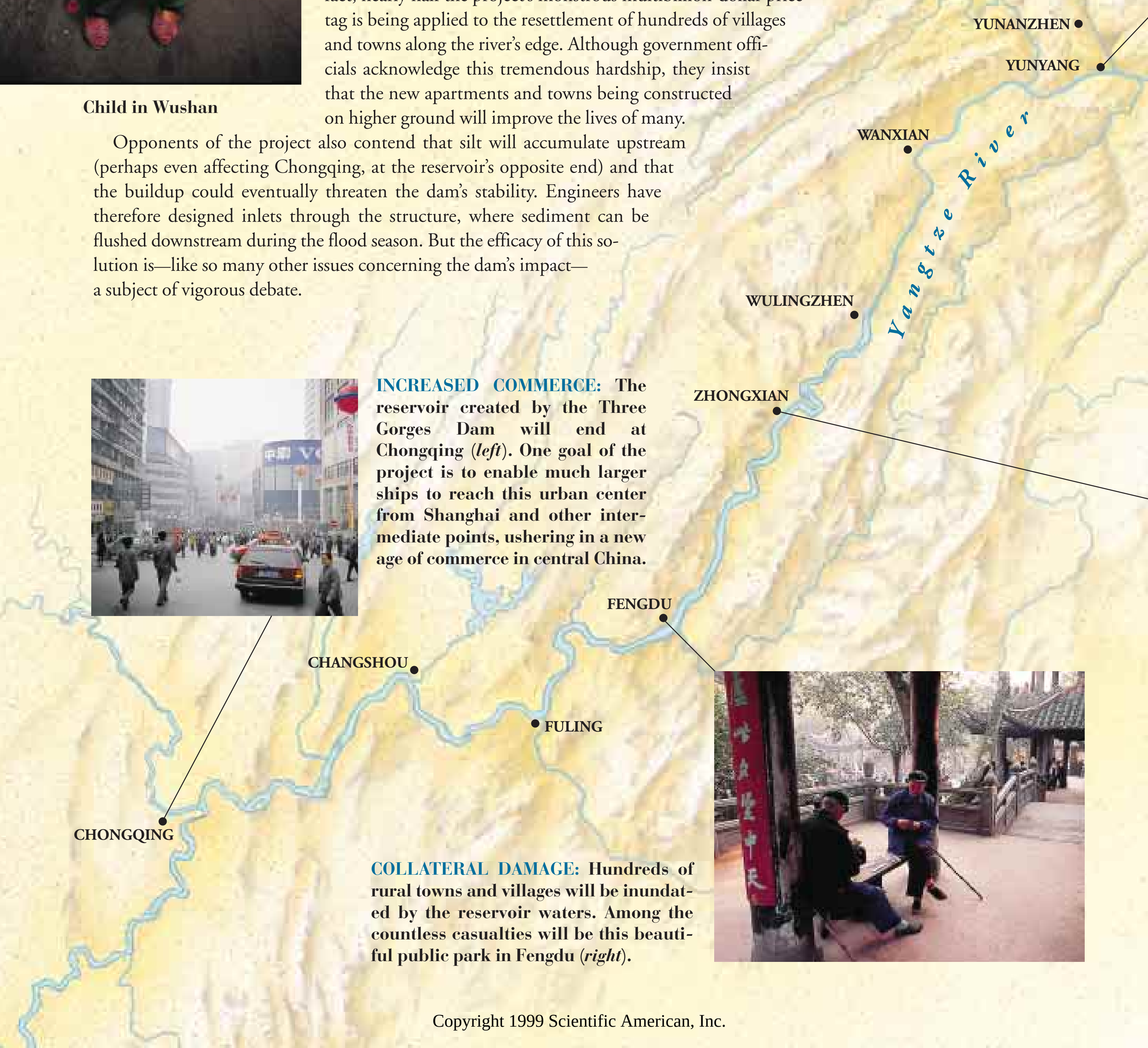


Child in Wushan

Every megaconstruction project has elicited controversy, and the Three Gorges Dam is no exception. Proponents assert that not only will the dam generate a tremendous amount of "clean" energy (that is, electricity without the burning of fossil fuels), it will also help control catastrophic flooding along the heavily populated middle and lower reaches of the Yangtze, the world's third longest river. But critics argue that the project's overall toll will far outweigh its potential benefits.

The Three Gorges Dam will increase the water level of the Yangtze for some 370 miles upstream, affecting the habitat of various wildlife, including a rare species of river dolphin, and forcing the relocation of up to two million Chinese living in what will become a reservoir. In fact, nearly half the project's monstrous multibillion-dollar price tag is being applied to the resettlement of hundreds of villages and towns along the river's edge. Although government officials acknowledge this tremendous hardship, they insist that the new apartments and towns being constructed on higher ground will improve the lives of many.

Opponents of the project also contend that silt will accumulate upstream (perhaps even affecting Chongqing, at the reservoir's opposite end) and that the buildup could eventually threaten the dam's stability. Engineers have therefore designed inlets through the structure, where sediment can be flushed downstream during the flood season. But the efficacy of this solution is—like so many other issues concerning the dam's impact—a subject of vigorous debate.



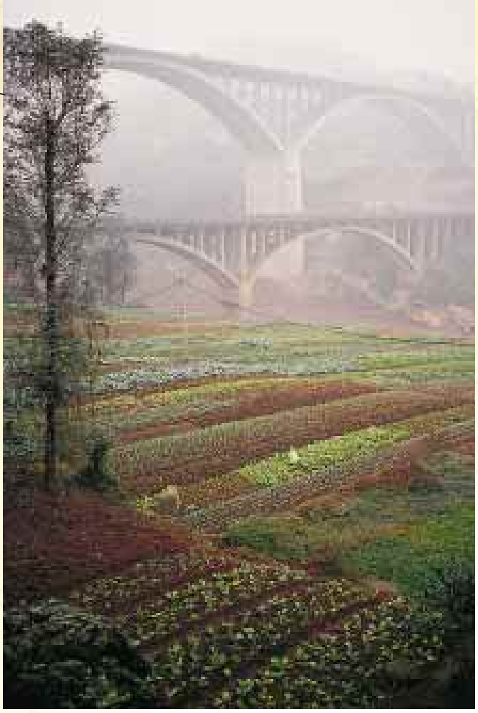
INCREASED COMMERCE: The reservoir created by the Three Gorges Dam will end at Chongqing (*left*). One goal of the project is to enable much larger ships to reach this urban center from Shanghai and other intermediate points, ushering in a new age of commerce in central China.

COLLATERAL DAMAGE: Hundreds of rural towns and villages will be inundated by the reservoir waters. Among the countless casualties will be this beautiful public park in Fengdu (*right*).

SHIFTING ECONOMICS: On this beachhead in Yunyang (*left*), workers repair and repaint boats for travel on the Yangtze. With the construction of the Three Gorges Dam, the resulting reservoir will engulf the beachhead, forcing a shift in the livelihoods of many inhabitants of the town.

GORGEOUS GORGES: The Three Gorges Dam is named after three breathtaking canyons—Qutang, Wu and Xiling—that will be forever changed with the project's completion. One estimate is that the waters in Wu Gorge (*below*) will rise by some 300 feet.

FERTILE LANDS: Agriculture has been the mainstay for untold generations in Zhongxian. These two bridges (*below left*) indicate the difference in water level before and after the dam has been built. In addition to being fertile, Zhongxian is rich with artifacts of archaeological significance, some of which have been taken for granted. These ornamental bricks from the Ming dynasty (*above left*) were unearthed by a farmer who used them to build an enclosed structure for his pigs.

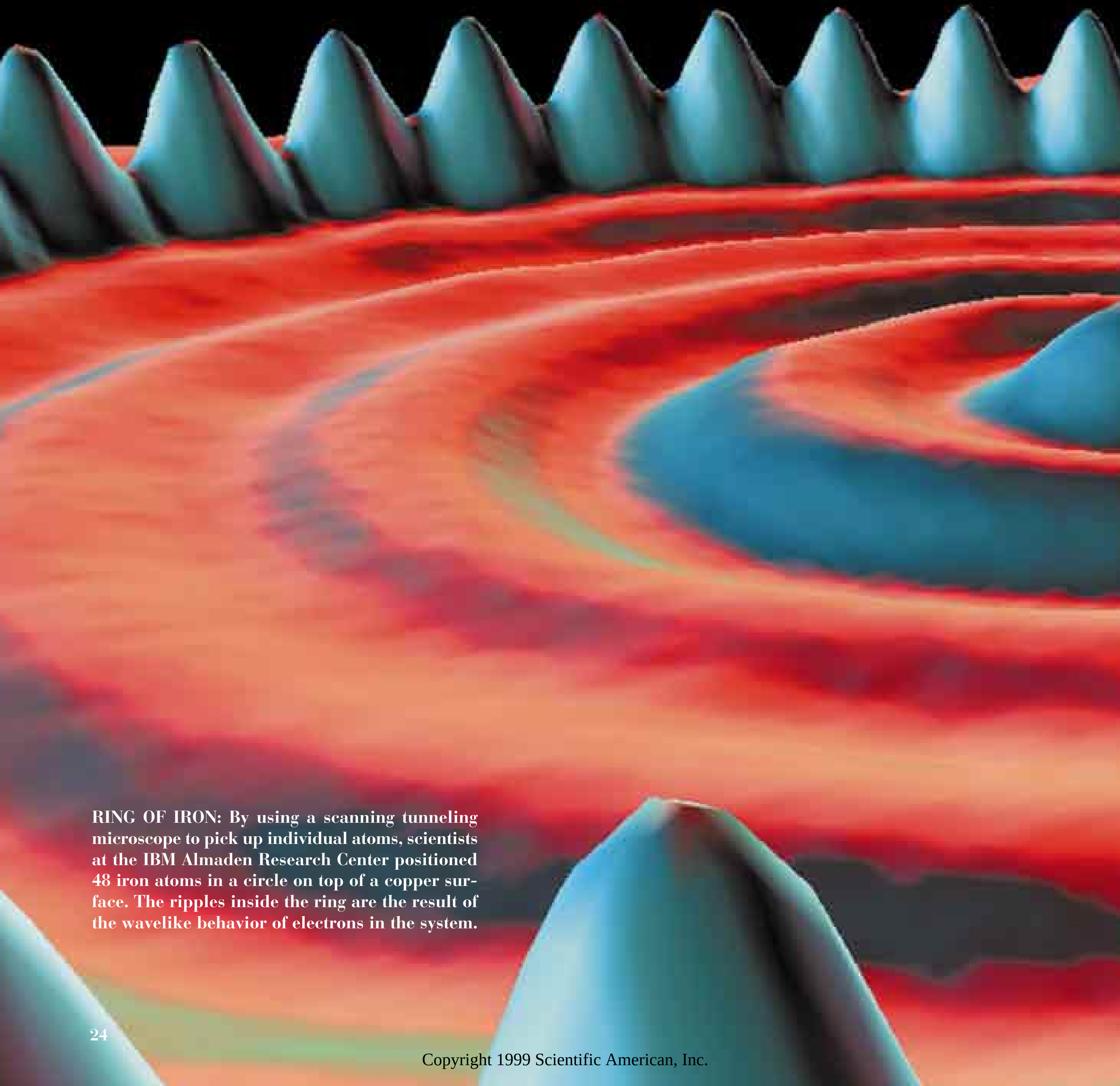


TO SAVE A TEMPLE: The Yangtze Valley is home to thousands of archaeological sites, many dating as far back as the Neolithic. The Chinese government recognizes the need to move historic structures, such as this mausoleum in Zigui (*above*), to higher ground, but critics contend that insufficient time and funds remain to salvage China's precious past.

MAP BY SUSAN CARLSON; INSET MAP BY SARAH L. DONELSON

Some Assembly

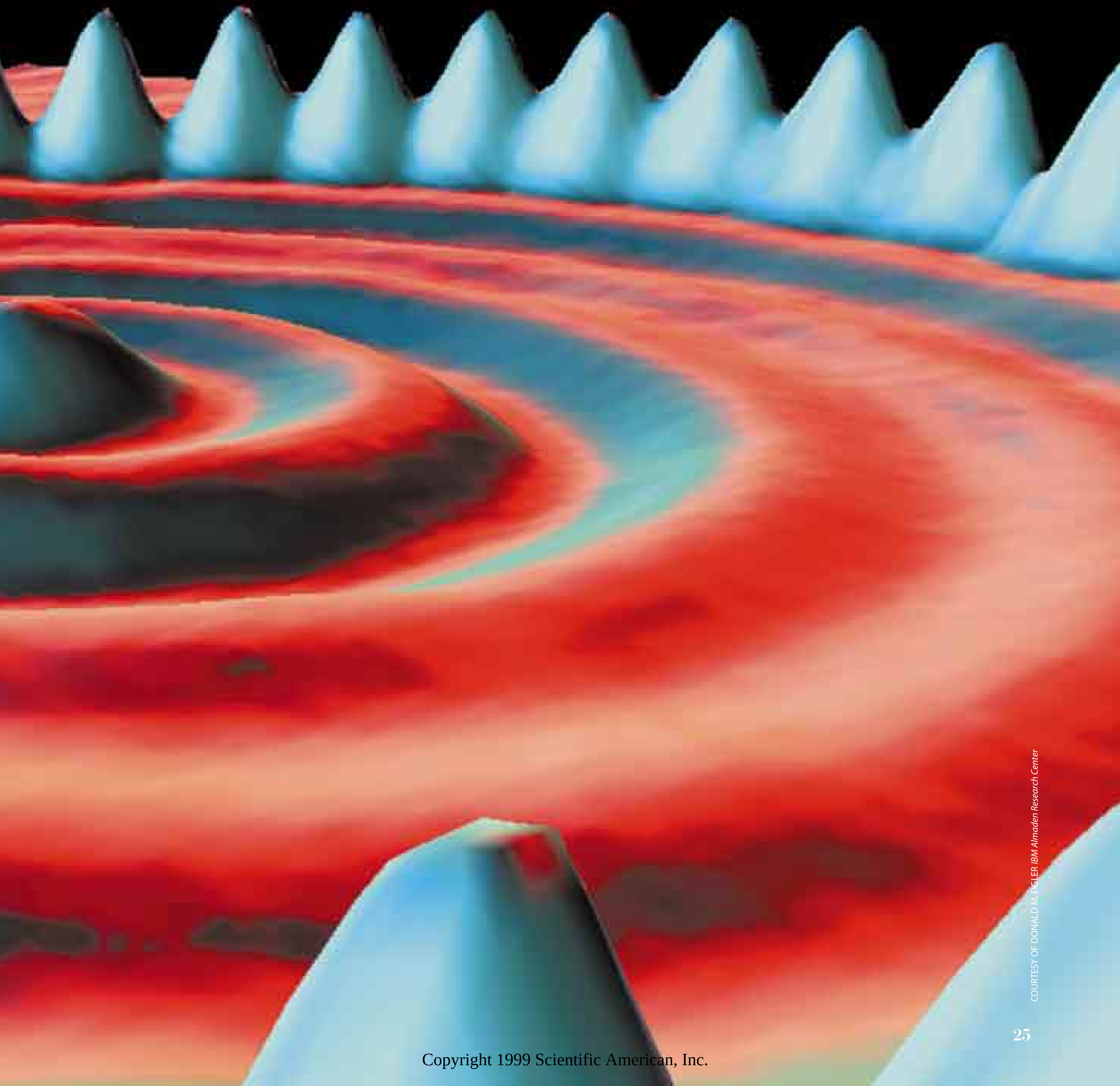
Scientists can now grab an individual atom and place it exactly where they want. Welcome to the new and exciting world of atomic engineering



RING OF IRON: By using a scanning tunneling microscope to pick up individual atoms, scientists at the IBM Almaden Research Center positioned 48 iron atoms in a circle on top of a copper surface. The ripples inside the ring are the result of the wavelike behavior of electrons in the system.

Required

by Sasha Nemecek



COURTESY OF DONALD M. EIGLER *IBM Almaden Research Center*

Everything around us—from concrete blocks to computer chips—is made of atoms. They are nature's Tinkertoy set, but it can take a Herculean effort for humans to rearrange individual, all but weightless, atoms. Consider how minuscule they are: some two trillion would fit in this letter A. But researchers have now developed tools that enable them to see, grasp and move these tiny particles.

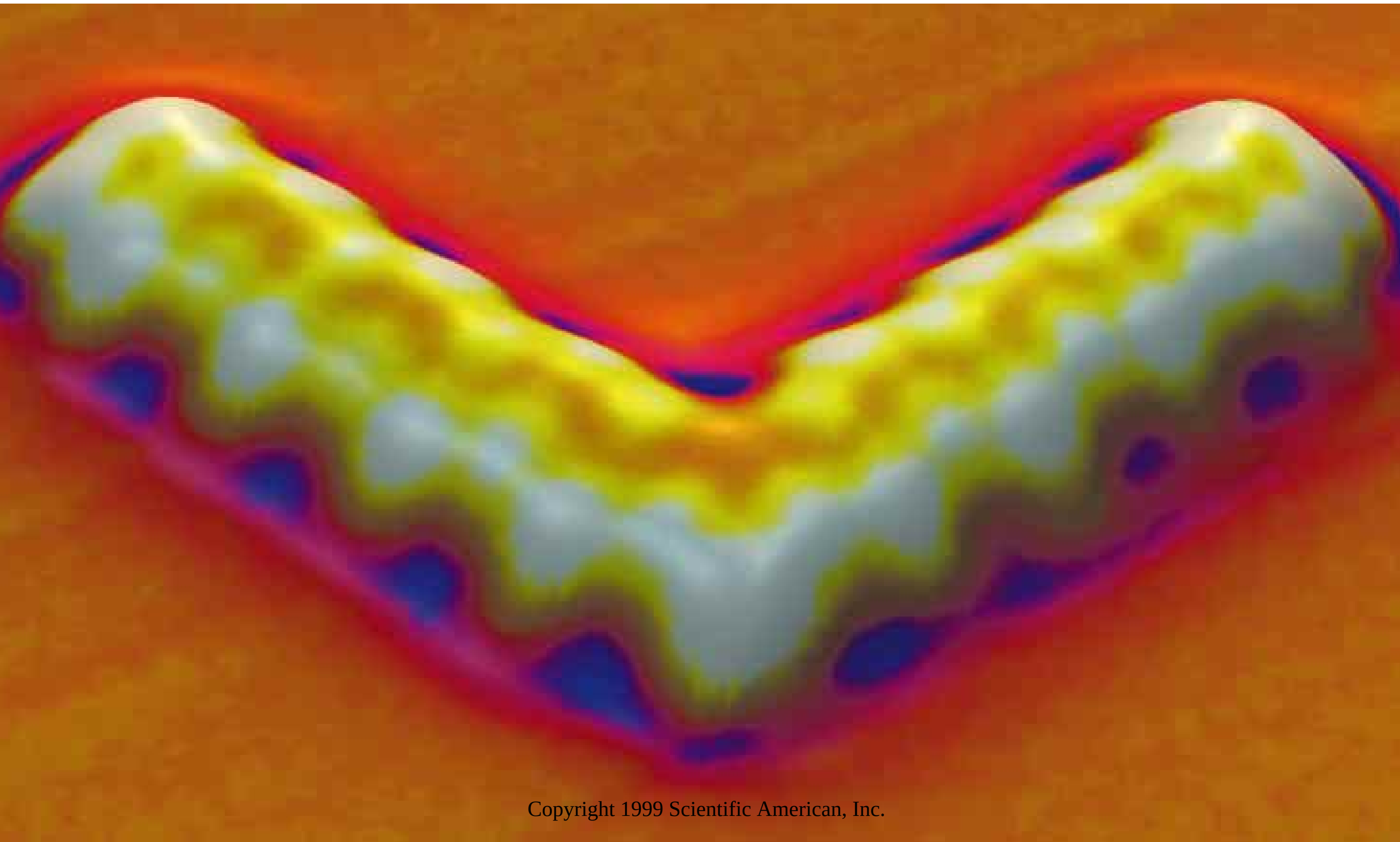
The technology dates back to the early 1980s, when two European physicists, Gerd Binnig and Heinrich Rohrer, working at the IBM Research Laboratories in Zürich, built the first instrument that could display images of atoms: the scanning tunneling microscope, or STM.

Despite its name, though, the STM is not a true microscope. Rather than capturing direct images with the help of lenses, optics and light, an STM relies instead on translating electric current (from the surfaces of conductors—metals, semiconductors or superconductors) into images of atoms.

The most important feature of any STM is its ultrasharp probe—typically a thin wire designed so that a single atom hangs from the tip. Atoms consist of a positively charged nucleus at their center surrounded by negatively charged electrons, in what scientists call an electron cloud. In the case of atoms positioned at the surface of any material, these electron clouds protrude just slightly above the plane, like rows of tiny foothills. Once the STM probe comes close enough to one of the surface atoms—around a nanometer (one billionth of a meter) away—the electron cloud of the atom on the end of the probe and that of the surface atom begin to overlap, causing an electronic interaction. When a low voltage is applied to the STM tip, a so-called quantum tunneling current flows between the two electron clouds. This current turns out to be highly dependent on the distance between the tip and the surface.

A helpful way to think of the STM probe is like a finger reading Braille. Researchers using an STM typically program the computer controlling the probe to keep the current between the tip and the surface atoms at a constant level. So as the feedback probe scans back and forth across a sample, it also shifts up and down, following the contours of the electron clouds. For instance, as an electron cloud emerges from the plane of the surface and the tip comes closer to the atom, the tunneling current at the probe would ordinarily increase. As soon as the computer registers this difference, however, it tells the tip to pull back from the surface and in this way maintains a stable current reading.

Alternatively, as the electron cloud falls below the surface plane and the tip separates from the atom, the probe would normally detect a lower tunneling current. Once again, though, the probe responds to this change, coming closer to the surface to preserve a constant current



MIX-AND-MATCH MOLECULE: Atomic engineers eventually hope to create molecules from scratch, adding atoms exactly as needed to perform specific functions. This molecule, with 18 cesium and 18 iodine atoms, was built—one atom at a time—with a scanning tunneling microscope (or STM).

COURTESY OF DONALD M. EIGLER *IBM Almaden Research Center*

THE HOLY GRAIL FOR THESE ATOMIC ENGINEERS IS TO BUILD A MOLECULE ATOM BY ATOM.

level. Over time the probe generates a topographical survey of the surface, essentially "feeling" the size and location of atoms.

The results of STM scans can be stunning. Scientists use computer programs to translate the probe's motion into images of the surprisingly rugged terrain of seemingly smooth surfaces, often adding color to emphasize the peaks and valleys of the atomic geography. Indeed, early work with the STM centered on generating images of the atoms at the surface of metals, semiconductors and superconductors, revealing unexpected and often informative patterns and imperfections.

More recently researchers have discovered they can also use the STM to move individual atoms. Instead of just hovering right above the atoms, the STM tip can actually reach down and pick up a single atom. This trick is possible because the interaction between the atom on the probe's tip and the surface atom becomes stronger as the tip moves closer to the surface. Eventually this interaction leads to a temporary chemical bond between the two atoms, which is stronger than those between the surface atom and its neighbors. Once this bond forms, the tip essentially holds on to the surface atom, permitting scientists to move the probe and its guest to the desired location.

COURTESY OF HONGJIE DAI *Stanford University*

SHORT LIST: A carbon nanotube—essentially a "buckyball" stretched into a hollow tube of carbon atoms some 10 nanometers wide—has been transformed into a writing implement. Using an atomic force microscope with a nanotube tip, researchers at Stanford University removed hydrogen atoms from the top of a silicon base. The exposed silicon oxidized, leaving behind a visible tracing.

Today the technology behind the STM has been adapted for use in a variety of similar imaging devices. The atomic force microscope, or AFM, for instance, enables scientists to study biological systems, from DNA to molecular activity within a cell. Instead of relying on changes in the quantum tunneling current between the tip and surface atoms, the AFM exploits fluctuations in other types of atomic and molecular scale forces—mechanical or electrostatic forces, for instance—again feeling the surface geography. AFM has become a significant tool for biologists and chemists.

The holy grail for these atomic engineers is to build a molecule atom by atom, with the goal of one day constructing a new type of material. Physicist Donald M. Eigler, who works at the IBM Almaden Research Center in San Jose, has produced in his laboratory a molecule consisting of 18 cesium and 18 iodine atoms [*see STM image on opposite page*]—the largest molecule ever to be assembled in atomic installments. And although there is no immediate use for such a compound, there is plenty of interest in the technology. The dream is to build new materials that might serve, say, as ultrahigh-density data storage for future computers or as a novel medical device. All of this with a few atomic Tinkertoys. SA

About the Author

SASHA NEMECEK is co-editor of this issue of *Scientific American Presents.* She wrote this article with her own nanopencil.

Building GARGANTUAN Software

by Eva Freeman

Imagine a stack of paper the height of a 19-story building. That's what a printout of Microsoft's Windows 2000 would look like, if anyone cared to print it. With 29 million lines of code written mainly in the C++ computer language, the new operating system (OS) is by far the largest commercial software product ever built. In fact, the development of Windows 2000, and its implementation in a wide range of computer systems and locations, is arguably the most extreme feat of software engineering ever undertaken.

To understand how software could grow to such immensity, think of it not as a monolithic object but as an assemblage of snap-together blocks. There's the core OS, large enough by itself but just one part of the whole that is Windows 2000. Also bundled in are such components as an Internet browser, transaction processing (tools for updating information almost instantaneously as new data are received) and a multitude of drivers, which link peripheral devices such as printers to the OS. The drivers alone account for more than eight million lines of code, with just one of them comprising in excess of a million lines by itself.

So it is conceptually not difficult to comprehend how an operating system with a plethora of features could grow to become a digital behemoth. Less obvious, though, is why Microsoft chose to take on this daunting venture of extreme software engineering and, after deciding to do so, how the company was able to build the product.

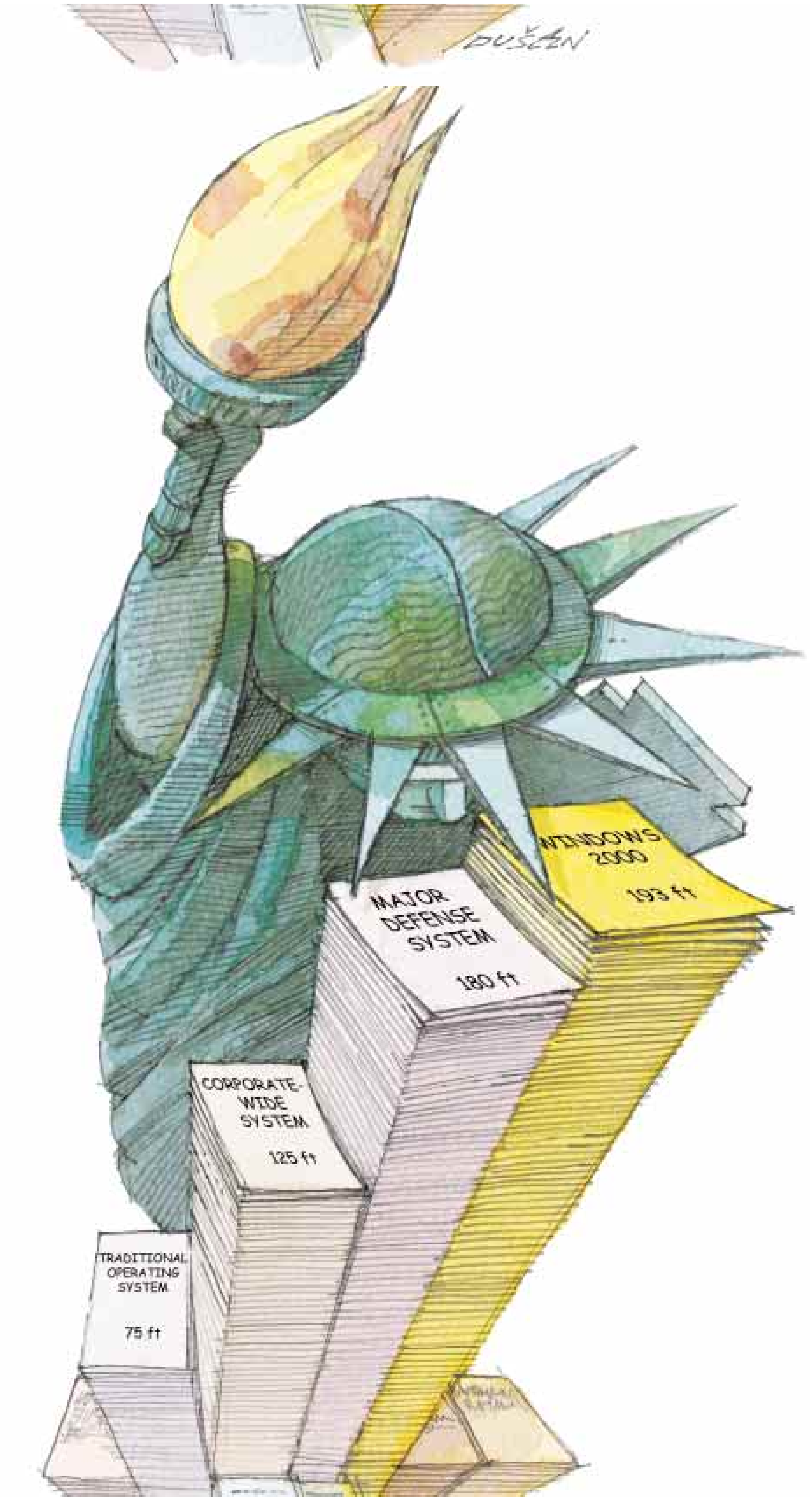
Microsoft officials assert that their reason for taking an all-encompassing approach to the design of Windows 2000 is simple: customers asked for it. Company management was well aware that software complexity and bugs grow roughly geometrically with size, but major customers, especially at Fortune 500 corporations, had stated that they needed certain capabilities included in the operating system. The underlying concept is controversial—that it is more efficient for Microsoft to integrate a comprehensive set of subsystems all at once, rather than for each organization on

Everything about Windows 2000 is huge, starting with its 29 million lines of code. To tame this monster, Microsoft had to develop a new set of strategies, all while getting more than 4,000 computer geeks to work as a team its own to integrate the particular functions it requires.

It's a trade-off: the benefit is that the OS will perform a breathtaking number of functions; the cost is that the OS becomes very large and potentially slow, unstable and buggy (what critics refer to as "bloatware"). "We knew from the start how hard it would be to build such a functionally rich OS," remembers Brian Valentine, vice president of the Windows OS division at Microsoft. "But our customers were demanding this level of complexity. What we created with Windows 2000 was not so much a new OS as a new view of the role of the OS."

Traditionally, operating systems have handled only a limited set of tasks, for instance, the allocation of resources such as computer memory, depending on whether the OS was designed for personal computers, network management or another specialized application. Windows 2000 takes an alternative approach; it is a single OS that spans most uses, thereby providing uniform security and system services to myriad computers, from individual laptops to clustered servers in corporate data centers. The theoretical advantage is that users will need to learn just one program—albeit a mammoth one—for a wide variety of systems and applications.

Along with a novel way of thinking about operating systems, Microsoft had to invent a different methodology for developing software. Specifically, simulation tools for modeling how the software would work were of limited usefulness. (Unlike other massive engineering projects, the Microsoft venture found scale models essentially worthless.) More important, at the level of size and complexity of Windows 2000, writing code was no longer the central activity. Indeed, testing and debugging have accounted for between 90 and 95 percent of the work.



INSOMNIACS' BEDTIME READING: If the code for Windows 2000, the largest commercial program ever written, were printed, the resulting stack of paper would reach past the Statue of Liberty's chin. In comparison, the software for a typical major defense system would be 13 feet shorter.

DUSAN PETRICIC; DATA FROM ARTEMIS MANAGEMENT SYSTEMS

The greatest challenge in building Windows 2000, however, was not technical. Because every team member possessed so much specialized knowledge, a high level of staff turnover would have devastated the effort, which started three years ago. “My main responsibility is to make sure that the people who joined the project at the start stay with it to the conclusion,” Valentine says.

As the individual responsible for managing the entire Windows 2000 team, Valentine has grown to appreciate how crucial the human side is for developing megasoftware: “The difference between extreme engineering in software and other types of extreme engineering is that [with software] the architects are also the builders. Virtually everyone working on this project is highly trained, and no one is expendable or easily replaced. There are no unskilled laborers here, and the most important thing I do is to try to keep everyone on board.”

One vital means of keeping the Windows 2000 staff together was to create a sense of family—not an easy job on a project of this size. Consider these numbers: Valentine is ultimately responsible for 4,200 people, including 2,000 Microsoft staff, 800 employees of Microsoft’s partners (Intel, for instance) working full-time on the company’s Redmond, Wash., campus and 1,400 contract personnel. Another 1,500 Microsoft and contract staff are working on Windows 2000 in other parts of the U.S. and around the world, notably in Israel and India, using the design and test tools on Microsoft’s global network to coordinate their efforts with the main campus.

IN A TYPICAL DAY, WORKERS EXCHANGE ABOUT 90,000 E-MAIL MESSAGES ON THE PROJECT.

So every Friday afternoon, the entire Windows 2000 team comes together in the company cafeteria, the only room on the Redmond campus that can hold several thousand people. Part weekly report, part pep rally, these meetings are used by Valentine as much to maintain camaraderie as to keep the staff well informed.

Sensing that the anonymity involved in such a massive endeavor was becoming an issue, Valentine brought thousands of markers to one Friday meeting. “I wish each of you could put your signature on the OS, but as the next best thing, let’s put our names on the cafeteria,” he told them, laughing. By the end of the meeting, the walls were covered with thousands of signatures.

For holidays, Valentine dresses appropriately, as on St. Patrick’s Day, when he gave the weekly report while wearing a leprechaun costume. On April Fools’ Day, the floors were covered with thousands of Superballs, those toy rubber balls with superhigh bounces. “Brian will do whatever it takes to keep the team together,” says Iain McDonald, the Windows 2000 project manager. “I don’t think anything embarrasses him, so long as it works.” And, of course, each major release of the fledgling software is always an excuse for a huge party.

The week may end on a playful note, but the rest of the time is pure business. Because of the critical importance of testing and debugging, a group of 50 to 60 managers meets at nine in the morning every weekday (as well as on Saturdays and Sundays when a release date approaches) to go over the daily reports of errors found in the Windows 2000 code. These bugs arrive from a variety of sources: independent software vendors from the outside who are developing application software that will run on Windows; select customers at so-called beta sites, who test the software under the actual conditions of usage; Microsoft’s internal tests, which involve a large portion of the computer systems at the company; and overseas test sites.

During this “war room” conference, which McDonald usually chairs, each bug’s impact is carefully assessed. How much damage will it cause? Will the fix introduce a new problem? Who should take care of it?

The bug is then handed over to the test department, headed by Sanjay Jejurikar, who assigns it to one of 25 triage teams. They log the severity of the bug into a database, then make the necessary fix. After that is done, the revised code is sent to the Build Lab, the center of Windows 2000 testing.

Working in the Build Lab has got to be a hardware geek’s idea of heaven. To ensure that Windows 2000 will run successfully on every possible hardware configuration, the multiple rooms of the Build Lab contain at least one of every type of system, storage device, modem card, Internet card and other electronic accoutrement. For video cards alone, as just one example, the computers in the Build Lab host almost 1,200 designs and configurations.

To enable the test group to release an updated version of Windows 2000 every day, Microsoft enforces a strict schedule for submitting revisions to the software. The day’s changes—about 250 is a typical number—are checked in between 1 and 4 P.M. After that deadline, the Build Lab begins to enter the changes, and the new release, referred to as the “build,” is typically ready between 6 and 8 P.M. This latest version of Windows 2000 is then available for download over the company’s internal network. Additionally, by 9 P.M. the Build Lab has pressed and distributed about 2,000 CDs of the software. Before 7:00 the next morning, the build verification test, which evaluates the stability of the previous day’s build, is under way.

ROBBIE McCLARAN SABA

BALANCING WORK WITH PLAY: Keeping morale high is a goal of the weekly staff meetings, attended by thousands. Realizing that staff turnover could derail Microsoft's efforts to bring Windows 2000 to market, one company vice president says, "The most important thing I do is to try to keep everyone on board."

About 3,000 individuals at Microsoft use the daily build, locally known as "dog food," as the operating system of their personal computers. Why dog food? Edmund H. Muth, group product manager for the Windows OS division, explains, "Before dog food manufacturers try their latest product in a test market, what do they do? They bring in their own dogs. Their own dogs have usually developed pretty picky habits, and if they don't like the dog food, the manufacturer doesn't test it on someone else's dog. It's the same thing here. We don't send the OS to beta sites until our internal users have said they like it."

Getting to that point has not been easy. The daily test cycle ends around 3:30 P.M., at which time all comments and criticisms are collected for the next day's war room. One benchmark of what extreme testing entails: in a typical day, workers exchange about 90,000 e-mail messages on the project.

Additional tests to stress the software in lifelike conditions are conducted in one- and two-week cycles. Every six weeks those chunks of code that have been thoroughly tested are evaluated one last time and then locked. Valentine explains the underlying theory: "We found that we can only screw up so much in six weeks. Longer than that, and it gets too hard to figure out what's going on." The code, however, is never cast in stone. If a subsequent bug is discovered, Microsoft will fix it, even if that means running additional extensive tests to ensure that the correction will not trigger problems in other parts of the program that have already been frozen.

But not every bug is fixed. "In a software system of this size, you always have to consider the risk that fixing a bug could impact the system somewhere else," Jejurikar, the head of testing, says. According to him, Microsoft always fixes four broad types of bugs: those that cause system crashes, introduce security holes, create Y2K problems or lead to users being denied some type of service. Other kinds of glitches that the company may decide are not worth eradicating include ones that will surface only under unusual conditions, affecting just a small number of customers. Microsoft documents these types of errors and saves possible fixes so that they can be provided to users as needed.

In a perfect world—and with projects to develop simpler software—the idea of intentionally leaving in bugs might seem unthinkable, but Windows 2000 brings home the reality of extreme software engineering. A system of this magnitude cannot be flawless; it can only be tested and documented as thoroughly as time constraints allow.

That said, Microsoft is in the final stage of preparing Windows 2000 for prime time. This last and most massive part of testing is occurring not within Microsoft but at beta sites of the company's key customers and partners, including thousands of firms that manufacture the accompanying computer hardware and complementary software applications. All told, the final test version of Windows 2000 is being poked and prodded in 23 languages and 130 distinct dialects at 300,000 corporate sites located in more than 50 countries.

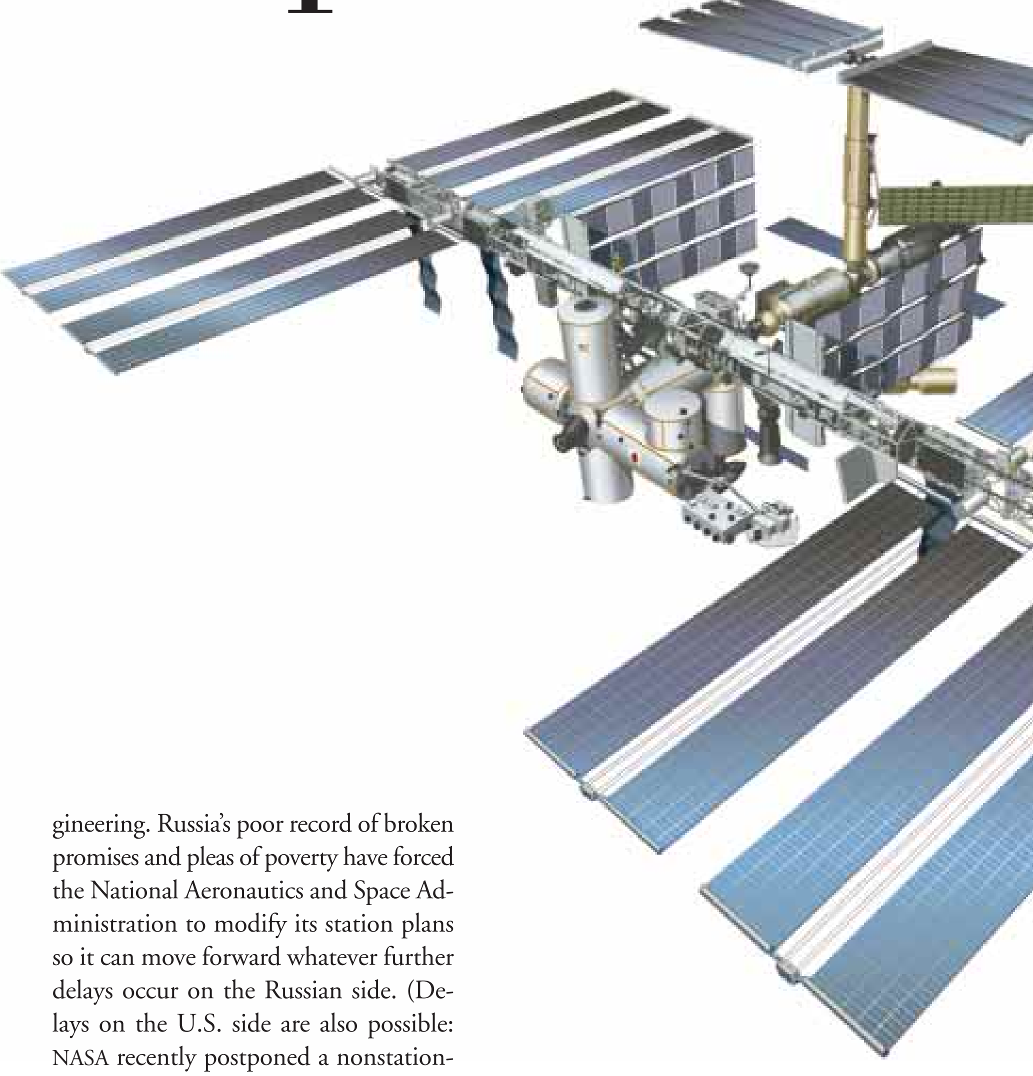
At press time, Windows 2000 was scheduled for official release in the fourth quarter of 1999, nearly a year late (not uncommon in large software projects). Many financial analysts who follow Microsoft believe the company's future will depend on the success of the product. If that turns out to be true, every bug fixed will have been well worth the effort. SA

About the Author

EVA FREEMAN is a freelance high-technology writer based in Bellevue, Wash. She prefers to use the Macintosh operating system.

Life in Space

by Tim Beardsley



As long as no last-minute problems intervene, the International Space Station will come to life in earnest sometime in the next few months. In December 1999 or January 2000 the long-delayed Russian Service Module, Zvezda (“Star”), will dock with the station components already flying—the U.S. Unity node and the Russian-built Zarya (“Sunrise”). Because it will provide power and living quarters during the station’s early years, Zvezda is the most vital component of the whole huge program. Its successful docking will clear the way for the first station crew, a U.S. astronaut and two Russian cosmonauts, who are scheduled to arrive in March 2000. By the time this pioneering party returns to Earth five months later, the station should have its initial complement of solar panels and other essentials for long-duration spaceflight, delivered by three U.S. shuttle missions.

A successful launch of Zvezda will be a triumph not only of technical engineering but also of political and financial engineering. Russia’s poor record of broken promises and pleas of poverty have forced the National Aeronautics and Space Administration to modify its station plans so it can move forward whatever further delays occur on the Russian side. (Delays on the U.S. side are also possible: NASA recently postponed a nonstation-related September flight of the shuttle *Endeavour* because of an electrical problem.) Should any obstacle prevent Zvezda from docking with the embryonic orbital outpost, a backup U.S. Interim Control Module—designed when it was unclear whether Russia would ever complete Zvezda—could be ready to fly just nine months later, according to station senior engineer W. Michael Hawes, Sr. And NASA will most likely launch the Interim Control Module at some point even if Zvezda does join the station, because the U.S. module will help preserve the project schedule in the event of future launch or technical problems.

After Zvezda, NASA is banking on rather little by way of space station help

The International Space Station, the only extraterrestrial construction project, will be ready for inhabitants by March 2000

ILLUSTRATION BY GEORGE RETSECK; PHOTOGRAPHS COURTESY OF NASA

IT'S NO HOLODECK: Life on board the International Space Station is not all work. A mock-up of the station here on Earth offers a glimpse of the facilities that astronauts can expect (*from left, on opposite page*): the movie "theater," the hand-washer, the kitchen and dining area.

from Russia. Under the terms of the original agreement with Russia, that country was to build, in addition to Zvezda and Zarya, two research laboratories, a life-support module and a solar-panel tower. There are no signs that Russia is putting any significant effort into the research laboratories. The same is true, Hawes reports, of the supposed life-support module; consequently, Boeing is now building a component known prosaically as Node 3 that will provide room for life-support equipment that originally would have been housed in the Russian module. NASA is also proceeding with plans to construct a propulsion module not foreseen in the initial plan. It will ensure that the station stays in orbit even if, as now seems likely, Russia cannot deliver on its commitment to provide seven refueling flights each year.

Despite Russia's weak performance, Hawes sees grounds for optimism that it will yet play a constructive role. The Russian Space Agency has recently restarted design work on its solar-panel tower, and although the Russian space program is still underfunded, it has at least been receiving regular disbursements for the past year, Hawes notes—a definite improvement. "Things are getting better from a financial standpoint," he says.

Moreover, the Russian and U.S. teams tracking and monitoring Zarya and Unity from their respective countries have started to work well together, according to Hawes. Other components are also taking shape: Italy recently delivered a storage module, and Japan is making progress on its lab module. The space station—arguably one of the most complicated engineering tasks ever attempted—could be ready to support its full crew of seven as early as November 2004. SA

TIM BEARDSLEY is an associate editor at Scientific American. *He would consider staying on the space station only if he could bring the 50 pounds of books he is always planning to read, along with his collection of Emerson, Lake and Palmer CDs.*

A Small

Miniature diagnostic labs, PCR-on-a-chip, reports from the world of microscopic

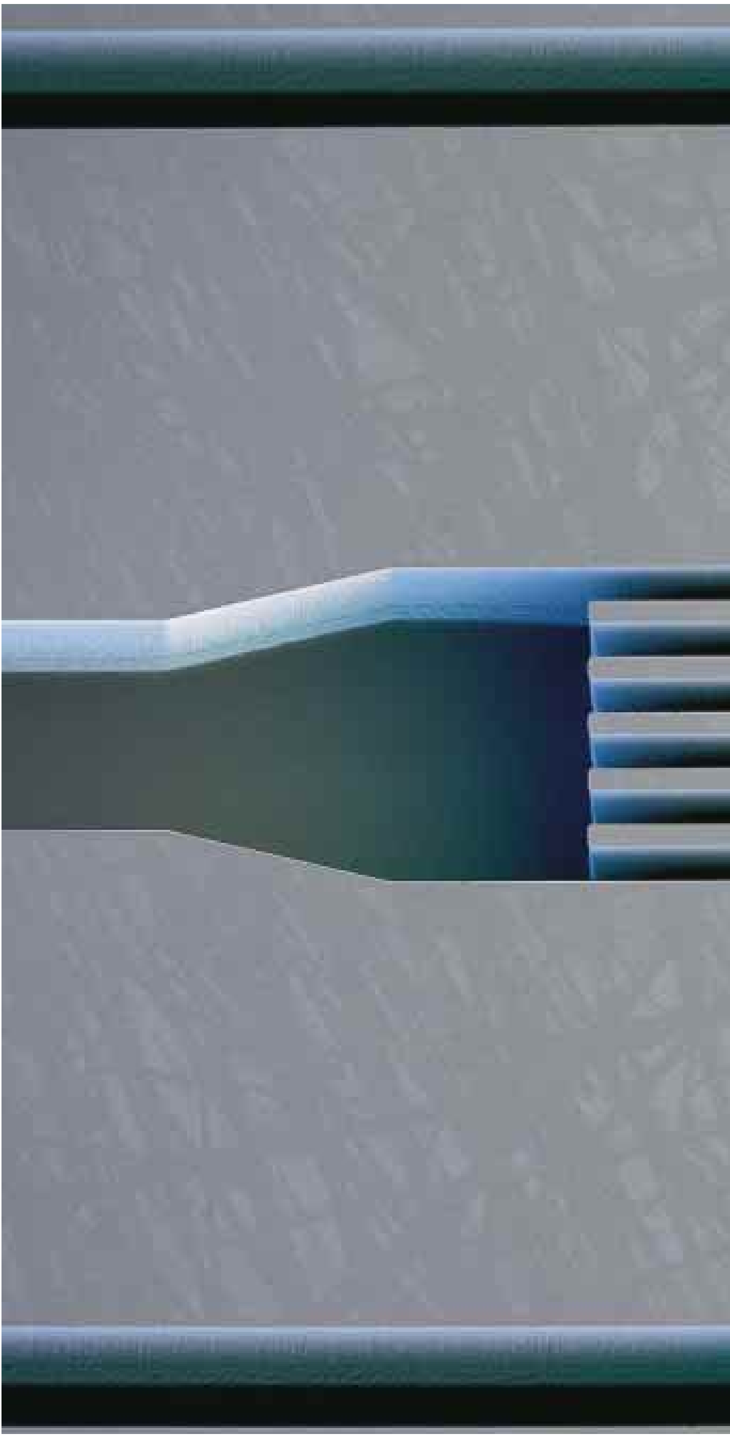
by David Voss

Back in the 1966 movie *Fantastic Voyage,* a band of intrepid travelers were scrunched down to the size of blood cells so they could swim through the veins of a big-shot diplomat and destroy a life-threatening blood clot. Today real-life explorers are attempting projects along the same lines: they are trying to shrink whole biomolecular laboratories and diagnostic instruments to such a size that they can be implanted in the body or easily carried around for on-the-spot analysis and treatment. These researchers are using the tools of bioMEMS—*m*icro*e*lectro*m*echanical *s*ystems with *bio*logical applications—in which everyday objects such as pipes, valves and pumps are re-created at dimensions of one micron (one millionth of a meter), or about the size of a bacterium.

Techniques for manufacturing miniature tools, such as photolithography and micromachining, hold the promise of producing biocompatible gadgets so small you could put 1,000 of them on a pencil eraser and so inexpensive you could use them and then brush them away like dust. High-tech but cheap gadgets are extremely desirable in biology and medicine: for instance, doctors would love to analyze test results using sophisticated chips that are as sterile and disposable as hypodermic needles or tongue depressors.

With such goals in mind, researchers have been asking if the complex technology of DNA sequencing and gene analysis could be reduced to the size of a credit card. Then perhaps you could carry around a credit-card-size biolab, breathe into it and find out if you were about to get the flu, based on which microbes were present in your system. Medical tests that currently require days in a large diagnostic lab might take minutes and cost much less. Now scientists are going beyond asking the questions to producing working models.

Chemistry labs around the globe spend many years and huge sums of money sifting through and testing collections of millions of compounds in search of those few that might have medical uses. With miniaturization, however, the lengthy slog through the chemicals in a pharmaceutical library might be slashed dramatically, resulting in many more successful drugs at lower cost. (Other time-consuming tasks such as gene sequencing make attractive



DAVID SCHARF; DEVICE COURTESY OF CEPHEID

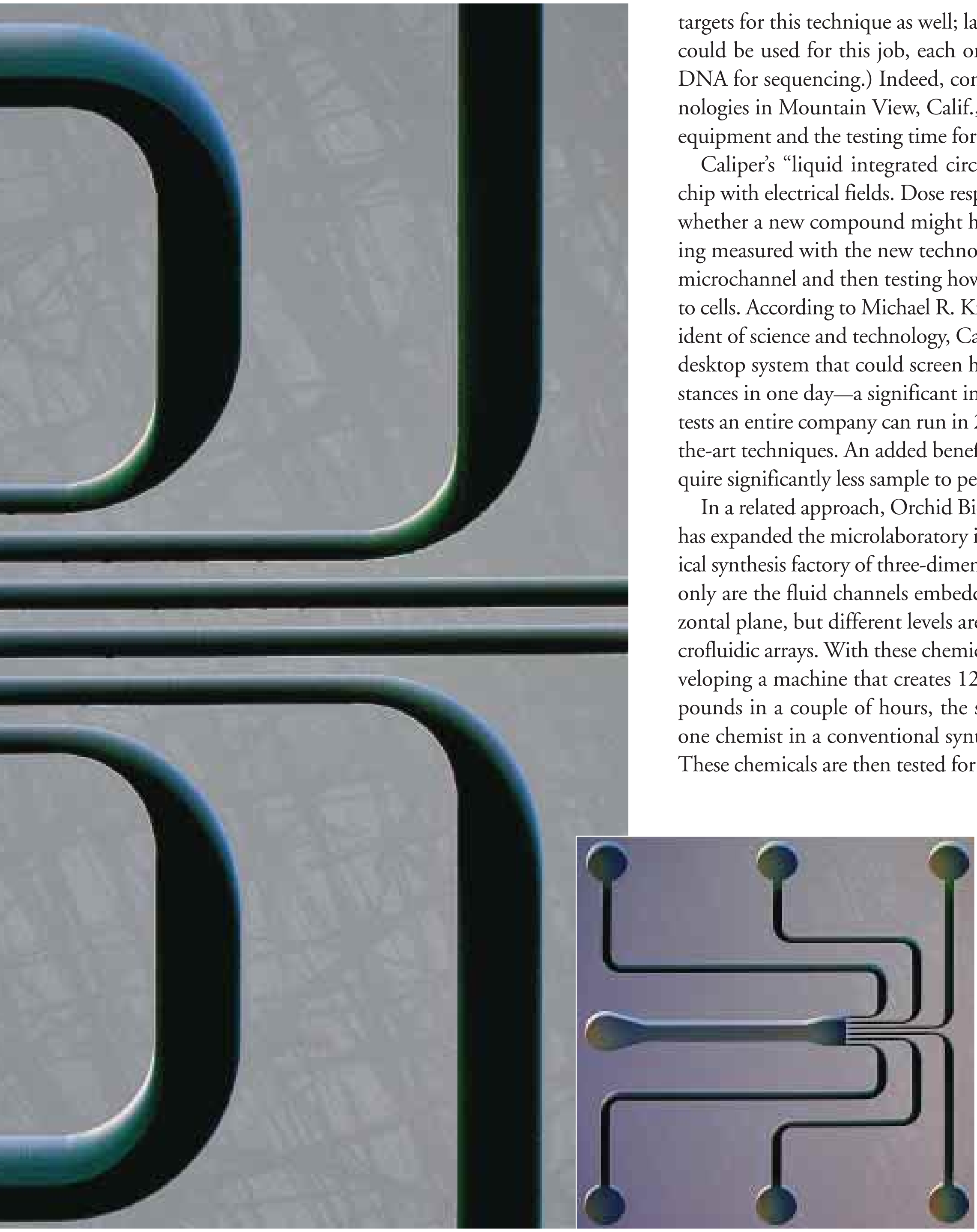
World

handheld biotoxin sensors and other biological and medical devices

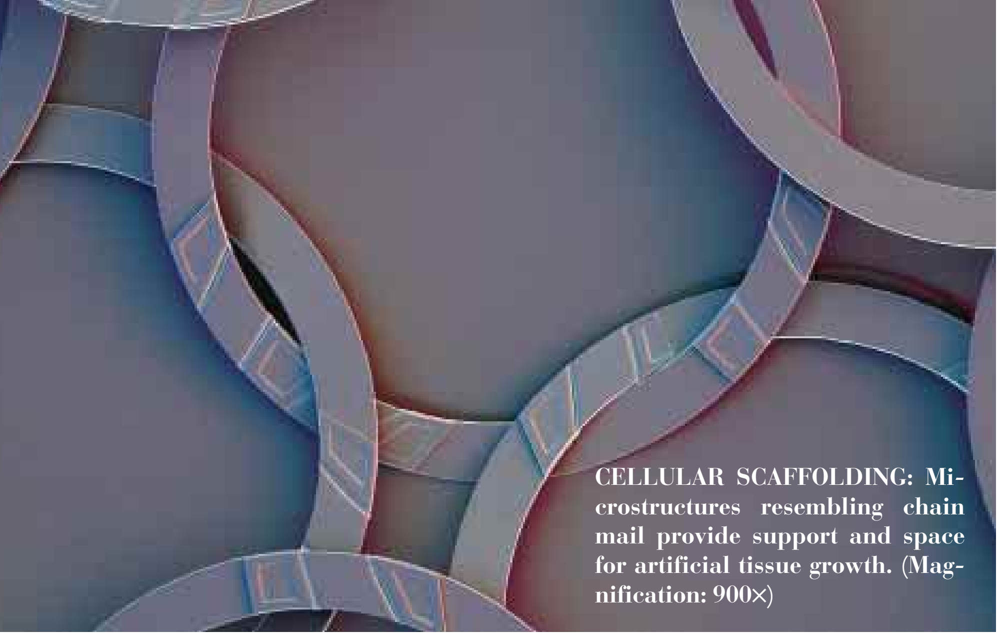
targets for this technique as well; large batches of micromachines could be used for this job, each one grabbing a small chunk of DNA for sequencing.) Indeed, companies such as Caliper Technologies in Mountain View, Calif., are trying to shrink both the equipment and the testing time for finding new drug candidates.

Caliper's "liquid integrated circuits" move samples around a chip with electrical fields. Dose response curves, a benchmark for whether a new compound might have a biological effect, are being measured with the new technology by combining fluids in a microchannel and then testing how strongly the substance binds to cells. According to Michael R. Knapp, the company's vice president of science and technology, Caliper's goal is to create a single desktop system that could screen hundreds of thousands of substances in one day—a significant improvement over the 100,000 tests an entire company can run in 24 hours with current state-of-the-art techniques. An added benefit would be that microlabs require significantly less sample to perform tests.

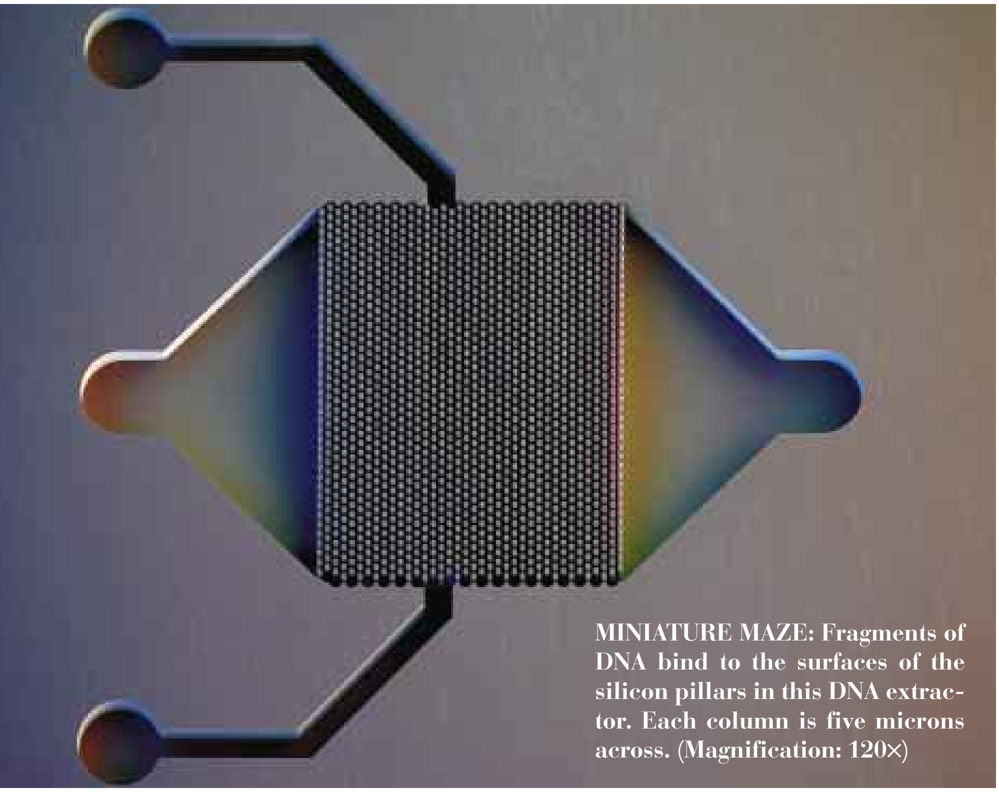
In a related approach, Orchid Biocomputer in Princeton, N.J., has expanded the microlaboratory into a massively parallel chemical synthesis factory of three-dimensional microfluidic chips. Not only are the fluid channels embedded inside the chips in a horizontal plane, but different levels are hooked up to make 3-D microfluidic arrays. With these chemical factory chips, Orchid is developing a machine that creates 12,000 different chemical compounds in a couple of hours, the same amount of time it takes one chemist in a conventional synthesis lab to run one reaction. These chemicals are then tested for use as possible drugs.



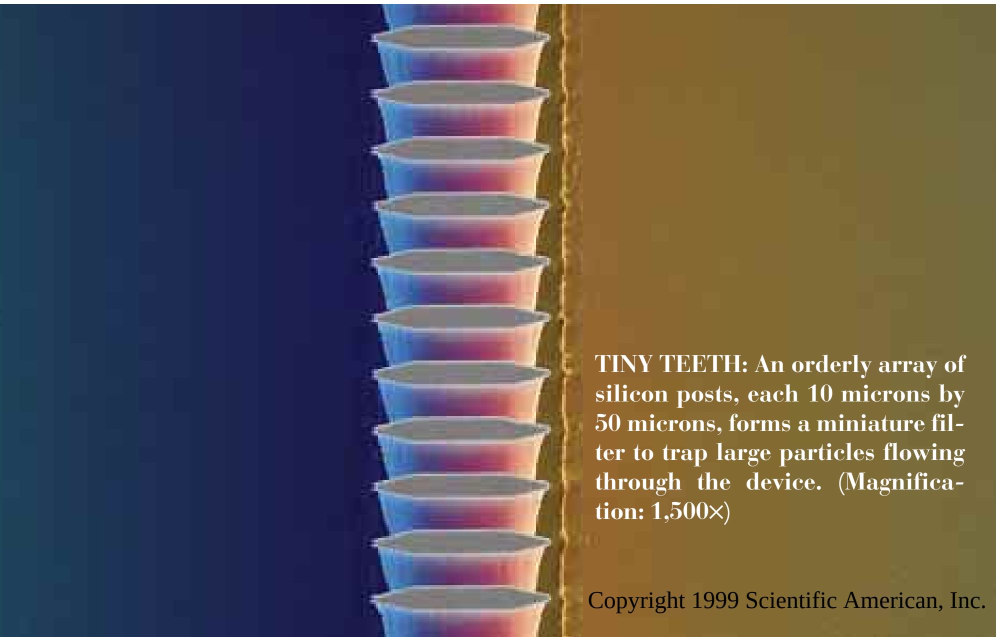
MICROCHANNELS: The miniature mixing chamber (*inset*), sculpted in silicon, allows chemical reagents to mix during DNA analysis. The channels (*left*) sweeping away from the main chamber are 20 microns wide. (Magnification, *left:* 560×; *inset:* 69×)



CELLULAR SCAFFOLDING: Microstructures resembling chain mail provide support and space for artificial tissue growth. (Magnification: 900×)



MINIATURE MAZE: Fragments of DNA bind to the surfaces of the silicon pillars in this DNA extractor. Each column is five microns across. (Magnification: 120×)



TINY TEETH: An orderly array of silicon posts, each 10 microns by 50 microns, forms a miniature filter to trap large particles flowing through the device. (Magnification: 1,500×)

One particular reaction-on-a-chip has garnered special attention: chemistry professor Andrew de Mello and his co-workers at Imperial College of the University of London made headlines in 1998 with their device for running PCR on a chip. PCR, the polymerase chain reaction, is the workhorse of gene research. It's a chemical copying machine that takes small pieces of DNA in low concentration and generates exact replicas until there is enough sample to study. De Mello is now refining his prototype system. "The goal is to have a system where you can take the instrument to the sample, not the sample to the instrument," he says. This arrangement would shorten the length of time it takes to get results as well as lower the costs of analysis.

By carrying out the reaction in a tiny microchannel on a chip, rather than on laptop-computer-size plastic trays, scientists can take advantage of some unusual characteristics of reduced size. Matter behaves differently at micron dimensions; for instance, the physics of fluid flow are completely different. It is almost impossible to create turbulence in such small systems, so fluids can stream along side by side and never mix until they are forced to do so in a reaction chamber, thus eliminating some of the plumbing typically required for moving fluids around. Furthermore, heat transfer is rapid through such a small system, so temperatures can be raised and lowered quickly. As a result, de Mello says, his group can carry out the heating and mixing required for PCR in about 90 seconds instead of hours.

De Mello's team is now working to shrink down the other system components, such as the detection module. This device processes the results of PCR and adds fluorescent tags that light up if specific gene sequences are present. Right now his system uses a large gas laser that covers an entire tabletop; de Mello hopes to replace this setup with a solid-state laser about the size of a match head.

The ability to create these minilabs brings scientists closer to producing what some are calling "personal diagnostic systems," devices about the size of a Palm Pilot that take a blood or tissue sample, do a complex series of biochemical tests

DAVID SCHARF; DEVICE COURTESY OF KAIGHAM J. GABRIEL *Carnegie Mellon University (top)*; DEVICE COURTESY OF CEPHEID *(middle and bottom)*

and then display the results. It would be a big step forward for rapid screening for HIV, checking for toxins in food and testing for environmental contaminants.

Researchers at companies such as Cepheid in Sunnyvale, Calif., are developing handheld systems based on microfluidics and microelectronics. "We are now demo'ing our GeneExpert," says company president Kurt Petersen. "It takes five milliliters of urine and detects infectious diseases [including chlamydia and gonorrhea] in about 30 minutes." Results from such procedures usually take about two days to come back from a conventional diagnostic lab, he notes.

But microsystems are not limited to merely analyzing fluids taken out of the body. Researchers also are designing systems to put material directly into the body. One such application being considered is implant technology for diabetics. Not only are the daily lancings to check blood glucose levels and the insulin injections a painful burden, but the variations in blood chemistry caused by the discrete dosing are anything but optimal. A better treatment might be a continual trickle of insulin in response to constant monitoring of glucose concentration.

Marc Madou, director of the bioMEMS group at Ohio State University, has been working on his own version of this concept. His group has developed a material with an array of tiny holes and little artificial muscle elements that expand and contract in response to chemical changes. The idea would be to make an insulin reservoir out of this array and have the pores open and close in response to glucose levels, creating a direct chemical feedback loop. Madou says this is not feasible now but may be in several years, once researchers resolve the issues of how to prevent proteins in the body from clogging pores, how well the valves will close and what the leakage rate will be.

Another possible future use of bioMEMS is what Kaigham J. Gabriel, professor of electrical and computer engineering and robotics at Carnegie Mellon University, calls the "smart" hip joint. It's a striking example of how bioMEMS could integrate sensing and telecommunications. Hip replacement, now a fairly common medical procedure, involves replacing the worn-out joint with an artificial one made of titanium, ceramic and polyethylene. Unfortunately, after several years the artificial joint often loosens from the stresses of normal use, requiring surgical repair. Gabriel speculates that it might be possible to incorporate micropressure sensors into the area around the joint that would send data about the forces acting on the contact surfaces back to an external receiver. Other bioMEMS devices incorporated into the joint could realign the contact points, making it possible to adjust the configuration of the artificial joint constantly and thereby prolong its life.

Although smart hip joints may appear to be decades away, much progress is already being made. A group led by Farid Amirouche, a professor of mechanical engineering at the University of Illinois at Chicago, has tested pressure-sensitive films positioned inside joints. The data from these sensors will allow surgeons to position hip implants more accurately. Amirouche expects to start human clinical trials soon.

And if we can monitor the inside of our bodies, what about the surface? David J. Beebe of the University of Illinois at Urbana-Champaign has been working on a material that he calls "smart" skin, a flexible polymer film studded with tiny sensors. Smart skin isn't intended to replace natural skin but rather to serve as a way of obtaining data about how the body functions. It can be applied to fingers like bandages, and it reports back on stresses experienced during some hand activity.

Smart skin could, for example, be used to determine what forces acting on the joints of the hand might cause carpal tunnel syndrome; the data acquired from fingers moving on a keyboard could be correlated with mechanical models of the internal forces acting on the bones, muscles and nerves as a way to understand, prevent and treat the syndrome. Beebe says the sensors can also be used to study the bedsores that plague bedridden hospital patients and the wheelchair-bound.

Other explorations of bioMEMS are in the service of protecting soldiers from biological and chemical weapons. Such agents act in countless ways, but the one thing they all have in common is that they make cells sick. So why try to design a synthetic sensor when you can let the cells do the sensing, reasons Gregory T. A. Kovacs, a physician and professor of electrical engineering at Stanford University.

Kovacs has found a way to use cells as miniature sensors in a handheld detection system—a miniature canary-in-a-coal-mine. A thousand or so cells harvested from chickens or rodents are grown in a cheap disposable cartridge and maintained with life support to regulate temperature and to supply nutrients. When something comes along to disturb the cells—such as toxic chemicals or bacteria-laden air—the monitoring equipment detects changes in the cells' electrical activity. An onboard microprocessor registers the disturbance and sounds the alarm.

After years of the hype and sound bites that have typically characterized the field of MEMS research, Kovacs is pleased to report that real systems are now starting to be demonstrated in rigorous ways. "The upside of this field is huge," he says. But Kovacs is quick to point out that despite very real progress, obstacles remain. In particular, researchers must address the issue of getting bioMEMS to interact in living environments where proteins are sticky, blood often clots, and bodies tend to surround implants with protective tissue. And scientists need a greater understanding of the biocompatibility of the materials in MEMS before any of our blood vessels or organs are retrofitted with microhardware. Yet with each advance, the scenario in *Fantastic Voyage* moves closer to science than fiction.

About the Author

DAVID VOSS is a freelance writer based in Silver Spring, Md. He dreams of having intelligent agents to research his articles and a flock of nanorobots to do the writing, leaving him more time to spend on the beach.

Bringing Back

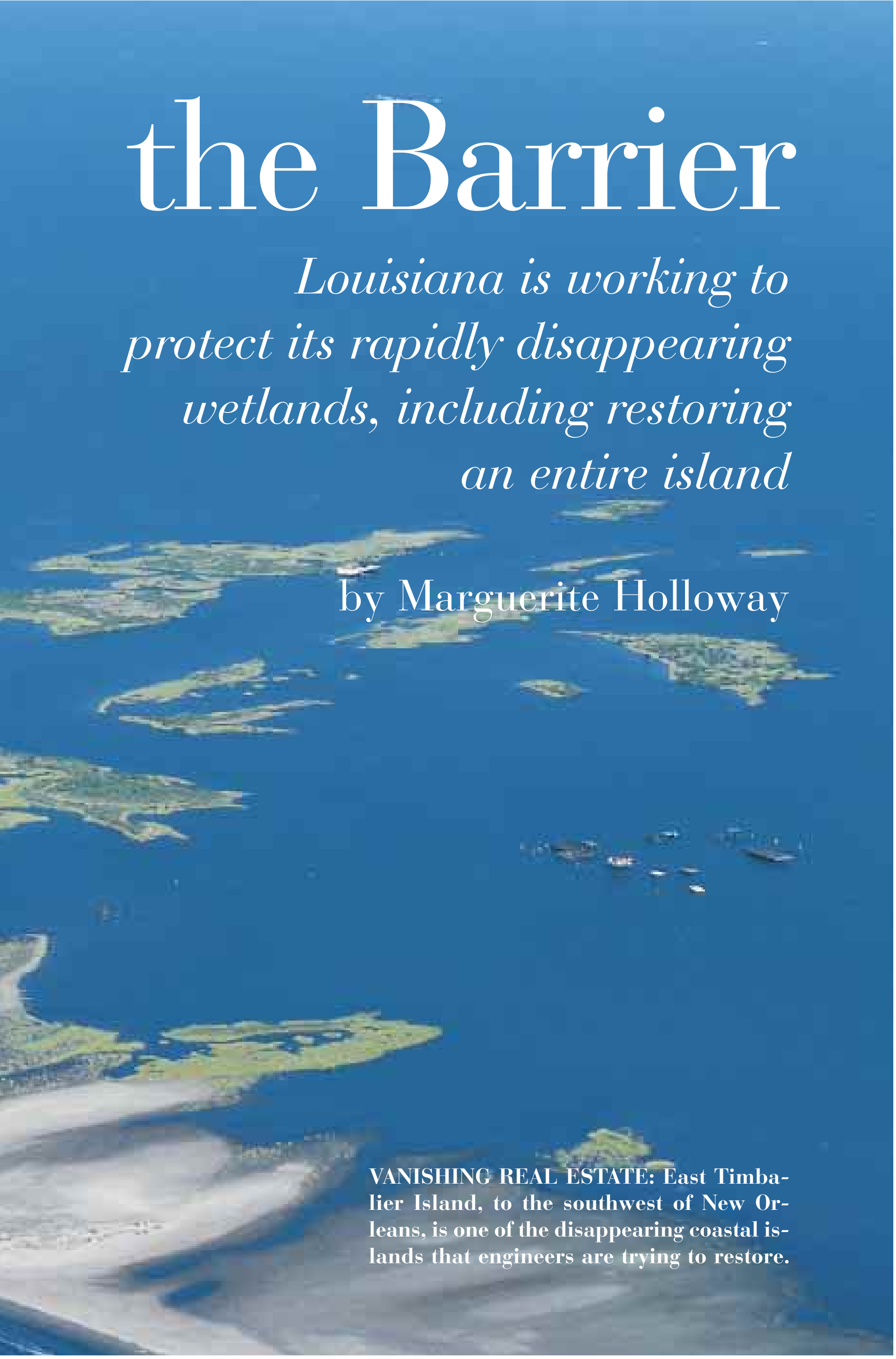
From the air, it is clear that East Timbalier Island is just a shadow of its former self. One in a series of barrier islands that protects about a third of the fragile Louisiana coastal wetlands from the eroding winds and waves of the Gulf of Mexico, East Timbalier used to stretch four and a half miles from east to west. It was a gently curved, shallow crescent where migrating shorebirds rested and where, in the 1940s, Cajuns came to camp and fish. Now the outline of the original island can be traced only by connecting the dots—those patchy remains of dune or marsh that make up the battered bits of East Timbalier. Narrowed and nipped by subsidence, hurricanes and erosion and gouged by canals from oil and gas exploration efforts, East Timbalier has been expected to disappear in just a few years, perhaps even as early as 2004.

And so it would have if Al Mistrot and his team hadn't spent this summer turning back the tide. Mistrot, an engi-

the Barrier

Louisiana is working to protect its rapidly disappearing wetlands, including restoring an entire island

by Marguerite Holloway



VANISHING REAL ESTATE: East Timbalier Island, to the southwest of New Orleans, is one of the disappearing coastal islands that engineers are trying to restore.

ALL PHOTOGRAPHS BY ALEX MacLEAN *Landslides*

neer who is working for the Louisiana Department of Natural Resources, and his crew of 57 men have been laboring in two shifts, 24 hours a day, to rebuild East Timbalier to its late-1950s condition. By moving massive amounts of sand and shaping it into dunes and marshes, they are building in just a few months what it took currents and wind and the Mississippi Delta thousands of years to create. They are building it with the knowledge that their handiwork will be washed away, that the new East Timbalier will be as temporary as the old one, that in the long run, the Gulf will win.

But, for the time being, the important thing is to keep East Timbalier afloat beyond 2004. Barrier islands—those shifting ribbons of offshore sand—are important habitats. Those along Louisiana, in particular, provide wintering places for 70 percent of the waterfowl migrating through the central U.S. In 1907 President Theodore Roosevelt designated East Timbalier a federal bird sanctuary, and although it no longer holds that status, black skimmers, royal terns and sandwich terns have recently nested there. The barrier islands and their marshes also provide nurseries for fish and shrimp. And Louisiana State University researchers are discovering that barrier islands are crucial nurseries for sharks.

By reducing wave energy, the barriers also keep waters calmer in coastal bays, thereby protecting fishermen, oil and gas infrastructure, and the critically important shoreline marshes. Louisiana contains 40 percent of the coastal wetlands in the contiguous U.S., and 80 percent of wetland loss occurs there: about 25 square miles (66 square kilometers) disappear every year. At this rate, according to one recent study, New Orleans will be a coastal city in just 50 years. And if East Timbalier disappears, Port Fourchon—the nearby hub for the oil and gas industry—will wash away well before the French Quarter becomes beachfront property. “If we lose our barrier island, this facility will become an island,” explains Ted Falgout, director of the port. “We need a restrictive force; otherwise huge currents and tidal exchange suck the land right out of the marsh.”

For these many reasons, Mistrot and his colleagues found themselves on this slip of land for the summer. Their work moving sand began in early July with the arrival of a dredge called the *Beachbuilder*. The dredge is stationed to the west of East Timbalier in a channel called Little Pass, where, like a gargantuan vacuum cleaner, it inhales the bottom of the Gulf. Powerful jets of water loosen the sediment, which is then sucked up and injected into a floating pipe that runs 1,850 feet (562 meters) away from the boat before plunging 20 feet to the bottom and connecting with a steel pipe that workers laid down on the Gulf floor. Like an umbilical cord, the buoyant flexible part of the pipe allows the *Beachbuilder* to move back and forth as it does its work, as well as up and down with the often four-foot waves of the channel.

Once on the bottom, the pipe runs about three miles to East Timbalier, where it spews out the mixture of sand

and water at the feet of the land crew. The men on the island let the water drain off and the sediment accumulate. The quantity of runoff is carefully calculated to ensure that enough sand builds up. The engineers have estimated a cut-to-fill ratio of 1.5 for this project; in other words, about a third of what is taken from the Gulf floor washes away when it reaches the island. By the end of the project, nearly three million cubic yards of watery sand will have been pumped into East Timbalier.

After enough sand has accumulated to fill in a gap in the island, backhoes push it into place. To approximate East Timbalier as closely as possible, the sand must be shaped into the right elevations for dunes and marshes. To protect the island for what the experts term a nine-year storm return—which, oddly, translates into an 18-year life span—the dunes need to be at an elevation of five feet. To function optimally, the marshes need to be lower, at a height of two feet—which will allow for subsidence and an ultimate elevation of about one foot. “You want the water to flush in and out,” Mistrot says. If the sand is packed is too high, it won’t become a marsh, even after it is planted next spring, which could have devastating consequences, he adds. Mistrot, who is on loan from the Army Corps of Engineers, has worked on many restoration efforts in the region and remembers one failed marsh that led to an outbreak of avian botulism because the birds’ waste was not being regularly flushed out of their feeding site.

By mid-July the westernmost section of East Timbalier has been filled in. The wet sand looks gray, and the elevations are clearly cut, like steppes. White herons, sandpipers, skimmers, terns, gulls and pelicans ply the recently upheaved sand for small crustaceans and other benthic treats. A remnant of the original marsh on this part of the island has been carefully protected, and the exacting Mistrot talks with the backhoe operators again to make sure they keep the machines away from the wetlands.

Because this western section is complete, the pipe has just been extended east—segment by segment—from the outflow point toward the next lacuna in the island. By the time they are finished, the workers will have stretched pipe all the way to the remote eastern fragment of East Timbalier, which lies across a mile and a half of water from the more intact body of the island. Filling this huge, watery divide will be a challenging part of the project because no marsh or remnants of beach exist to build on. But in July no one is worrying about that much. They have a bigger problem.

The project engineers chose Little Pass as the place to remove sediment because it is where the eroding sands of East Timbalier have been flowing. And the *Beachbuilder* was chosen because it has several long anchor lines, which means it can ride out the large waves of the Gulf with relative ease and stability, explains David Rabalais of Picciola and Associates, the engineering company overseeing the project. It also has about eight feet of freeboard—that is, the distance between the water and the deck—so it can handle high seas. The trade-off was that the *Beachbuilder* can only loosen sediment using its high-pressure water jets and then pump it away. It does not cut into sand, as a traditional cutter dredge would. A cutter dredge can chop through tough material such as clay, but it has less freeboard—only about two to three feet—and several rigid columns, or spuds, that keep the dredge in position but that can also be snapped during rough weather. A week or so into the project, however, it was clear that Little Pass was full of densely packed clay that the *Beachbuilder* simply couldn’t remove.

In August, after about a month of struggling to increase the water pressure of the jets and thereby move more sediment onto the island, the dredge contractor—Weeks Marine in Kenner, La.—gave up and brought in a cutter called the *Arkansas*. They had been pumping an average of only 12,000 cubic yards a day with the *Beachbuilder,* as opposed to the anticipated 40,000 cubic yards. Because their contract pays them for how

REBUILDING AN ISLAND: The restoration of East Timbalier Island entails several stages (*from left to right*). Two dredges pump sediment into a pipe that runs several miles to East Timbalier. The watery sediment gushes out of the pipe and gradually accumulates. Backhoes then push this sand and clay into the right elevations for dunes and marshes. Recently filled-in sections of the island appear light gray; restoration will ultimately join the main part of the island with the remnant seen in the distance.

much they cut, Weeks Marine was watching money wash away almost as fast as East Timbalier was.

By late August the new dredge was finally extracting more than 30,000 cubic yards daily, according to Rabalais and Mistrot. But the project was by then two months behind schedule and may not finish until the end of October. As the fall hurricane season approaches, "we are very likely to get rough weather," Rabalais says. "In thunderstorms it can get real choppy and rough. They would have to stop dredging."

The question of constructing offshore dikes presents yet another complication for the restoration effort. The eastern part of the island has several strips of rocks that sit way off in the water—along the original shoreline of East Timbalier—and that were placed there in the 1960s and 1970s to protect the oil and gas infrastructure on the island from hurricane damage. But there is a gap of more than a mile in the dike between the western end and the easternmost tip of the island. Putting down a five-foot dune along that section without also putting in an offshore dike makes little sense to Mistrot, Rabalais and Dave Burkholder of the Louisiana Department of Natural Resources. "If I were designing the project today, I would put rock all along there," says Burkholder, noting that East Timbalier lost about 25 acres just in the past year because of storms. He adds that Hurricane Bret alone washed away about 3,300 cubic yards of recently dredged dune.

And so, during a recent visit by officials from the National Marine Fisheries Service and the secretary of the Department of Natural Resources, Mistrot and others made a pitch for more funding. They estimated that they need about $250 to $300 a foot for four tons of rocks and the durable plastic material, called geotextile, that rocks must be laid on so the ocean floor doesn't wash away beneath the dike. The additional $1.5 million or so would push the total cost of the project over $13 million—85 percent of which is paid for by the taxpayer-funded National Marine Fisheries Service and the remainder by the Louisiana Department of Natural Resources. But the agencies decided not to put up money this season.

Whether it will be allocated to East Timbalier in the future is anyone's guess. East Timbalier is just one of 18 restoration projects that the National Marine Fisheries Service oversees in Louisiana. In 1990 Congress passed the Coastal Wetlands Planning, Protection and Restoration Act, setting aside $35 million a year to protect Louisiana's wetlands. The National Marine Fisheries Service works with other state and federal agencies to manage about 90,000 acres of wetlands in the state. Several of these projects entail protecting the barrier islands to the west of East Timbalier, and in large part the biologists and engineers have been figuring out the science as they go. "Seven or eight years ago no one knew how to do this," says Tim Osborn of the National Marine Fisheries Service.

In that time, Osborn adds, expectations of what restoration means have also changed. Scientists are not trying to re-create the original exactly—an impossible task, given that the ecosystems of Louisiana have been so altered by people. Indeed, that would mean getting rid of the 29 locks and dams on the Mississippi River, letting its sediment run down into the delta again to rebuild the marshes and barrier islands and letting the mighty river jump 100 miles—right over New Orleans—to join the Atchafalaya River, the channel it has been wanting to flow into for about a century. A complete restoration would also mean removing much of the oil and gas infrastructure.

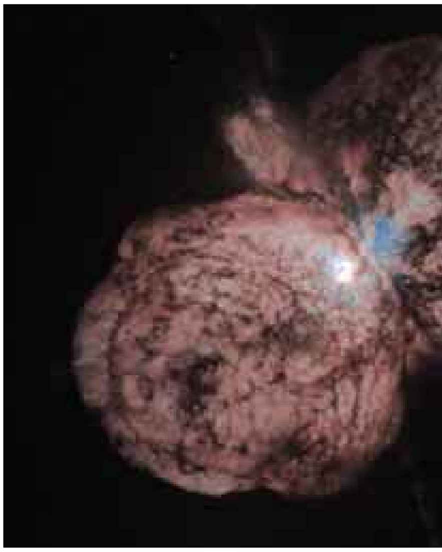
So in this highly engineered system, the goal of restoration is simply to bring back some of the characteristics and functions of the original site. In the case of East Timbalier, these include the bird and fish habitats as well as the protection offered many nearby oil and gas heads and Port Fourchon. And then, if the money and the will are there, to manage the site—but if these resources are not, to let it all wash away. "We don't expect to have what we are building in 20 years," Burkholder says. "It is just a question of where we would be without the project."

About the Author

MARGUERITE HOLLOWAY is contributing editor and chief dredge operator at *Scientific American.*

Seven Wonders of Modern Astronomy

by George Musser



View of the ultramassive star Eta Carinae

Choosing only seven wonders out of the myriad accomplishments of modern astronomy is an impossible task—just the sort I like. The mere attempt encourages a tour of the golden age of astronomy in which we are now living, a time of big questions and proportionately big efforts to answer them.

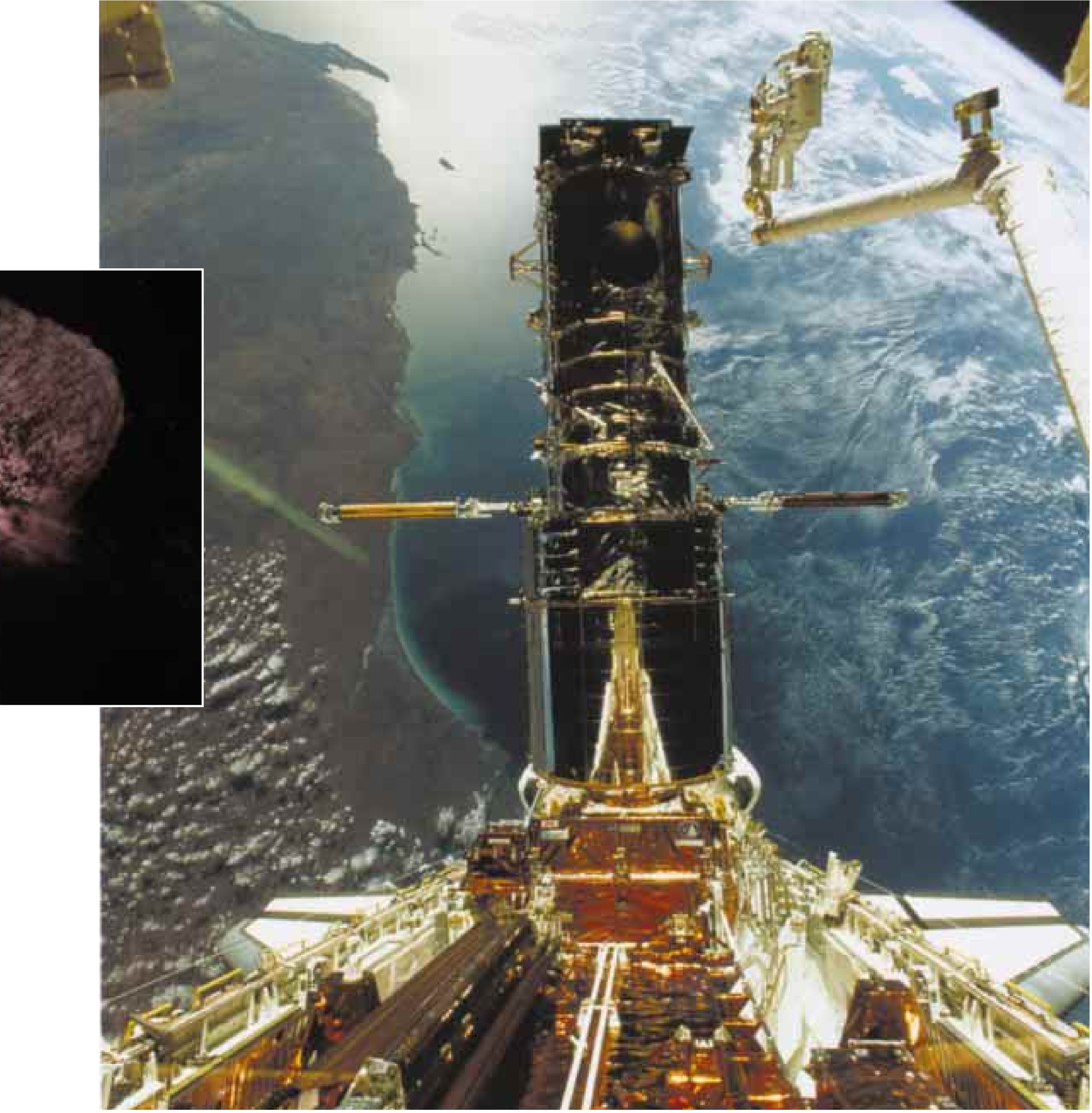
For many people, astronomy sounds like a quaint science—they imagine a recluse perched on a mountain, quietly pondering the inky skies. To a large extent it is indeed a battle of the solitary mind with the almighty heavens. But sky-watching was also the first Big Science. Nineteenth-century astronomers wielded huge budgets, commanded armies of peons and reigned over megafacilities at a time when physicists' labs were simple affairs, just some magnets and oil droplets. And the tradition extends even further back: consider the great observatories of Jaipur and Delhi, the sky temples of the Maya, Stonehenge.

Nowadays the term "Big Science" is generally reserved for particle accelerators and genome projects. Yet astronomy still qualifies, even if you leave aside planetary exploration, a subject perhaps better thought of as an offshoot of geology. A major observatory is like a factory, filled with pallets of equipment, DANGER signs, gangways, metal ladders, bustling workers and the buzzing of great machinery—all to catch a sliver of light from the dawn of time.

The wonders are many; any big adventure is really a succession of small victories. Another list might focus on the cosmic marvels themselves, but those already tend to get the attention. Some lists concentrate on the technological breakthroughs, whose size is often in inverse proportion to their importance: for instance, charge-coupled-device (CCD) microchips, the exquisitely sensitive detectors that have supplanted photographic film in observatories big and small over the past decade. Or a list might preview the mindblowers soon to come: the plans to detect new forms of radiation, say, or to see the continents and oceans of a distant planet. But here I present my own idiosyncratic selection of seven noteworthy telescopes now in operation or just gearing up.

GEORGE MUSSER is an editor at Scientific American. *He hopes one day to become chief of the magazine's Mars bureau.*

1



NASA JOHNSON SPACE CENTER; JON MORSE *University of Colorado* AND NASA (*inset*)

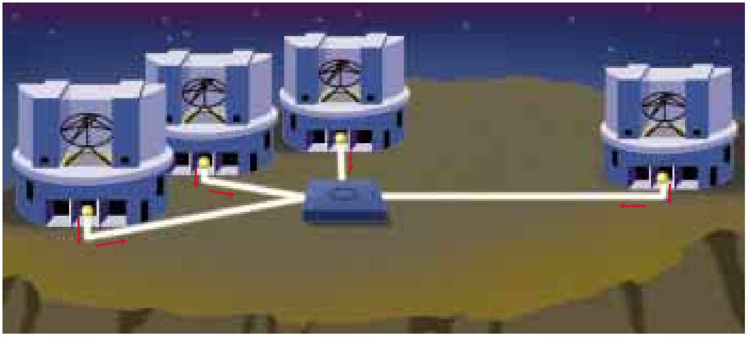
Refurbishing the Hubble Space Telescope high above the western coast of Australia

THE SHARPEST What would a list of astronomical wonders be without Hubble? The space telescope, after all, has broken all kinds of records, including probably the most newspaper headlines produced by any single astronomical project. Although its 2.4-meter (94-inch) mirror is a runt by today's standards, Hubble and its ilk are still the most complex robotic spacecraft ever built. One reason is the tracking mechanism. Above the madding clouds and turbulent distortion of Earth's atmosphere, the optics can attain its theoretical limit of resolution, but only so long as the spacecraft remains rock-steady despite the orbital motion and various buffeting forces. Hubble effects this stability using an interlinked system of mini-telescopes and flywheels.

Nine years ago, however, Hubble would have been placed on the list of projects that never made it—a victim of bureaucratic mismanagement, space program politics and technical snafus. Most infamously, the space telescope became a $1.6-billion example of the difference between accuracy and precision: because of a faulty measuring device, its mirror had been sculpted with utmost care to the wrong shape. But since astronauts fixed it in a dramatic series of space walks six years ago, even seasoned researchers have seen the universe in a new light. The gleam of comet crashes, the dainty arcs of gravitational lenses, the stellar corpses that look uncannily like eyeballs or sperm—Hubble is the Ansel Adams of our age.

EUROPEAN SOUTHERN OBSERVATORY

The summit of Cerro Paranal



LAURIE GRACE

Four telescopes act as one when their light is merged

2

THE BIGGEST The nicest thing about the Very Large Telescope (VLT) is the charm of its lyrical names. Its four constituent telescopes were recently rechristened Antu, Kueyen, Melipal and Yepun—which mean the sun, moon, Southern Cross and Sirius in the indigenous Mapuche language of Chile. It is something of an improvement on Unit 1, Unit 2, Unit 3 and Unit 4.

Each of those 8.2-meter instruments is itself a very large telescope. Ten years ago such devices were impossible, but since then engineers have developed various ways to fabricate and support their huge, unwieldy mirrors. The European Southern Observatory—the consortium that built the VLT in northern Chile for $500 million—decided on single pieces of glass just 18 centimeters (seven inches) thick. Too thin to maintain their shape on their own, they are each propped up by 150 pistons, which are readjusted whenever the telescope shifts to a new position.

What justifies the "V" in VLT, however, is the way the individual scopes will work in unison to achieve the resolving power of a whopping 200-meter device. Beginning in 2002, their light will be funneled into a central lab and merged in a technique known as interferometry. Although the technique has long been used in radio astronomy [*see opposite page*], its arrival in optical astronomy awaited two recent developments. First, laser rangers can now gauge distances to one part in a billion, the precision needed to align and merge the shorter wavelengths of visible light. Second, new adaptive optics—in the VLT's case, a small extra mirror fine-tuned 100 times a second—can correct for atmospheric distortion so that the interferometer won't merely take a sharper picture of a blurred star. Similar interferometers should even be able to detect minute disturbances in the fabric of space itself, such as might occur during the birth of a black hole.

3

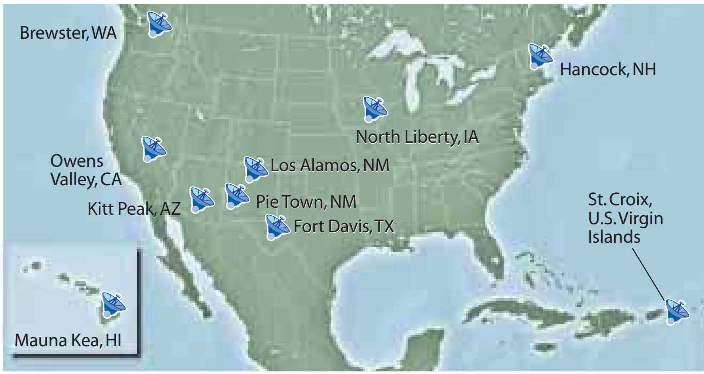
THE FARTHEST FLUNG In high school physics, my favorite lab exercise—to be honest, the only thing I remember at all—was the wave tank. For one of the experiments, we had to send a wave of water toward a barrier with two gaps. Two pieces of the wave squeezed through the gaps and then blended into a distinctive pattern. Little did I know at the time that such patterns would make possible a radio telescope bigger than planet Earth.

A telescope, too, is a gap in a barrier. It only lets through part of a wave of light; the rest gets chopped off at the edge. An observer notices this chopping as a slight smearing of the image. The larger the scope is relative to the wavelength, the less the smearing. Because radio astronomers deal with wavelengths measured in centimeters or meters, rather than in millionths or billionths of a meter, they suffer from such smearing more than their optical colleagues do.

So in the late 1940s they decided to punch another hole in the barrier. That is, they built two dishes and blended their outputs—two pieces of the same wave from a cosmic source. From the resulting pattern, they could calculate what the unsmeared light must look like. It was as though they had constructed two segments of a single telescope equal in size to the separation between the dishes.

Researchers have now taken this technique of interferometry to an extreme. Six years ago the National Radio Astronomy Observatory opened the $85-million Very Long Baseline Array: 10 radio dishes scattered from Hawaii to the U.S. Virgin Islands. Collectively they act as a single telescope more than 8,000 kilometers across. Astronomers record the signals—along with the exact time as measured by an atomic clock—and later merge them computationally. When they also mix in signals from a new Japanese radio satellite, the effective size swells to over 20,000 kilometers. For short radio wavelengths, the system produces sharper images than even the Hubble does. In fact, it is so sensitive that continental drift shows up in some of its observations.

Ten radio dishes equal one enormous telescope



Radio dish, 25 meters (82 feet) across, in Owens Valley, Calif.

NRAO/AUI; LAURIE GRACE (*map*)

4

THE MOST EXTENSIVE Here's a subversive thought: Instead of observing the cosmos piecemeal, pointing your telescope at this galaxy today and that one tomorrow, what if you just took one big picture of the whole sky? Crudely speaking, that is the goal of astronomical sky surveys, such as the Palomar Observatory sky survey in the mid-1950s. Such surveys have not replaced observations of individual celestial bodies; rather they offer a macro view of the heavens, revealing the broad patterns.

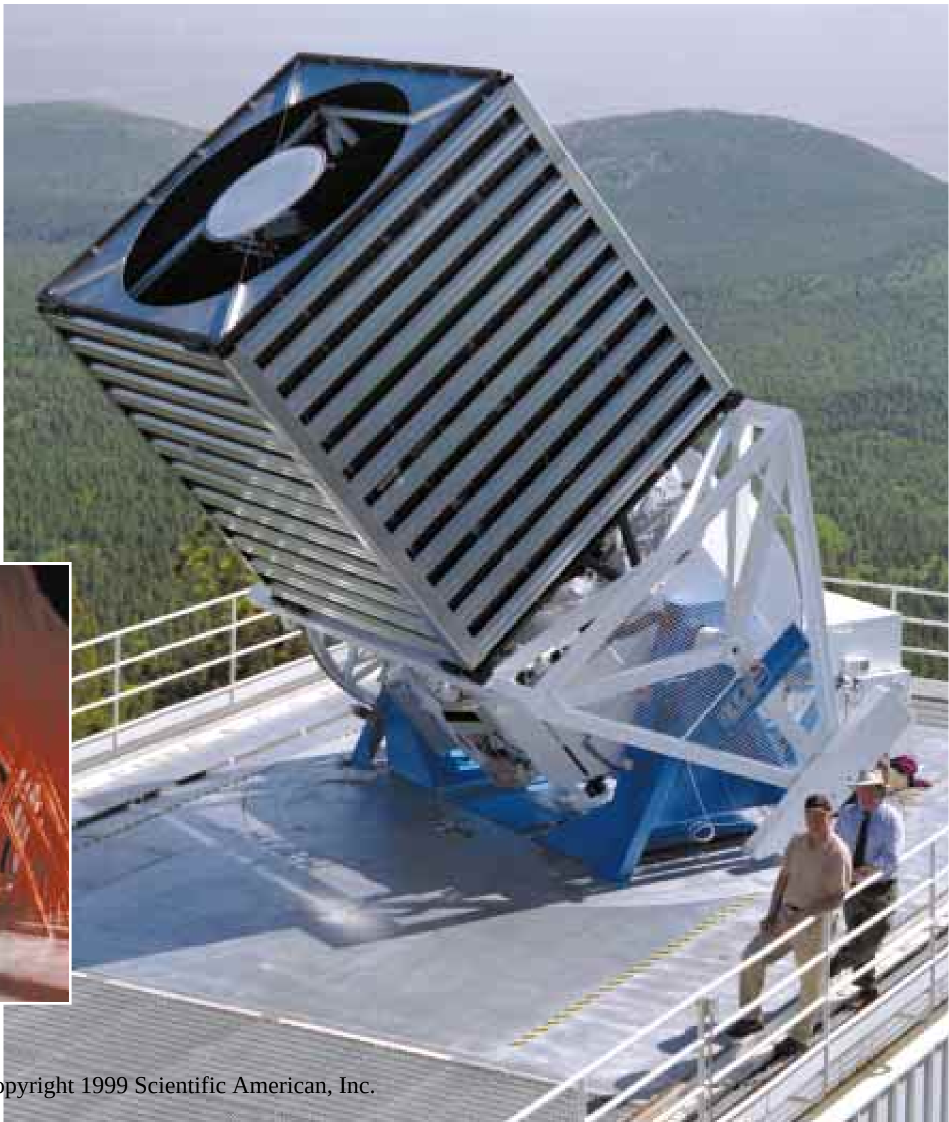
Recently astronomers embarked on the most ambitious effort yet: the Sloan Digital Sky Survey. Over the next five years, this $77-million American-Japanese collaboration will scan a quarter of the sky (avoiding the crowded Milky Way) out to a distance of 1.5 billion light-years from Earth. The researchers expect to tabulate 100 million stars, one million galaxies and 100,000 quasars. They say that if the completed data set were to be printed and bound in books by someone who had little concern for the world's trees, it would nearly fill the Library of Congress.

The survey utilizes a 2.5-meter telescope on Apache Point in southern New Mexico, specially designed to capture as much of the sky as possible at a time. The light alternately feeds one of two instruments. The first is said to be the most complex camera ever built: 54 CCDs that take images in green and red light as well as in ultraviolet and near-infrared. The second is a pair of spectrographs, fed by a forest of optical fibers so that they can analyze the light of more than 600 objects in one go.

Sloan is expected to answer a key question in cosmology: How far do you need to zoom out before the matter in the universe, which on smaller scales is blatantly clumped into planets, stars and galaxies, begins to arrange itself uniformly? By determining where this transition occurs, Sloan could help resolve the age-old debate over the fate of the universe: Will it end in fire or ice, or something else?

FERMILAB VISUAL MEDIA SERVICES; THOMAS NASH *Fermi National Accelerator Laboratory (inset)*

Apache Point Observatory



Fiber optics feeding the Sloan spectrograph

5

ROTSE-1

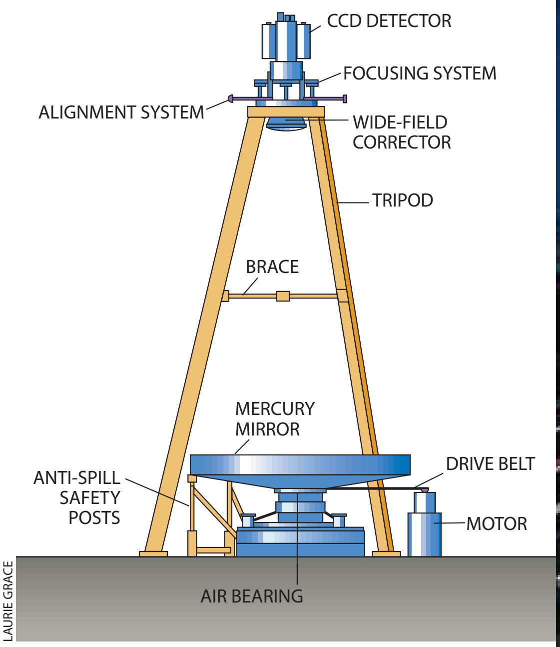
ROTSE-2

W. CARL AKERLOF *University of Michigan*

THE SWIFTEST Once upon a time pagers were only for doctors. And astronomers. As eternal and unchanging as the night sky might sometimes seem, it is actually filled with flickers and flashes, explosions and eruptions that flare up and fade out in a matter of seconds or hours. To catch these flighty phenomena, scientists have to be standing by at all hours, ready to reposition satellites and swivel telescopes at a moment's notice. In fact, this is one of the areas of astronomy where amateur astronomers, by virtue of their wide fields of view and sheer numbers, have made crucial discoveries.

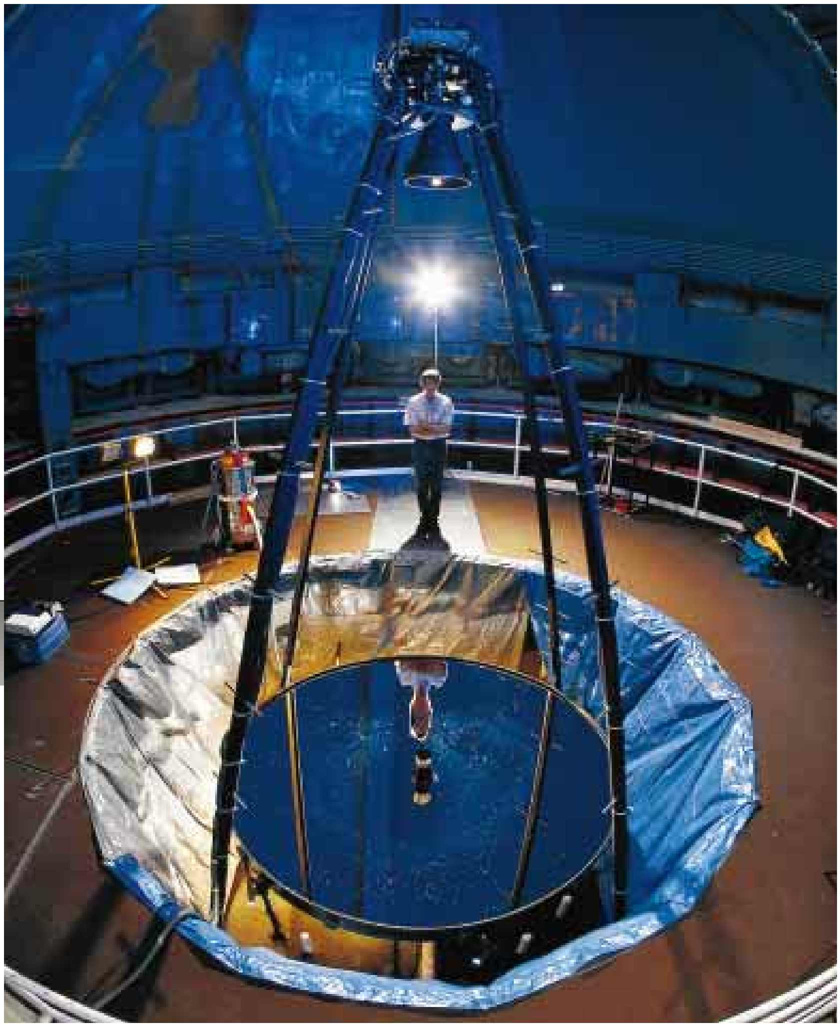
The latest entrant in the fast lane is ROTSE, the Robotic Optical Transient Search Experiment, in Los Alamos, N.M. Its first incarnation, ROTSE-1, looks like something from the camera bags of the paparazzi: a set of four 200-millimeter telephoto lenses cobbled together on a high-speed mount. The recently installed ROTSE-2 is a pair of half-meter telescopes. Whereas the standard telescope drive relies on precision gears, like a clock, ROTSE-2 uses position encoders and a feedback control loop, like a robot.

As does a sky survey [*see opposite page*], ROTSE sacrifices sensitivity and incisiveness for speed and sweep. It can capture 1 percent of the sky in a single exposure; during normal operation, it photographs the entire sky twice a night. Whenever an event of interest occurs, ROTSE suspends surveying, swings around and snaps away. In January the instrument proved its mettle. Satellites saw a gamma-ray burst—an intense but ephemeral blast of high-energy radiation—and sent out rough position information via the Internet. Within 10 seconds ROTSE had pinpointed the burst. Never before had astronomers caught such an event in visible light while it was still flaring in gammas.



LAURIE GRACE

Layout of earlier, 2.7-meter liquid-mirror telescope


CHIP SIMONS PHOTOGRAPHY

Taming quicksilver in the cause of astronomy

6

THE DEADLIEST It is enveloped in poisonous vapors that can cause progressive kidney and brain damage. It can look only straight up; slewing would create an instant toxic waste dump. In short, a mercury mirror is not for everyone. But how else could you build a six-meter telescope for $500,000?

Any swirling liquid naturally assumes a parabolic form, whereas glass requires expensive grinding and hefty supports even to approximate that shape. Over the past two decades astronomers have built several bargain-basement telescopes using mercury, the shiniest element known.

The largest will soon be the Large Zenith Telescope (LZT) near Vancouver. A collaboration among Canadian and French astronomers, the LZT contains 28 liters (30 quarts) of mercury in a large pan that spins at the rate of one rotation every 8.5 seconds. The only real hassle has been the bearing. A mechanical bearing would have been too jerky, and no air bearings of the required size were available commercially, so the team had to design its own. Still, the observatory has cost a hundredth as much as one with a glass mirror.

The restriction on pointing straight up might seem a bit of a disadvantage. But it works just fine for studying representative samples of stars, galaxies and even space junk in Earth orbit. By synchronizing the CCD output rate to Earth's rotation, the telescope can electronically track objects as they move through its field of view. Even the mercury isn't as much trouble as you might think. It oxidizes on contact with air, partially trapping the noxious vapors. To be sure, no one will go near the mirror during normal operation, and the building is sealed to contain any spill.

7

THE WEIRDEST Most telescopes look up. This one looks down. Most capture some sort of light. This one seeks an invisible subatomic particle. Most telescopes are in remote locations, but this one goes to extremes: it is buried under more than a mile of ice at the South Pole.

The Antarctic Muon and Neutrino Detector Array (AMANDA) is the world's largest detector of the mysterious neutrino—and the first that can claim to be an astronomical instrument rather than a physics experiment. It trades sensitivity for the sheer size needed to catch a meaningful number of high-energy neutrinos from distant objects, which include many of the violent felons on astronomers' most wanted list: the swirling gas around black holes, the innards of stellar explosions, the decomposition of the unidentified matter that dominates our cosmos.

So far the observatory, a $7-million collaboration among U.S., Belgian, Swedish and German universities, consists of 424 glass orbs, each the size of a basketball. They watch for the eerie blue glow indirectly emitted when neutrinos collide with atomic nuclei in the ice or underlying rock. The orbs point downward so that Earth will screen out extraneous particles. To deploy them, workers first used pressurized hot water to melt a column of ice half a meter across and 2,400 meters deep. Then they lowered in the orbs, strung on a cable like beads on a necklace, and let them freeze in place. Ultimately, scientists want 5,000 orbs on 80 cables throughout a cubic kilometer of ice.

It turns out that ice is a friendly place for neutrino detectors. At depth it is crystal-clear, so the orbs can spot flashes of light hundreds of meters away. AMANDA exemplifies a new breed of telescope that has redefined what it means to "see."

UNIVERSITY OF WISCONSIN

Lowering detectors into the ice cap

Inside the hole

THE AMANDA COLLABORATION

A Bridge to a Composite Future

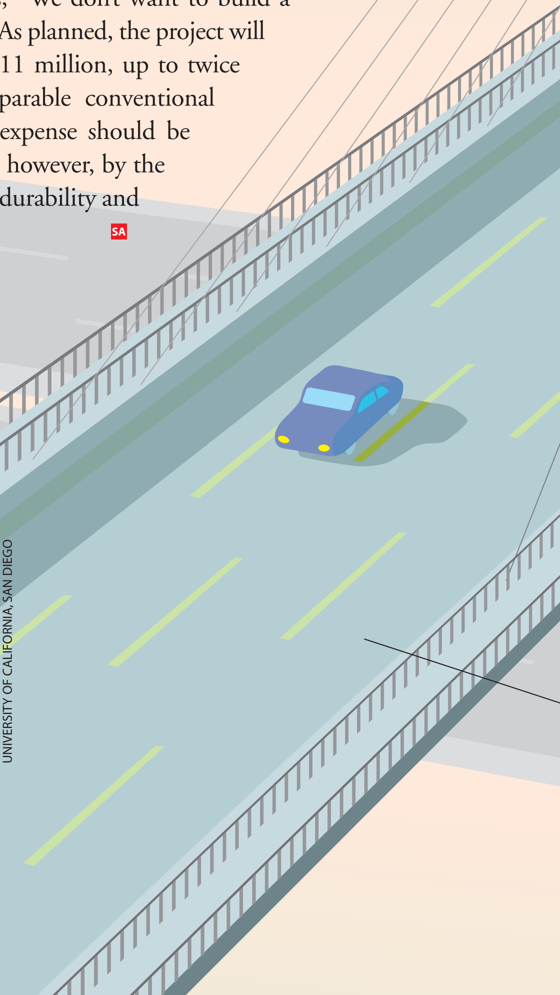
by Jessa Netting

A barrage of natural and man-made forces threaten bridges, from the imperceptibly slow degradation of salt water, corrosive soils and heavy traffic to the sudden catastrophic destruction of earthquakes. Southern California mercilessly serves up all these onslaughts, challenging the creativity, imagination and ingenuity of structural engineers. One of these technological visionaries is Frieder Seible, chair of the department of structural engineering at the University of California at San Diego. During the next two years, Seible and his team, along with the California Department of Transportation, will undertake an ambitious project to fabricate the world's longest cable-stayed bridge having main structural members built from fiberglass, carbon and other unorthodox construction materials.

Designed to connect two sections of the U.C.S.D. campus, the bridge will stretch 450 feet (140 meters) over Interstate 5. In place of sober concrete and impassive steel, much of the 60-foot-wide structure will begin as filaments of glass, carbon or gold-toned aramid (a lightweight polyamide material). The delicate black or translucent strands, which look like pieces of yarn made of thousands of twisted fibers, hardly seem capable of supporting the weight of a four-lane bridge. But their delicacy belies hidden properties. According to Seible, these composite materials can be up to five times lighter and stronger than structural steel (the actual strength depends on fiber orientation). Just as important, the materials are largely inert. Unlike steel, they do not corrode in the presence of moisture or salt, nor do they suffer from water seepage that can freeze and enlarge cracks in concrete.

But these synthetic composites carry premium prices. So to stay within budget, the Seible team will also use some cheaper, traditional materials such as concrete. After all, Seible says, "We don't want to build a gold-plated bridge." As planned, the project will still require about $11 million, up to twice the cost of a comparable conventional bridge. The added expense should be mitigated over time, however, by the structure's increased durability and lower maintenance.

JESSA NETTING is a freelance science writer based in Santa Cruz, Calif.

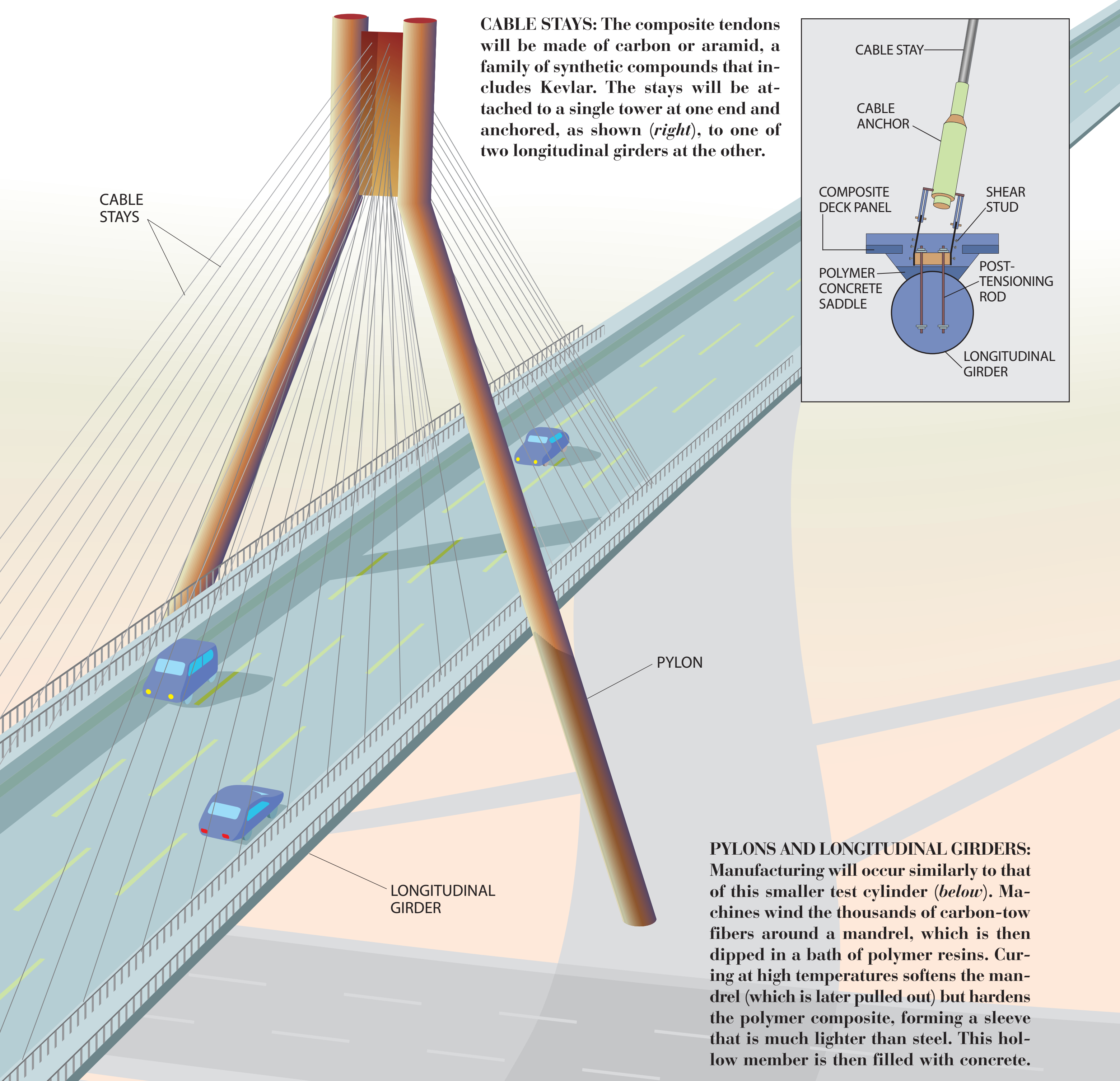


DECK SYSTEM: Arched forms (*right*) are made from lightweight polymer concrete, onto which fiber-reinforced concrete is later poured. Transverse tubular beams, fabricated by epoxying individual sheets of glass and carbon-fiber fabric, will support the deck. The stirrups shown will transfer lateral forces, such as those from earthquakes or wind, from the deck to the beams.

UNIVERSITY OF CALIFORNIA, SAN DIEGO

ILLUSTRATIONS BY BRYAN CHRISTIE

CABLE STAYS: The composite tendons will be made of carbon or aramid, a family of synthetic compounds that includes Kevlar. The stays will be attached to a single tower at one end and anchored, as shown (*right*), to one of two longitudinal girders at the other.



PYLONS AND LONGITUDINAL GIRDERS: Manufacturing will occur similarly to that of this smaller test cylinder (*below*). Machines wind the thousands of carbon-tow fibers around a mandrel, which is then dipped in a bath of polymer resins. Curing at high temperatures softens the mandrel (which is later pulled out) but hardens the polymer composite, forming a sleeve that is much lighter than steel. This hollow member is then filled with concrete.

UNIVERSITY OF CALIFORNIA, SAN DIEGO

Subterranean Speed Record

The massive installment currently under construction near Geneva will be the fastest particle accelerator ever built. When it opens in 2005, it will also be the largest science experiment in the world

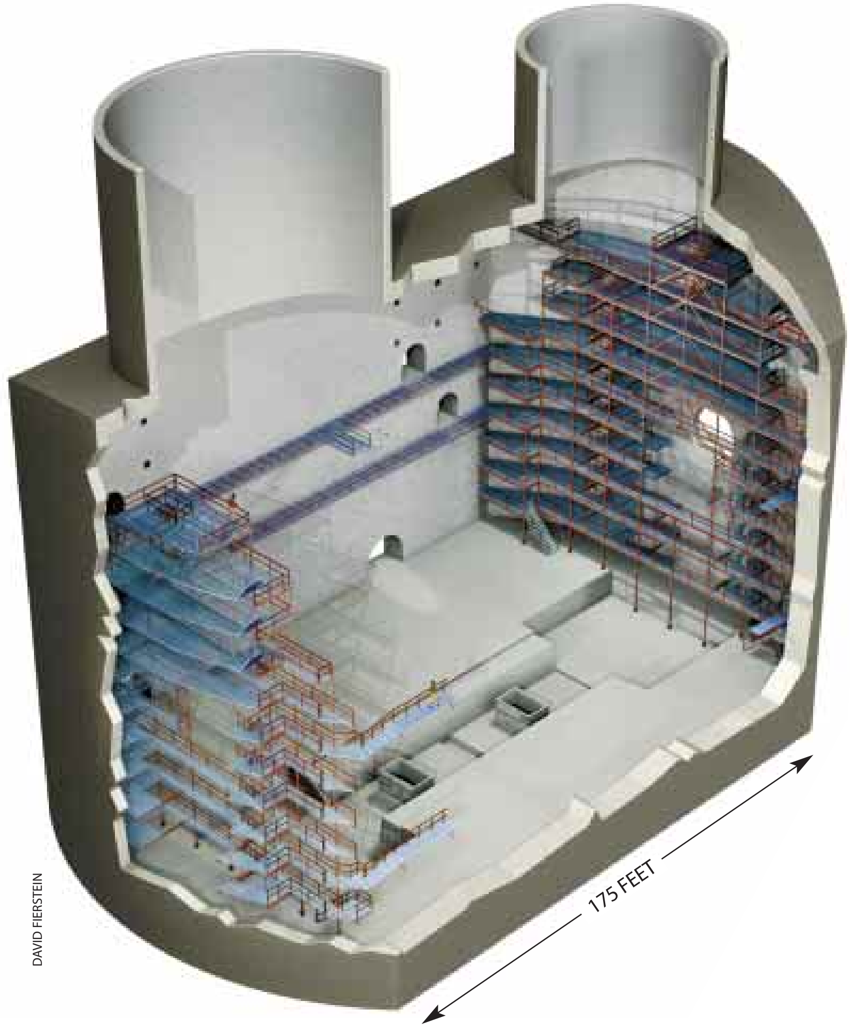
by Sasha Nemecek

Outside Geneva, underneath the quiet villages and picturesque farmland of southwestern Switzerland and eastern France, the pace of scientific research is astounding. If you could see the objects physicists will soon be tracking here at the world's fastest particle accelerator—which you won't be able to, even with the most powerful microscope—you'd catch only a glimpse as they zoomed past you at speeds approaching that of light. The facility at CERN, the European laboratory for particle physics, is a hotbed of research into such subatomic particles as quarks, gluons and bosons, all infinitesimal yet fundamental building blocks of the universe. And right now an ultrapowerful accelerator is under construction at CERN: the Large Hadron Collider, or LHC, will be the largest science experiment ever built, to be used for studying the very tiniest particles in the universe.

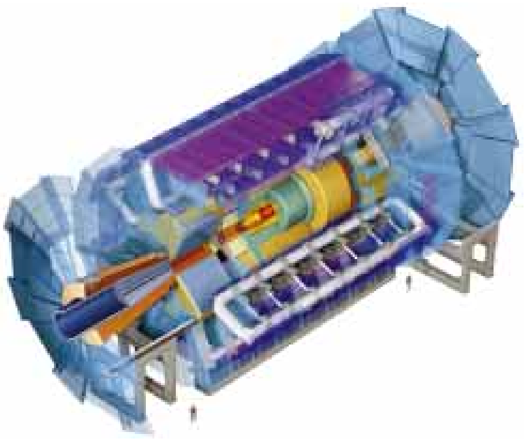
I visited CERN in the spring of this year, as the snow was melting and construction on the LHC was in its early stages. Located on the French-Swiss border, CERN is currently home to the Large Electron Positron collider, or LEP. For the past decade, LEP has been generating highly energetic beams of electrons and their antimatter counterparts, positrons, and then smashing the two into each other. The beams pick up speed and energy as they race at more than 660 million miles (one billion kilometers) per hour through a circular tunnel 17 miles in circumfer-

CERN PHOTO

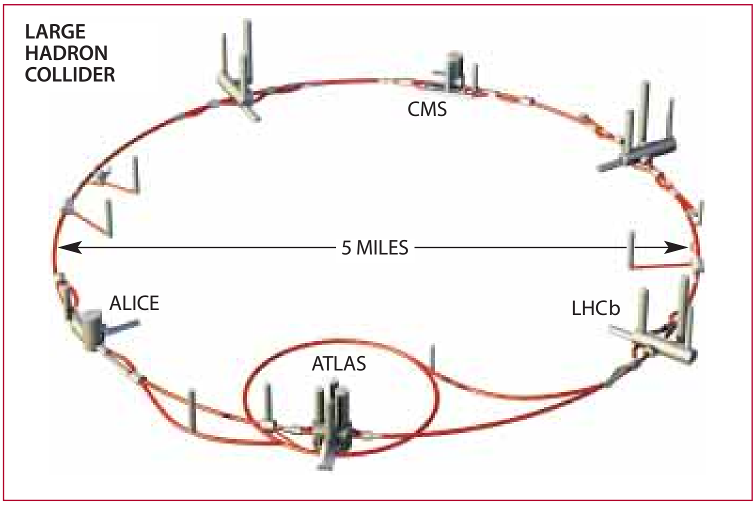
JOURNEY TO THE CENTER OF THE EARTH: A tunnel-boring machine is slowly lowered down a concrete-lined shaftway at CERN, the European laboratory for particle physics. The new, ultrafast particle accelerator now being built requires the excavation of two immense underground chambers as well as connecting tunnels more than 300 feet below the surface.



DAVID FIERSTEIN



COLOSSAL CAVITY: The 6,600-ton ATLAS detector (*below*), now being assembled for the Large Hadron Collider, will be housed in a chamber large enough to fit a six-story building (*top left*); the entire assembly will be more than 300 feet below ground level. The ATLAS detector is one of four being built for the LHC; work is also in progress on the CMS, ALICE and LHCb detectors (*bottom left*).



ence and some 330 feet underground. (Particle accelerators are built underground for a variety of reasons, including the increased stability afforded by the surrounding rock.) Because the beams collide with so much force, the impact produces an impressive spray of particles that scatter in all directions. Centered on the crash sites are detectors, each several stories tall, that enable scientists to monitor the newborn particles.

Detectors for these large colliders must be huge themselves for two reasons. First, the collisions researchers are trying to observe produce particles that fly outward with tremendous energy, which would simply overwhelm a small detector. Second, particle physicists study the curved path of these dispersing particles to learn about the particles' momenta, which relates to their mass, speed and direction. Longer paths allow more precise measurements of direction and curvature.

Although the LHC's accelerator will be housed in the same 17 miles of tunnel that LEP occupies now (with just a few short connecting segments added), workers must construct immense underground chambers for two of the four new LHC detectors. One of the two larger devices is known as ATLAS, short for *a t*oroidal *L*HC *a*pparatu*s*. When completed in 2002, the concrete chamber that will house ATLAS will be large enough to hold a six-story building. Specifically, it will be 115 feet tall (including the thick outer walls) with an essentially rectangular base 100 feet by 175 feet—all more than 100 yards below ground.

But at the time of my visit, construction on ATLAS was still relatively close to the surface. Jean-Luc Baldy, the head civil engineer on the LHC project, took me on a tour of the ATLAS site, where workers had hollowed out the first 75 feet or so of two concrete-lined vertical tubes that will eventually be used for shuttling people and equipment down to the chamber. The largest of these tubes is roughly 60 feet across, to accommodate the dimensions of some of the 6,600-ton detector's largest parts. An old shaftway, left over from when LEP was installed, was also being revamped for use in ATLAS construction. At Baldy's insistence (I'm no fan of heights), I peered down this tube, which plunges more than 300 feet below ground. Only after I recovered from vertigo did Baldy inform me that the men I saw were only halfway down.

Baldy, who also worked as a CERN engineer during the construction of LEP's tunnel, explained the challenges presented by the ATLAS chamber. It will be the largest underground structure ever built in the type of rock found here—sandstone and marl, both considerably softer and less stable than bedrock such as granite. So Baldy and his fellow engineers have recommended extending 65-foot-long steel rods from the exterior of the chamber into the surrounding rock to reinforce the walls. One of Baldy's CERN colleagues, Hans Hoffmann, the technical coordinator for the ATLAS project, described the finished product as "look[ing] like a porcupine."

CERN PHOTO

UNEARTHING DELIGHTS: Heavy equipment must be used to excavate the numerous shaftways and underground chambers required for the LHC. Workers will move nearly one million tons of dirt in all.

A primary goal of the LHC project is to produce and observe the elusive Higgs boson, a particle associated with the Higgs field. Physicists theorize that space is filled with the Higgs field, and that subatomic particles such as quarks and leptons acquire mass by interacting with this field. Capturing the Higgs boson—or at least some evidence that the LHC produced it—is a sizable task. According to Hoffmann, when the beams of protons intersect within the ATLAS detector, one billion collisions a second should result. To capture this rapid-fire activity, ATLAS must have more than 150 million sensors.

Hoffmann, a particle physicist by training, is head of the team devising the equipment that will fill the expanse of the ATLAS chamber once Baldy's crew is finished. Some 1,800 scientists from around the world have contributed to the ATLAS detector, making the organizational engineering at times "more difficult than the machine problems," Hoffmann said, chuckling. That might be true, but the ATLAS sensors themselves required an impressive feat of engineering.

Hoffmann referred to the instruments in the very center of ATLAS as "a mechanical engineer's dream." To measure the paths of electrically charged particles, the ATLAS designers plan to assemble some 400,000 plastic straws (obviously not the kind you drink with) standing lengthwise and arranged in a ring several feet across; each straw will have a wire running down its center and a high voltage between the wire and the straw wall. A particle that passes through the straw will induce electrical pulses that can be recorded; a detailed analysis of these data will allow scientists to assess the particle's momentum, direction and electric charge.

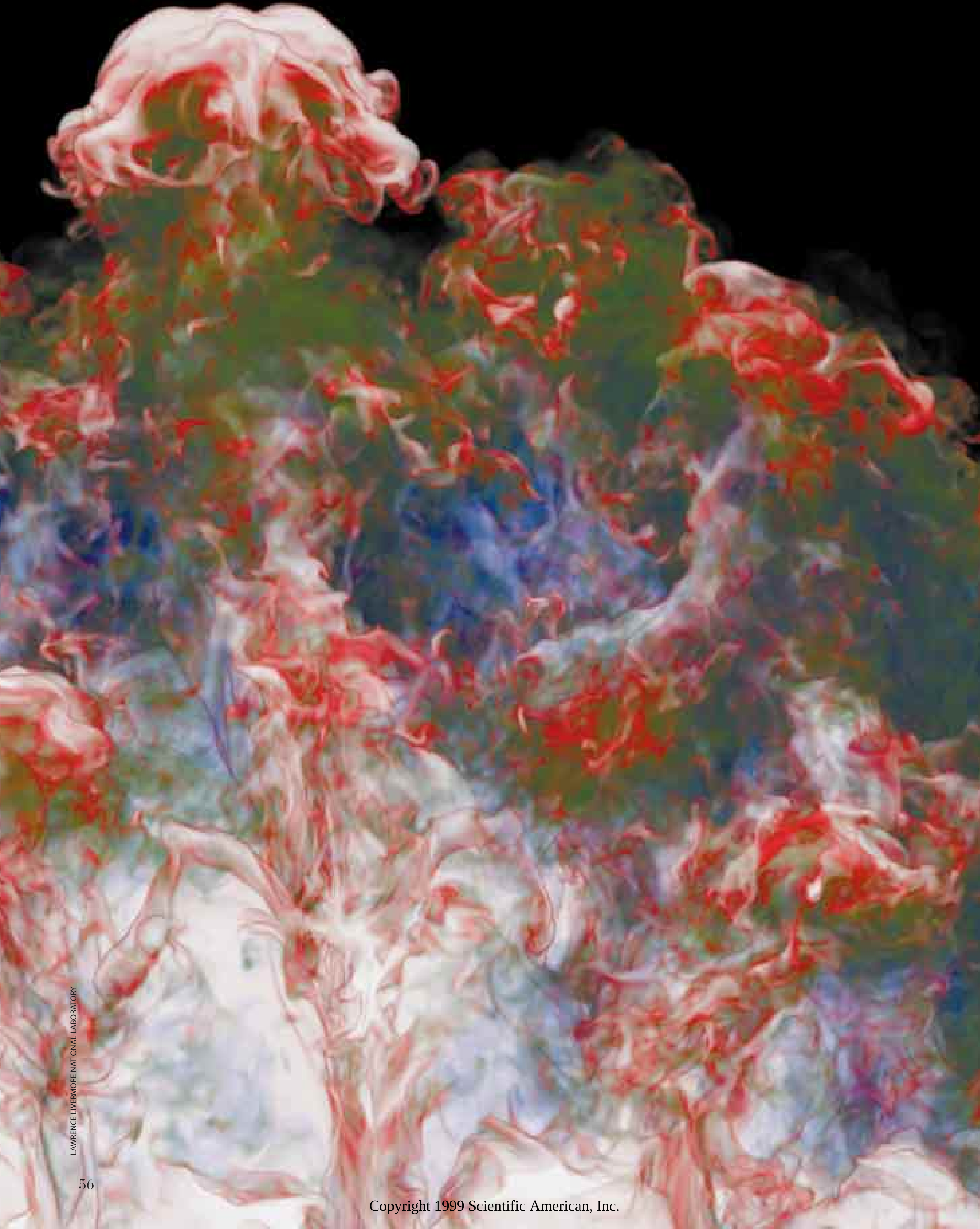
According to Hoffmann, engineers must be able to guarantee that these wires will remain in precisely the same position and at exactly the same tension inside the straw for more than 20 years at temperatures of below five degrees Fahrenheit (–15 degrees Celsius). But keep in mind that these straws make up just the so-called inner tracker. ATLAS will consist of three other types of sensors—a metal, plastic and liquid-argon calorimeter for determining particles' energies; yet another ring of larger straws, this time designed to detect muons (particles like electrons but 200 times heavier); and a system of magnets that will measure momentum. Altogether the three different parts of the detector should produce data at a rate equivalent to that of every person on Earth engaging in 20 telephone conversations simultaneously.

Unfortunately, my trip to CERN was only long enough to see the ATLAS site—just one of the four new LHC detectors. The second massive detector, the Compact Muon Solenoid, or CMS, will occupy a new underground chamber similar in size to the ATLAS building. The other two detectors—ALICE and LHCb—are relatively smaller and will reside in renovated LEP chambers.

In fall 2000, LEP will be permanently switched off, and workers will begin to remove the old detector. As my tour concluded, Baldy noted with a smile that LEP, which took six years to build, will be taken apart in just six months. And considering how relentless scientists are in their pursuit to unravel the secrets of how our universe works, I have no doubt that one day the LHC, too, will be dismantled, and a larger, faster, even more impressive experiment will begin. SA

About the Author

SASHA NEMECEK is co-editor of this issue of *Scientific American Presents.* She's building a miniature particle accelerator under her desk.



LAWRENCE LIVERMORE NATIONAL LABORATORY

BLITZING BITS

by W. Wayt Gibbs

Stroll into your local computer store, plunk down $2,000, and you can take home a fairly zippy machine. With a seventh-generation 600-megahertz processor, 128 megabytes of memory and about 13 gigabytes of disk capacity, a late-model personal computer can tear through that full-screen, full-motion, post-apocalyptic shoot-’em-up with scarcely a hiccup. But snazzy computer games are one thing. Simulating what actually happens inside a detonating nuclear bomb—or a collapsing star or a folding protein—requires a qualitatively different kind of machine, a machine that has not yet been built. It took the Blue Pacific system at Lawrence Livermore National Laboratory, currently the fastest supercomputer in the world, 173 hours to complete the turbulence simulation shown here. Your state-of-the-art PC would have to hum along for well over 16 years to do the same job, assuming it worked at its peak speed of 600 megaflops (million floating-point operations per second)—which, of course, computers never do. Every 20 days you would have to add another 13-gigabyte hard drive to store the results.

And yet, says Mark K. Seager, one of the supercomputer gurus at Livermore, this massive computation will shed light on just one small, idealized part of the problem. To confidently answer whether refurbished bombs will burst, how the globe will warm, how the universe took shape, and other questions that elude theory and experimentation, scientists need computers of 10 to 10,000 times the speed and capacity of Blue Pacific. One such machine is already under construction, and others are on the drawing board.

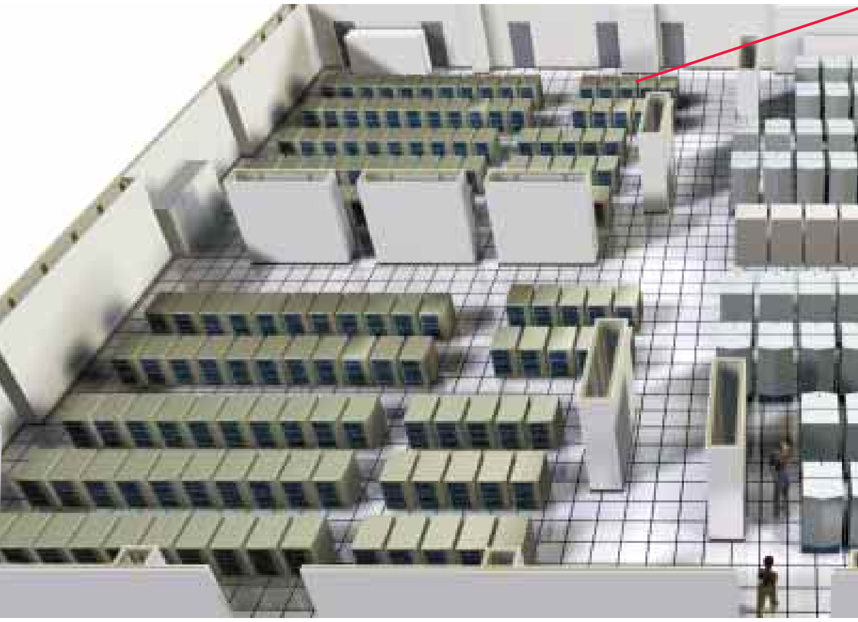
VIRTUAL VISCOSITY: In the biggest simulation of its kind ever attempted, the Blue Pacific supercomputer calculated how two adjacent fluids would mix after one was hit by a shock wave moving at Mach 3. Two thirds of the supercomputer’s 5,760 IBM processors worked on the problem, performing 308 quadrillion calculations. The results—a series of 27,000 three-dimensional images (one portion of one thin slice of one image is shown here)—filled 3.76 terabytes of disk space.

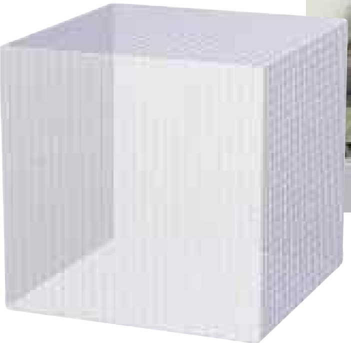
Inside the Fastest Computer

Blue Pacific, the U.S. Department of Energy's 3.9-teraflops (trillion floating-point operations per second) supercomputer, became fully operational in May 1999. Just over one year later it will be made obsolete by the next step in the DOE's Accelerated Strategic Computing Initiative (ASCI). In a giant lab in Poughkeepsie, N.Y., IBM engineers are constructing a $100-million, 10-teraflops successor, called ASCI White, which will occupy a large room (*below*) and is scheduled for demonstration in March 2000 and for operation by late summer. Like Blue Pacific, the new machine will divide up programs to run on thousands of processors simultaneously.

ASCI White is but the fourth of seven supercomputers planned by the initiative, which aims to produce a 100-teraflops system by 2004. That level of performance, says Livermore's Mark Seager, is "the absolute minimum" needed to simulate how an entire nuclear weapon would detonate—or not.

1 In January 1997 the sun expelled a wave of plasma that collided with Earth's magnetosphere, creating stunning auroras and providing a rich set of scientific observations that may help explain how our planet's magnetic shield works. To compare the observations with current theory, physicists at the University of Maryland created a detailed supercomputer simulation of the event, computing a kind of three-dimensional movie from the basic laws of physics.



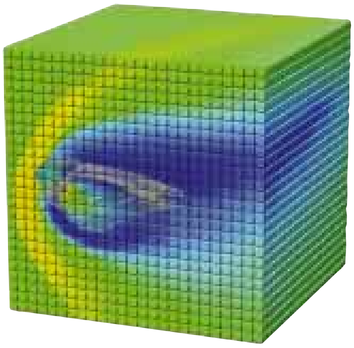


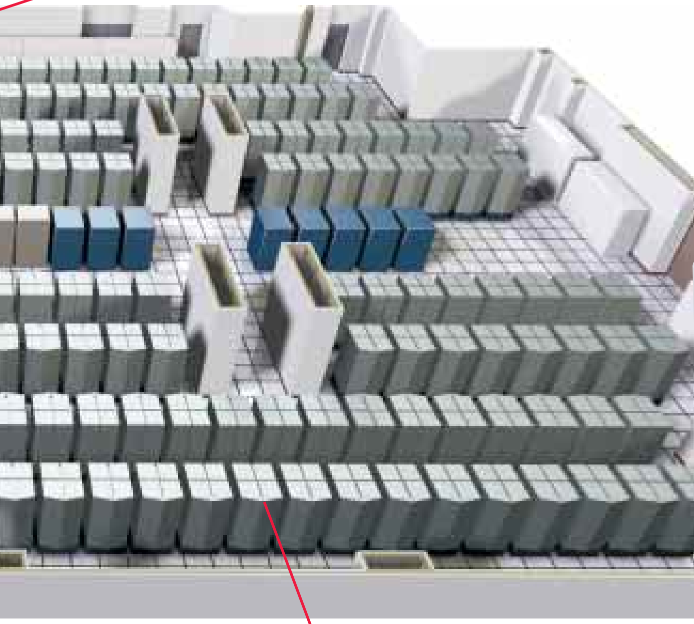
2 On ASCI White, such a simulation would first carve out an imaginary block of space around Earth. In order to perform the calculations as quickly as possible, the software would divide this volume (*above*) into perhaps 10 billion smaller "cubes." These units, each containing only a few mathematical operations and some initial numbers, would stream out of random-access memory (RAM) and move through a switch.

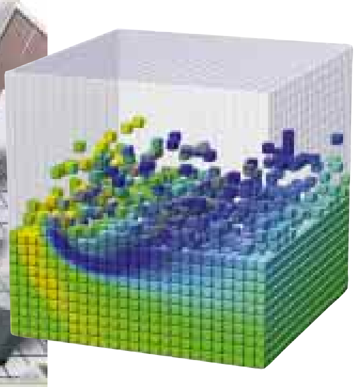
3 The heart of any supercomputer is the switch (*eight dark-blue boxes shown above*) that pulses data between and among processors, memory chips and disks. ASCI White uses a "multistar omega network," which connects the 8,192 processors in the machine with one another and with 10,752 external disk drives in such a way that any processor is never more than two hops away from any other one. The switch can move data to and from each group of processors at a rate of 800 megabytes per second—more than five times the speed of Blue Pacific's switch.

# of Tomorrow

6 After a week or two of around-the-clock operation, the final movie of 50,000 frames—a total of perhaps 500 trillion cubes—will be complete (*right*). To store such massive amounts of data, ASCI White will boast 195 terabytes of external disk storage (*left*). By way of comparison, the printed contents of the Library of Congress comprise about 10 terabytes.







5 As the cubes of information enter the nodes, they flow into memory and are distributed among the processors. If all the numbers are in place, the processor can do its mathematical work, filling the cube (*left*) with the results and sending it back out over the switch to be stored in the disk farm. Often, however, the data in a cube are in RAM or are spread among two or more processors that must pass messages to one another to cooperate in arriving at an answer. This process slows the computation enormously, and as a result supercomputers rarely operate at more than 20 percent of their theoretical peak speed.

4 The processors are organized into nodes, which are grouped four to a case. Every node (*left*) in turn houses 16 375-megahertz POWER3-II microprocessors. This chip is designed to execute four floating-point calculations simultaneously, for a peak performance more than twice that of a 600-megahertz Pentium III. In addition to more than eight megabytes of cache RAM per processor, every node contains at least eight gigabytes of local memory and two internal 18-gigabyte hard drives.

DAVID FIERSTEIN

Three Ways to Get from Here

For any other field of engineering, the idea that one could achieve a thousandfold increase in performance in less than a decade would be sheer lunacy. We will not soon see cars streaking along the desert at 700,000 miles (1.1 million kilometers) per hour or buildings that rise 280 miles into outer space. But many computer scientists believe that by 2007 they will be able to build a supercomputer that delivers one petaflops (a quadrillion floating-point operations per second)—three orders of magnitude faster than Blue Pacific.

If it were made in the mold of ASCI White, a petaflops machine would contain at least 250,000 microprocessors, draw one billion watts—the output of a large nuclear power plant—and cost roughly as much as a fleet of aircraft carriers, estimates Thomas L. Sterling of the California Institute of Technology. Its processors would waste most of their time waiting for data to arrive from memory. To skirt these obstacles, researchers are investigating at least three radically different designs.

1 A consortium led by Caltech is working on the most ambitious of the three approaches to petaflops capability, a so-called hybrid-technology multithreading architecture. "Hybrid technology" means that the researchers intend to use new kinds of chips, networks, disks—everything. Massive microchips will have logic circuits woven among large banks of memory, so that the two can communicate more rapidly. The "single quantum flux" chips will be cooled to near absolute zero so that they superconduct and use about one millionth the energy of conventional processors. This also should allow them to run at speeds exceeding 150 gigahertz, so that "only" 2,048 processors are needed for the system's multithreaded operation, in which a program is broken into individual tasks that can be performed concurrently.

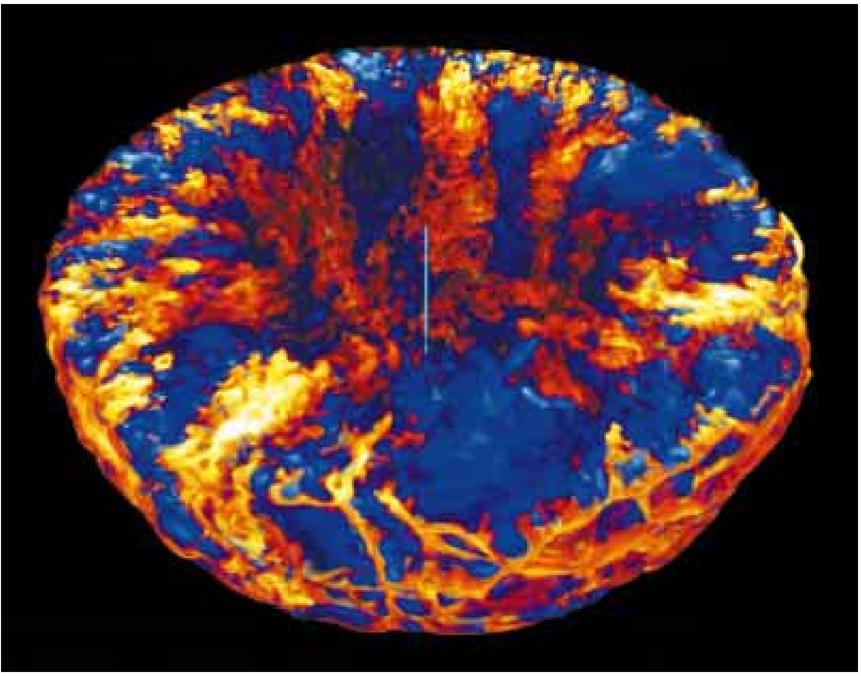
Information will flow through the system as light in optical fibers rather than as electricity in copper cables, increasing bandwidth by a factor of 100 or more. And up to one petabyte (million billion bytes) of data will be stored as holograms in crystals rather than as magnetic patterns on spinning disks, greatly boosting speed and reducing power consumption.

The consortium has prototypes of some of the components, but a number of the technologies are still in the research stage. Nevertheless, with backing from four federal agencies, this effort is the best funded of the petaflops supercomputer designs.

2 The first computer to break the teraflops barrier was no bigger than a large photocopy machine, and it sat in a humble room at the University of Tokyo. Called GRAPE-4, it did only one thing—calculate the gravitational attractions among many objects such as stars or asteroids—but it performed its job with exceptional efficiency, surpassing on that narrow range of problems the speed of even the mighty Blue Pacific.

GRAPE-6, now nearing completion, should set another milestone, hitting 200 teraflops by executing sizable chunks of its program on special-purpose microprocessors. This is a cheap way to build supercomputers if you need them for just one kind of problem, says Mark Snir, manager of scalable parallel systems at IBM. "We looked here at what it would take to build a multipetaflops machine customized to the problem of protein folding," he says. "We could do it for a few million dollars—much, much less than a general-purpose machine."

There may be a way to have the best of both worlds. Recent generations of so-called configurable chips—processors



COURTESY OF DAVID PORTER *University of Minnesota*

STELLAR SECRETS: The seething interior of a young star (modeled here by researchers at the University of Minnesota who used a Silicon Graphics Origin2000 supercomputer with 128 processors) is one of many mysteries that petaflops-speed supercomputers may one day unravel.

to Petaflops

LUNAR BIRTH: **The origin of the moon (*gray cluster at top left*) was simulated in record time and detail by the HARP supercomputer, a predecessor of the GRAPE-4 machine that used special-purpose chips to calculate the gravitational attractions among many objects, including stars and asteroids.**

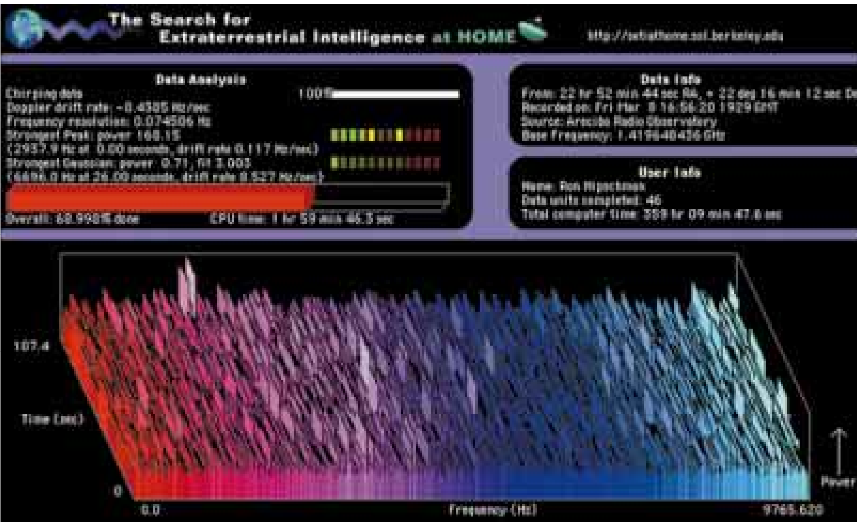
EIICHIRO KOKUBO *University of Tokyo*; HITOSHI MIURA *Musashino Art University*

that can rewire their circuitry on the fly—raise the hope of supercomputers that can transform themselves into ultrafast machines custom-designed for the problem at hand. But configurable chips are still so slow and expensive that the idea remains little more than a hope.

3 As of late August, the fastest and hardest-working computer system on the planet was not behind razor wire at a classified lab or humming in the bowels of some university building. It cost less than $1 million to set up and almost nothing to run. It never had to come down for maintenance, and it grew faster every day.

SETI@home, a small program written at the University of California at Berkeley and distributed over the Internet, was released this past May. Within three months, more than a million people had downloaded the software, which scans signals recorded by the Arecibo radio telescope in Puerto Rico for signs of extraterrestrial intelligence. With SETI@home installed, each PC downloads from Berkeley a chunk of data to process, performs the calculations while the machine would otherwise be idle and then sends the results back.

By September the results were pouring in at the rate of seven teraflops. Put another way, a popular screensaver had in four months zipped through computations that would have taken the Blue Pacific supercomputer about 26. This may be a special case, points out Dan Werthimer, the project's chief scientist. "I don't think we could attract one million people in 224 countries to help with one of the 'grand challenge' problems," such as turbulent mixing.



VIRTUAL SUPERCOMPUTER: **The screensaver SETI@home has enabled more than one million PCs to join the search for extraterrestrial life.**

SETI@HOME PROJECT *University of California, Berkeley*

But at Berkeley and elsewhere, SETI@home does provide inspiration to researchers who are trying to build "virtual supercomputers" by connecting, say, all the computers in a university or a hospital and harnessing processing power that would otherwise go to waste. That research raises the possibility that one day in the near future, the Internet will offer a way not merely to communicate but also to tap into a nearly unlimited reservoir of computing power. SA

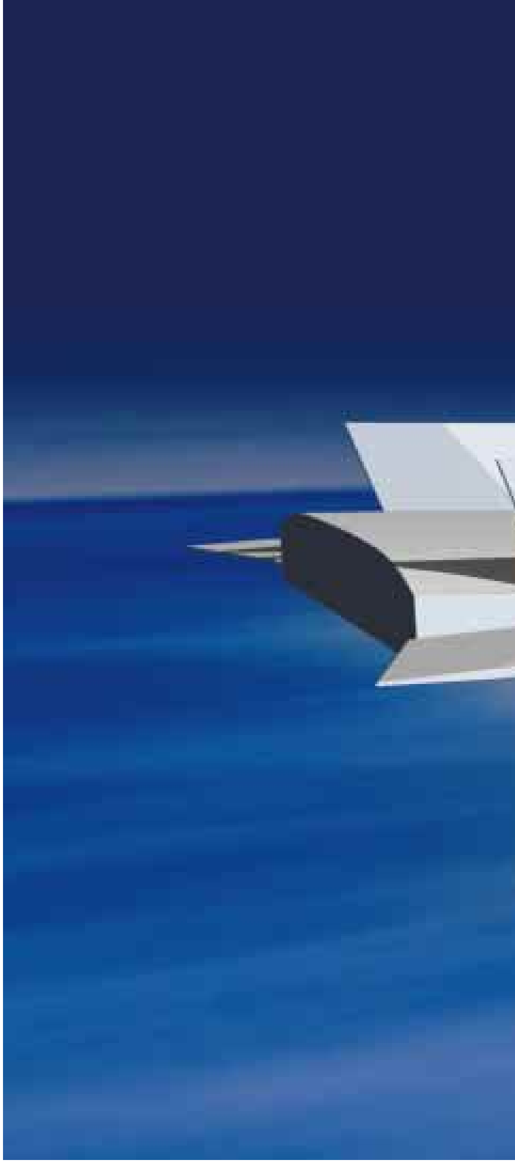
About the Author

W. WAYT GIBBS is senior writer at *Scientific American.* He has completed some 30 units for the SETI@home project but has discovered no E.T.s phoning home.

Harder Than Rocket Science

If launching a rocket to the moon sounds tough, try flying an aircraft into space at speeds topping Mach 20

by Ken Howard



NASA LANGLEY

As a project manager with the National Aeronautics and Space Administration, Charles McClinton likes to pilot his own single-engine Cessna to business meetings. He also flies on vacations with his wife, who is writing a book about their flight experiences, entitling one chapter "Terror in the Cockpit." But McClinton, an engineer by training, has a cautious approach to flying. "Close calls?" he asks. "Not really, but I've had plenty of adventure ... expanding the envelope to learn the limits ... without exceeding them."

That may be true for McClinton the pilot (his wife's protests aside), but for the past 30 years McClinton the NASA engineer has been trying to break through one limit, working to build a jet aircraft capable of hypersonic speeds so far reached only by rockets. Early next year NASA's Hyper-X program, on which McClinton serves as technology manager, will test the world's first air-breathing—that is, nonrocket—engine to be propelled by its own power to Mach 7, or seven times the speed of sound.

If this new type of jet engine succeeds, the implications could be huge. "The paradigm shift could be as significant as the shift from propellers to jets," asserts Hyper-X program manager Vincent Rausch. "It brings new potentials to access space and get from one place to another faster."

Air-breathing engines are what conventional military and passenger aircraft use for propulsion: air is sucked into an engine to be mixed with burning fuel, creating thrust, which propels the aircraft forward. Most of these engines are turbojets, which have a maximum performance of between Mach 3 and 4. The fastest aircraft propelled by an air-breathing engine, the SR-71 Blackbird, reached speeds of just over Mach 3. The Concorde can fly at Mach 2 and an F-15 fighter at Mach 2.5, whereas a 747 limps along at a

relatively sedate Mach 0.8, or about 550 miles per hour (880 kilometers per hour).

But to break free of Earth's atmosphere and enter space, a vehicle must reach the range of Mach 20 to 25. For satellite launches and the space shuttle, giant rockets provide this thrust. But rockets are heavy and nonreusable, and they have relatively low maneuverability and require vertical takeoffs. Safety is another issue. "There is a great advantage in getting away from solid rockets, where you're basically lighting a Roman candle and letting it burn," notes Laurence R. Young, Apollo Professor of Astronautics at the Massachusetts Institute of Technology.

Well aware of the disadvantages of rockets, scientists at NASA, the U.S. Air Force and many foreign laboratories have been trying to develop an alternative. Their efforts have yielded significant advances in engine design over the past 40 years. In conventional turbojets, turbines compress the incoming air, putting it under great pressure as it is fed to burning fuel. The combustion products then expand back to atmospheric pressure as they exit the engine, thus creating thrust. But turbines are inherently limited in how fast they can power a plane. As the blades spin faster, they bring in more air and create greater thrust. With the increase in plane speed, however, the air hitting the turbines dissipates more heat. The danger with supersonic flight is that the engine could literally melt away. According to McClinton, even state-of-the-art turbine materials can handle speeds only up to about Mach 3.5.

For faster vehicles, engineers have taken advantage of the supersonic airflow into the engine by designing the system to act as its own compressor. Turbines and a mechanical compressor are replaced by an inlet valve that funnels the air, ramming it into a space so quickly that it compresses itself. These engines, called ramjets, have enabled a leap in speed up to about Mach 6. They have been used with missiles in which propulsion is switched to ramjets once the rockets have achieved supersonic velocities.

Under such conditions, however, the air is moving so fast that when it hits the combustion chamber to mix with fuel, the resulting drop in airflow speed generates tremendous heat. At Mach 6, the temperature reaches 6,000 degrees Fahr-

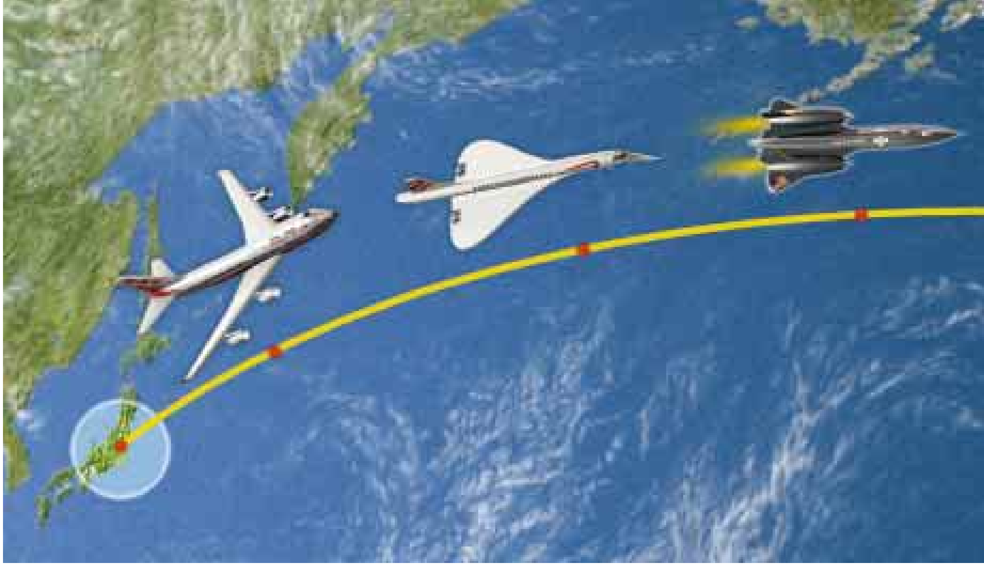
MUCH FASTER THAN A SPEEDING BULLET: A vehicle powered with a scramjet, a new type of jet engine currently under development at NASA and elsewhere, could theoretically fly faster than Mach 20, or 20 times the speed of sound.

enheit (3,300 degrees Celsius), leading to chemical dissociation. Combustion begins, but instead of water forming—which would be accompanied by a tremendous rise in pressure and enormous thrust—the reaction produces free radicals at much lower pressure and thrust. In other words, the aircraft slows.

To prevent that, engineers again redesigned the engine, changing the inlet valve so that the decrease in airflow speed is less severe. As a result, the temperature does not surge to the point at which the combustion process breaks down. Because this new design relies on the supersonic combustion of the rammed airflow, the engine was dubbed a scramjet.

But solving one problem—high temperatures—led to another. Now the challenge was to get the supersonically moving air to mix uniformly with the fuel and combust within milliseconds. The perfection of this technology, details of which are currently classified, finally allowed for the construction of a functional scramjet, McClinton says. According to him, the theoretical maximum speed has been upped again, this time to at least the Mach 20 to 25 needed to reach orbit and perhaps higher, as an upper limit has yet to be determined.

One drawback with scramjets (as well as with ramjets) is that they cannot operate at low speeds. "A scramjet doesn't do any good on the runway; it needs compressed air going into it," explains Joel Sitz, NASA project manager for X-43 flight research. One solution being investigated is multimode operation, with an aircraft being propelled first by an advanced turbine engine (for speeds up to about Mach 2 or 3), then a ramjet (to roughly Mach 6) and next a scramjet. "You then reach a point in the atmosphere where you run out of oxygen and a rocket would take over," Sitz says.


DAVID FIERSTEIN

Such plans aside, the actual operation of a scramjet remains theoretical. Although researchers have performed flight tests, most recently by Russia in conjunction with NASA in 1998, those experiments never used a vehicle flown under scramjet power. The engines, which were mounted on rockets, did provide thrust, so their aerodynamics, combustion and propulsion could be studied, but they never flew at hypersonic speeds (above Mach 5) under their own power.

In addition to rocket-assisted tests, vehicles and engines have been evaluated with models, both in wind tunnels and in computer simulations. But such investigations are restricted to about Mach 7, says Jack L. Kerrebrock, professor of aeronautics and astronautics at M.I.T. "As you go up in the Mach numbers," he explains, "the stagnation temperature, where the airflow is stopped at the nose of the vehicle, has to be simulated, and it gets to be very high. For Mach 10, it would be more than 4,000 kelvins. We don't know how to heat air to that temperature in a stationary facility sufficient for wind-tunnel tests."

Modern understanding of fluid dynamics is likewise limited, because above Mach 7 the physical phenomena, including the airflow through the engine, become too complex to model, even on powerful computers. "It's a very difficult flow to calculate accurately," Kerrebrock says, "and we don't have experimental data to validate the calculations, which is what the Hyper-X program will provide."


ANN STATES *SABA*

TO THE TEST: Charles McClinton, a NASA engineer, will soon learn whether scramjets can indeed fly. An unmanned prototype (a full-scale replica is shown here, upside down) is scheduled for a flight test at Mach 7 in spring 2000.

Indeed, scientists are eagerly awaiting the results from the NASA program's upcoming flight test, scheduled for spring 2000, of an unmanned scramjet at Mach 7. "People have been working on scramjets for 40 years, and this is the first time we have an integrated vehicle that we're confident about," Sitz says. "There are two main challenges for this test: getting it to move and not melt in the process."

The vehicle, called the X-43, is air-

FASTEN YOUR SEATBELTS: A scramjet traveling at Mach 7 (about 4,600 miles per hour) could fly from Tokyo to Washington, D.C., in 1 1/2 hours. In that time, an SR-71 Blackbird, the fastest military jet, would not have traveled half the distance; the Concorde would have flown less than a third, and a 747 would still have more than 10 hours to go. A disadvantage of hypersonic travel, though, is the considerable sonic boom that such flights would generate.

craft and engine as a single unit. Because of the extreme hypersonic stresses and the need to decrease them by fine-tuning the aerodynamics, there is no functional difference between aircraft and engine, McClinton says. The 12-foot-long (3.5-meter-long) vehicle, weighing 3,000 pounds (1,400 kilograms), was designed to minimize weight while providing maximum thermal protection. Specifically, the X-43 must withstand intense heat generated from combustion and the resulting shock waves caused by the aircraft's hypersonic movement through the atmosphere.

The five-foot wingspan is constructed from a high-temperature alloy, and the structural components and outer surface are a combination of titanium, steel and aluminum lined with the same thermal-protection tiles used on the space shuttle. The wing, tail and vehicle nose are reinforced with carbon-fiber composite material, which actually strengthens as the temperature rises. Gaseous hydrogen will serve as the fuel, with silane, a chemical that ignites on contact with air, acting as the spark plug. The test data will come principally from more than 500 gauges on the vehicle, which measure pressure, temperature and strain.

NASA will mount the X-43 onto a modified Pegasus rocket, dubbed the Hyper-X launch vehicle (HXLV). The X-43 and the HXLV will be attached to a B-52, which will travel at Mach 0.5 at an altitude of approximately 20,000 feet off the coast of California near Los Angeles. From there the Pegasus will be launched, and the rocket will boost the X-43 to Mach 7 into the stratosphere at about 100,000 feet, after which the X-43's engine will fire. The rocket and X-43 will then separate, leaving the aircraft to fly on its own. This particular maneuver at hypersonic speeds is the high-risk part of the experiment. "[The] aerodynamics haven't been tested anywhere," Sitz says. "We have it modeled, but you're never sure until you fly something."

On separation, the X-43 has approximately seven seconds of fuel, during which researchers hope the vehicle will accelerate. Once its engine shuts down, the X-43 will follow a preprogrammed course of maneuvers so that scientists can assess its stability control, lift and drag as it decelerates and loses altitude. The total journey will be about 700 nautical miles and last for approximately 12 minutes, culminating in a splashdown at up to 300 miles per hour. Even at that speed, the vehicle should survive the water impact. "This thing is built like a brick," McClinton says.

And like a brick, it will sink to an unrecoverable 16,000 feet. The performance data, though, will have already been collected. During the flight, a U.S. Navy P-3 aircraft will record and transmit the X-43 measurements to the ground while another P-3 and an F-18 will videotape the flight. Additionally, a weather balloon will record atmospheric temperature and pressure in the area.

This experiment is the first in a series of three, with a second flight at Mach 7 scheduled for fall 2000 and another at Mach 10 a year later. The goals are to prove that a scramjet-powered vehicle can indeed fly and then to use the data acquired to validate and recalibrate the design methods, including the wind-tunnel experiments and computer simulations.

Beyond the initial tests, the possibilities are intriguing, including President Ronald Reagan's dream of passenger service from Washington, D.C., to Tokyo in two hours. But Rausch, the Hyper-X program director, cautions that even the most likely first application—lighter military missiles that can then be fired from more remote (and safer) locations while still reaching a target quickly—is probably eight to 20 years in the future. Scramjet flight into space, then, might be decades away.

Even McClinton, in the dual roles of cautious pilot and intrepid engineer, is quick to acknowledge that the X-43 is just one step along the way to an operational system. Still, after first becoming captivated by hypersonic air-breathing propulsion in the 1960s, McClinton can hardly be blamed for his mounting excitement. "Taking something to flight is a researcher's dream," he declares. "It gets us fired up." SA

About the Author

KEN HOWARD is a freelance writer based in New York City. He would like to be a passenger on the inaugural hypersonic flight from Tokyo to Washington, D.C., but only if he has sufficient legroom.

The Sky's the Limit

Citicorp Center
(New York City;
915 ft; 1977)

Empire State Building
(New York City;
1,250 ft; 1931)

World Trade Center
(New York City;
1,368 and 1,362 ft; 1972 and 1973)

Sears Tower
(Chicago;
1,450 ft; 1974)

Future skyscrapers will lift high-rise technology to new heights. But the economic challenges are daunting

by Alden M. Hayashi

They stretch toward the sky, piercing clouds as they soar to spectacular heights, majestically mocking gravity and humbling everything on the ground below. The Empire State Building, the Sears Tower, the Petronas Twin Towers. These heavenly high-rises, surging well past 1,000 feet (300 meters), have been a striking testament to humankind's technological strength throughout the 20th century.

And the progression skyward promises to continue. The São Paulo Tower, the Shanghai World Financial Center and 7 South Dearborn in Chicago are among the proposed structures looking to join this elite group of the supertall. The new superskyscrapers, representing a variety of daring structural concepts, will test the limits of high-rise

Central Plaza (Hong Kong; 1,227 ft; 1992)

Bank of China Tower (Hong Kong; 1,209 ft; 1989)

Jin Mao Building (Shanghai; 1,380 ft; 1999)

Petronas Twin Towers (Kuala Lumpur; both 1,483 ft; 1997)

Jakarta Tower (Jakarta; 1,830 ft; proposed)

Shanghai World Financial Center (Shanghai; 1,509 ft; planned)

technology. Space frames, aerodynamic tuning, intelligent elevators and computerized damping systems are but a few of the innovations pushing building heights toward 2,000 feet.

But whether any of these structures makes it from the drawing board to reality is, more than anything else, a financial issue. "If you had enough real estate, you could build a building to the moon," declares Leslie E. Robertson, one of the world's leading structural engineers. Understanding the crucial economics of superskyscrapers requires a quick lesson in engineering and some basic arithmetic.

For millennia, buildings have waged an ongoing battle with the implacable forces of nature. As high-rises stretch higher, the advantage increasingly goes to nature. First, there is gravity. In a high-rise, a typical column at street level must support not only the nearby area on the second floor but also the cumulative weight of each respective portion of every story above that.

But the real test of a building is its ability to withstand hurricanes and earthquakes. To prevent those lateral forces from toppling a structure, its base must be sufficiently wide. For stability, the height of a skyscraper divided by its width typically must be between six and eight. This so-called aspect ratio for the Sears Tower in Chicago, for example, is 6.5 (the building's height of 1,450 feet divided by its width of 225 feet). So a 2,000-foot high-rise might need to be about 330 feet wide. Thus, the footprint of a superskyscraper could easily consume multiple city blocks. Obviously, finding the necessary real estate is a difficult—and expensive—proposition,

São Paulo Tower
(São Paulo; 1,624 ft; proposed)

7 South Dearborn
(Chicago; 1,537 ft; proposed)

Landmark Tower
(Hong Kong; 1,883 ft; proposed)

Citygate Ecotower
(London; 1,509 ft; proposed)

ILLUSTRATIONS BY DANIELS & DANIELS

particularly in congested areas like Tokyo and Manhattan.

To finance such extravagance, developers need rentable space—and lots of it. “Rentable” for an office building in the U.S. means that the maximum distance to a window should be less than about 50 feet. Meeting that requirement in a high-rise hundreds of feet wide is no simple matter.

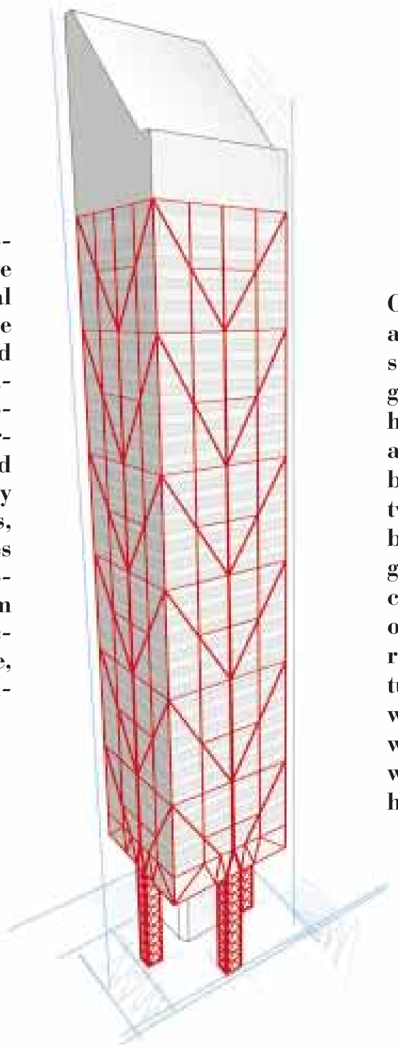
Consequently, many experts contend that constructing taller buildings is not merely a matter of simple scaling. “There will have to be changes in the way people think about supertall structures: they have to become more efficient, otherwise they’ll be too costly,” asserts Robertson, who is the director of design for Leslie E. Robertson Associates in New York City.

Already structural engineers have been rethinking their strategies for combating the wind, perhaps the single most important factor in the design of supertall structures. Consider that as a building’s height rises, the wind effects increase dramatically. Wind speeds are greater at higher elevations, and the wind pressure is related to the square of the velocity. Taller buildings also have a larger surface area for the wind to push against, and their additional height gives the wind a longer lever to topple them. For a 100-story skyscraper, the wind is the primary factor dictating much of the building’s structure, even in earthquake-prone regions like Los Angeles.

Gusts of wind can be particularly dangerous when they come spaced in intervals that approach a building’s nat-

Disinheriting the Wind

Of the total cost of a high-rise, a substantial proportion—sometimes more than one third—goes to its structural skeleton. (Other big-ticket items include the building's architectural facade and mechanical systems, such as the elevators, automated window-washing equipment, and heating, ventilation and air-conditioning.) The beams, columns and other structural members must not only support the building and its contents, they must also withstand earthquakes and—more important for superskyscrapers—high winds, including those from hurricanes. To combat such severe forces, which could easily topple a high-rise, engineers have devised ingenious solutions [*see illustrations through page 72*].



CITICORP CENTER: The triangle is an inherently strong shape. In the Citicorp Center, giant steel diagonal bracing, hidden behind a glass-and-aluminum facade, stiffens the building to resist swaying and twisting from the wind. At the building's base, smaller triangular bracing within massive columns enables the corners of the high-rise to be truncated, resulting in a striking architectural effect. After the Citicorp was built, its bracing system was reinforced with additional welded steel to resist strong hurricanes.

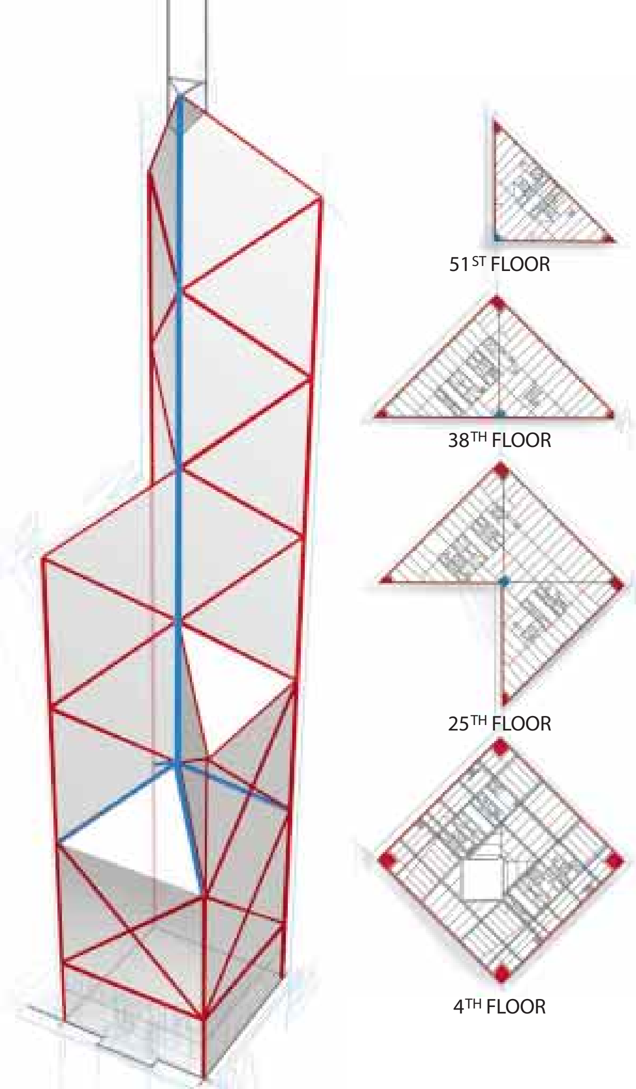
ural period: the amount of time the structure takes to complete one oscillation when it is swaying back and forth. In such situations, the wind can amplify the building's swaying—a physics phenomenon known as resonance. At the very least, such movement can cause motion sickness, along with aesthetic taboos such as swinging chandeliers and water sloshing in toilet bowls.

Interestingly, even a constant, uniform wind (essentially a "static" force) can lead to dangerous dynamic phenomena, including vortex shedding and flutter. With vortex shedding, a wind that blows around a high-rise creates alternating eddies, or vortices, that spin off the sides of the building, causing it to sway in a direction perpendicular to that of the wind. And when an object starts to oscillate, that motion can itself create its own airflow that can then make the building vibrate even more, a troublesome condition known as flutter. In addition to bending back and forth and swaying sideways, buildings can twist, and these various motions can reinforce one another. "Usually, with very tall buildings, the [wind] dynamics are just as important, if not more important, than the static aspect," avers Alan G. Davenport, director of the Boundary Layer Wind Tunnel Laboratory at the University of Western Ontario.

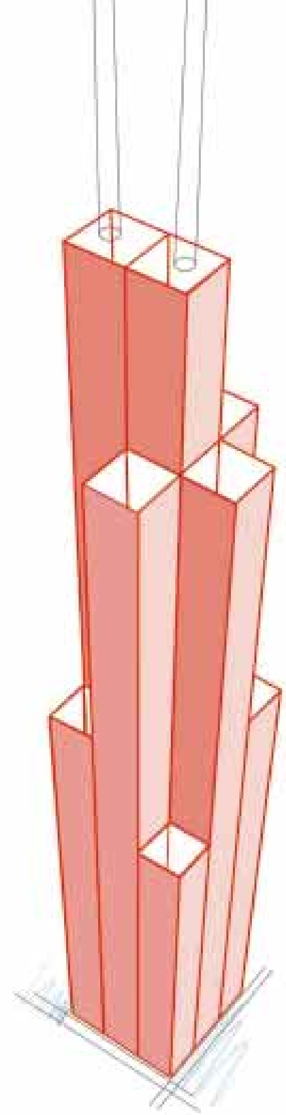
Therefore, architects and engineers have been paying greater attention to a building's aerodynamics. Generally speaking, uniform shapes—for example, a tall rectangular box—induce more vortex shedding than tapered buildings do. "Basically, you want to confuse the wind and inhibit its ability to build up significant forces," says Adrian Smith, a design partner with Skidmore, Owings & Merrill (SOM) in Chicago.

Smith's current project—the 112-story 7 South Dearborn, planned for Chicago—has an articulated shape reminiscent of an extended telescope [*see illustration on preceding page*]. And between its different cylindrical sections, the building has large notches (two to three stories high), where it recesses back to its center concrete core. "The notches are such that the wind never has a chance to set up a strong rhythm," Smith says. With the Shanghai World Financial Center, a dramatic opening—160 feet across (approximately the wingspan of a jumbo jet)—through the top of the 94-story tower helps to relieve wind forces.

Thanks to wind-tunnel tests and computer simulations, architects and engineers can fine-tune a build-



BANK OF CHINA TOWER: In a conventional braced-frame structure like the Citicorp Center, the frame exists in planes that are typically perpendicular or parallel to one another. With "space frames," a skyscraper like the Bank of China Tower can take full advantage of three-dimensional space. For example, note how the column that runs through the center of the building sits on the apex of a skeletal pyramid (*blue*) that is supported by the corner columns. The architect, I. M. Pei, modeled the building after a bamboo shoot, in which each new growth pushes the main stalk successively higher.



ing's shape, surface and structural characteristics (overall rigidity and mass, for example) to achieve optimum designs for withstanding high winds. Such modeling can also help determine if a new building will lead to dangerous gusts on the street below. "The shapes of superskyscrapers will start to be driven by their aerodynamics," predicts Charles Thornton, chairman of Thornton-Tomasetti Engineers/LZA Group in New York City.

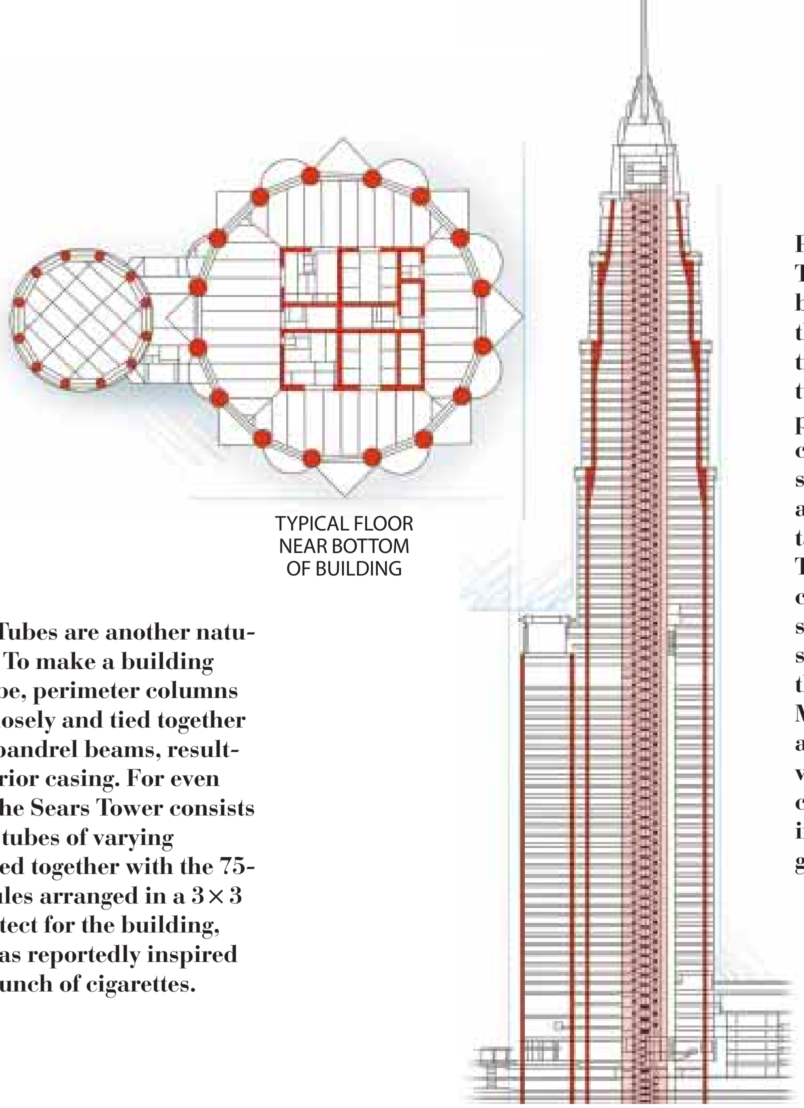
Further assistance can come from mechanical systems that absorb, or dampen, a building's vibrations. The Citicorp Center in New York City has deployed a 400-ton concrete block connected by a spring and hydraulic piston (functioning as a shock absorber). On windy days, the so-called mass damper, located on a floor near the top of the high-rise, moves in opposition to the structure's swaying, sliding on oil to help dampen oscillations by as much as 50 percent. The World Trade Center in New York City relies on a sticky polymer coating sandwiched between steel plates. Thousands of these viscoelastic dampers have been inserted between columns and beams; when the building sways, friction between the plates dampens the motion.

For future skyscrapers, some experts foresee more aggressive systems with servomechanisms that use microelectronics and robotics to produce forces in counterdirections to the wind and earthquakes. "With the current technology, an aspect ratio of 10 is absolutely feasible," says Thornton, who was the structural engineer on the 1,483-foot Petronas Twin Towers. "And with more active damper systems, you can go to 15, maybe 20."

There are other ways to skin the proverbial cat. The Maharishi Mahesh Yogi, famous for teaching transcendental meditation to the Beatles in the 1960s, has plans for supertall buildings in India, Florida and São Paulo. The tallest of the trio, scheduled for India, will have an astounding height of 2,200 feet. The interesting thing about the pyramid-shaped skyscrapers is that they will have a hollow core.

An advantage of such structures is that windows can be located on the inside, perhaps overlooking a spacious atrium, making the interior space more attractive—and rentable. But such a maverick design poses huge technical challenges. For one, in a typical building the floors act as diaphragms to secure the walls, making the overall structure more rigid against the wind. Hollow buildings, on the other hand, do not have that kind of inherent lateral stability. "The walls will kind of billow in and out," says Robertson, who is working on the buildings with

SEARS TOWER: Tubes are another naturally strong form. To make a building function like a tube, perimeter columns must be spaced closely and tied together at each floor by spandrel beams, resulting in a rigid exterior casing. For even greater stability, the Sears Tower consists of nine such steel tubes of varying heights, all bundled together with the 75-foot-square modules arranged in a 3 × 3 matrix. The architect for the building, Bruce Graham, was reportedly inspired by the sight of a bunch of cigarettes.



PETRONAS TWIN TOWERS: Tubes do not necessarily have to be uniform, square and steel, as in the Sears Tower. Each of the Petronas towers is a tapered circular tube with concrete columns on the perimeter. The interior concrete core that surrounds the elevator shafts also provides stability against the wind, as does the attached, smaller circular "bustle." These tall skyscrapers require concrete with a compressive strength of 12,000 pounds per square inch (psi), more than twice the 5,000 psi commonly used in Malaysia. The improvement was accomplished by the addition of very fine particulates that increased the surface-contact bonding between the cement and the gravel in the concrete.

Minoru Yamasaki Associates in Rochester Hills, Mich., the architectural firm that designed the World Trade Center. The preliminary drawings call for a giant "space frame," an efficient type of structure that Robertson used successfully in the 1,209-foot Bank of China Tower in Hong Kong [*see illustration at above left*].

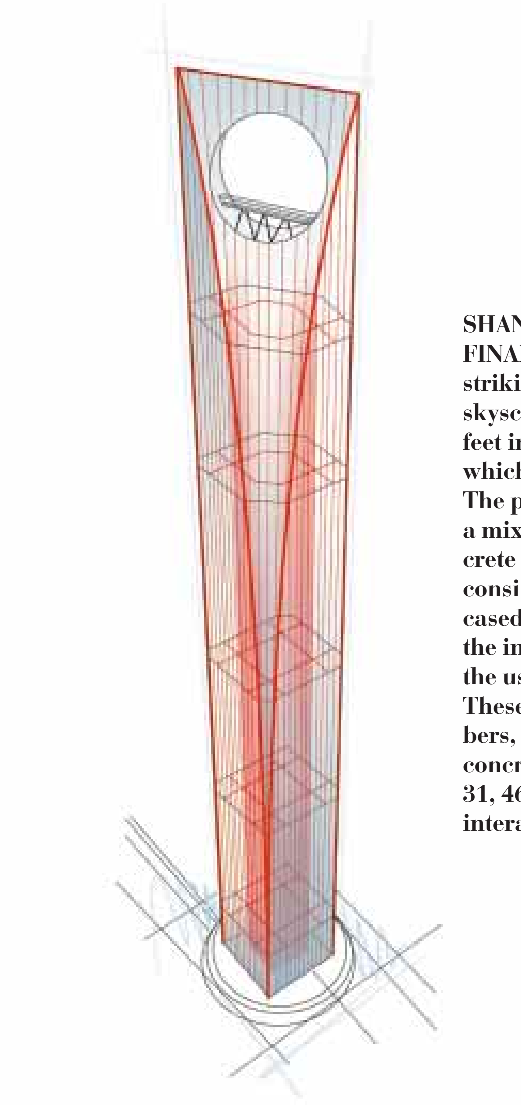
Many structural engineers predict that future superskyscrapers will be an extensively symbiotic mixture of concrete and steel. Concrete, an ancient material, provides excellent compressive strength, considerable mass to limit accelerations from wind, and good damping qualities because it will undergo harmless microcracking to absorb and dissipate energy. But concrete is weak in tension: when a strong wind pushes a building, the concrete columns on the windward side may stretch and begin to crumble. That's where steel comes in. "The trick is to use each of the materials for what it does best," notes John Zils, a structural engineer with SOM. As a striking sign of this trend, the 1,380-foot Jin Mao Building, which was recently completed in Shanghai, has a number of horizontal steel trusses that tie the building's concrete core to its exterior concrete and steel megacolumns.

Structural materials will not be the only composite thing about superskyscrapers. For economic reasons, many of them will have a mixed occupancy. For instance, 7 South Dearborn will include parking, offices and residences, with the top stories reserved for communications equipment for the building's 500-foot HDTV antenna. "Mixed use helps to make a building economically viable; the real-estate market cannot often bear several million square feet of office space being put onto the market at one time," says Smith, the lead architect on the project.

But mixed use can complicate a building's design. If a high-rise contains just offices, for example, the engineer can assume that workers won't be there during a typhoon. But if the office tower has a hotel tacked onto its top—as is the case with the Jin Mao and the planned Shanghai World Financial Center—engineers must minimize the acceleration of the building during a storm or risk motion sickness among the hotel guests.

Such technical challenges are nothing new to the architects and engineers of high-rises. Indeed, the century-old history of skyscrapers is replete with advancements in ancillary technologies, such as fluorescent lights, which enabled the relatively cool illumination of interior offices. It is ironic that elevators, which made it possible for high-rises to be built in the first place, have now become a major stumbling block.

For any building of noteworthy height, the elevator system consumes an immoderate amount of floor space: each of the



SHANGHAI WORLD FINANCIAL CENTER: The most striking feature of this elegant skyscraper is the large hole (160 feet in diameter) through its top, which helps to relieve wind forces. The preliminary drawings call for a mixed design using both concrete and steel. The exterior tube, consisting of steel columns encased in concrete, will be tied to the interior concrete core through the use of large "outrigger beams." These story-high structural members, fabricated from steel and concrete, will occur on floors 16, 31, 46, 66 and 80, resulting in an interactive composite system.

twin towers of the World Trade Center contains 99 elevators, for instance. "With supertall buildings you need to do very clever things or else you'll end up with a ground floor of just elevators," cautions Lynn S. Beedle, director emeritus of the Council on Tall Buildings and Urban Habitat at Lehigh University.

Part of the problem with elevators is speed. The human ear is slow to adapt to changing pressure, which restricts the acceptable speed of descent to a maximum of 2,000 feet per minute and ascent to 3,000 feet per minute. (Decreasing pressures are more tolerable than increasing ones.) Interestingly, the maximum acceleration—the "jerk"—is also limited by passenger comfort and by the bladder control of pregnant women.

Because of such factors, engineers have worked on increasing the efficiency of elevators, resorting to double-decker cars, such as those used in the Sears Tower to service even and odd floors simultaneously, and to transfer systems that deploy express and local elevators. A future advance might include cableless operation: the cars would be powered by their own motors and run on tracks, possibly with more than one car in the same hoistway. Other innovations include the use of fuzzy logic and neural networks in the dispatching system to decrease waiting times, particularly in peak traffic periods.

Recently, Schindler Elevator Corporation developed a clever system in which passengers enter their destinations on a keypad near the elevator bank, and the system responds by displaying which car they should take. Behind the scenes, a control computer efficiently groups people with the same destinations together in the same car, thus minimizing the number of stops people will have to endure before reaching their destinations. Schindler claims that the system could help reduce the number of elevators in a typical office building by as much as 25 percent.

Such technological advances are desperately needed to make superskyscrapers more economical. "None of these structures are cheaper as a single building than they would be as two buildings at half the height," admits SOM's Smith. As a cautionary note, the $800-million Petronas towers, which were completed in 1997, have stood just half full, mainly with government and Petronas employees. "One may ask whether it's rational to build much taller. Doesn't the tallness race become nothing but an egomaniacal gesture at some point—a form of high-profile indecent exposure?" wrote Paul Gapp, architecture critic for the *Chicago Tribune.*

To be sure, the issues are numerous. What kind of shadow will the new building cast? How will it affect the local real-estate market? Will traffic in the area become too congested? Will the skyscraper be a potential danger to airplanes? (Because of such concerns, the Taipei Financial Center, which at 1,667 feet was supposed to have become the world's tallest building, is currently being downsized.)

That said, there is a certain undeniable prestige that comes with height. In Malaysia, national pride helped push through the construction of the Petronas towers, a pet project of Prime Minister Mahathir Mohamad. Another intangible yet powerful factor is the egos of developers.

Nevertheless, a high-rise that doesn't make sense financially is a high-rise that will have trouble leaving the drawing board. Thornton, a veteran of the industry, has these words of wisdom: "Most of the world's tallest buildings that are proposed never happen." SA

About the Author

ALDEN M. HAYASHI is the coeditor of this issue of *Scientific American Presents.* At age four he constructed his first "skyscraper," a two-foot-tall tower of Legos.

To the Bottom of the Sea

by José M. Roesset

Offshore structures have been built in more than 3,000 feet of water. How much deeper can the technology be pushed?


SLIM FILMS

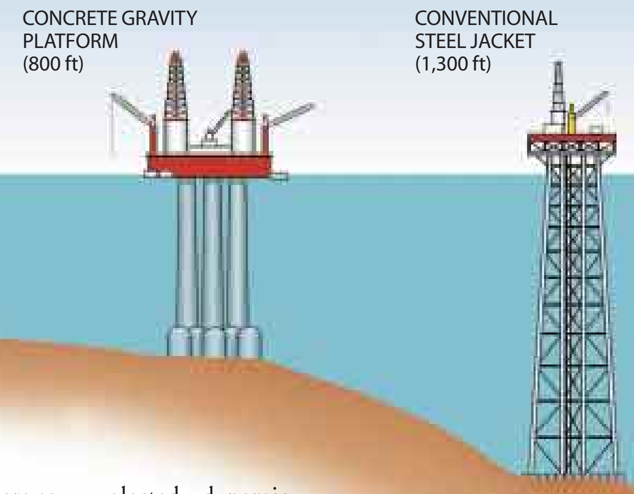
Oil reserves on land and on the continental shelf have become scarcer and more difficult to extract. Meanwhile the worldwide demand for gas and petroleum continues to grow almost linearly. It is not surprising that oil exploration and production have moved into deeper and deeper waters.

In just 50 years the offshore industry has built increasingly impressive platforms to extend oil production from just 20 feet of water to more than 3,000 feet (915 meters). Indeed, the excitement and challenge of structural engineering—once associated with tall buildings, large dams and long-span bridges—are currently in the offshore area. And for depths exceeding a mile, the industry is looking at new solutions, including subsea systems built directly on the ocean floor. With continued innovation, the extraction of oil from water depths of almost two miles will become a reality.

Oil production near water was already taking place in the 1870s in the Caspian Sea at Baku and in the 1880s near Santa Barbara, Calif. But it was not until 1947 that the first steel platform was erected offshore—out of sight of land—in 20 feet of water off the Louisiana coast. In the following years the design and construction of such facilities were based on engineering techniques developed for land structures. To account for unknowns and uncertainties with respect to environmental forces (the ocean waves, for example), soil conditions and the behavior of the materials used, engineers had to overdesign the platforms, making them heavier and stronger than necessary. Even so, the water depths of the structures

FLOATING CITY: The tension leg platform is a new type of offshore structure that could reach depths of 6,000 feet.

DEEPER DEPTHS: The illustration at the right gives the current maximum depths for five types of offshore structures. Not shown is the subsea system (6,000 feet), which is installed directly on the sea bottom with long pipes connecting to the shore or to an existing platform in shallower water. By making steel jackets more pliant and by securing them with guys, mooring lines or deep piles, engineers have extended such towers to 1,800 feet, and further improvements could increase that to 3,000 feet. Some experts believe that tension leg platforms and spars could be built in up to 6,000 feet of water and that modified tankers and subsea systems could be pushed to more than 10,000 feet.



have increased steadily and quickly, from 100 feet in 1955 to more than 1,300 feet in 1988 (Shell's Bullwinkle platform in the Gulf of Mexico).

All these projects were steel jackets—structures that rely on a frame of metal trusses for support. For shallow waters, the platforms were fabricated as a single unit and carried on a barge to the desired location, where the unit was launched into the ocean. A crane or derrick on another barge then picked up the structure and placed it vertically on the sea bottom. Piles were driven through the legs to the desired depth, and the deck units were welded into place. For such offshore platforms, the piles were the main structural elements and the jacket provided the needed bracing.

But as the water depth increased and the jackets got larger, hoisting them upright became unwieldy. One solution was to fabricate and install the jacket in multiple parts—a strategy used in 1978 by Shell to construct the Cognac platform in more than 1,000 feet of water in the Gulf of Mexico.

In the North Sea the much harsher environmental conditions, the stiffer soils on the sea bottom and the familiarity of European countries with concrete construction led to concrete gravity structures as an alternative or a complement to conventional steel jackets. Instead of pile foundations, these behemoths rely more on their substantial weight and large base diameter for their stability. The massive base, which also serves as storage for petroleum between tanker pickups, is usually built in a dock and towed to a protected deeper-water location, where the construction of the legs takes place. The deck is sometimes installed there as well, and the completed structure is then towed to the installation site.

Like skyscrapers and bridges, an offshore platform must withstand gravity (a structure's own dead weight could, for example, cause it to collapse on itself), wind and—depending on its location—ice, snow and even earthquakes. But deep-sea structures must also endure waves and currents, and it is these hydrodynamic forces that make such projects different from most other civil engineering efforts.

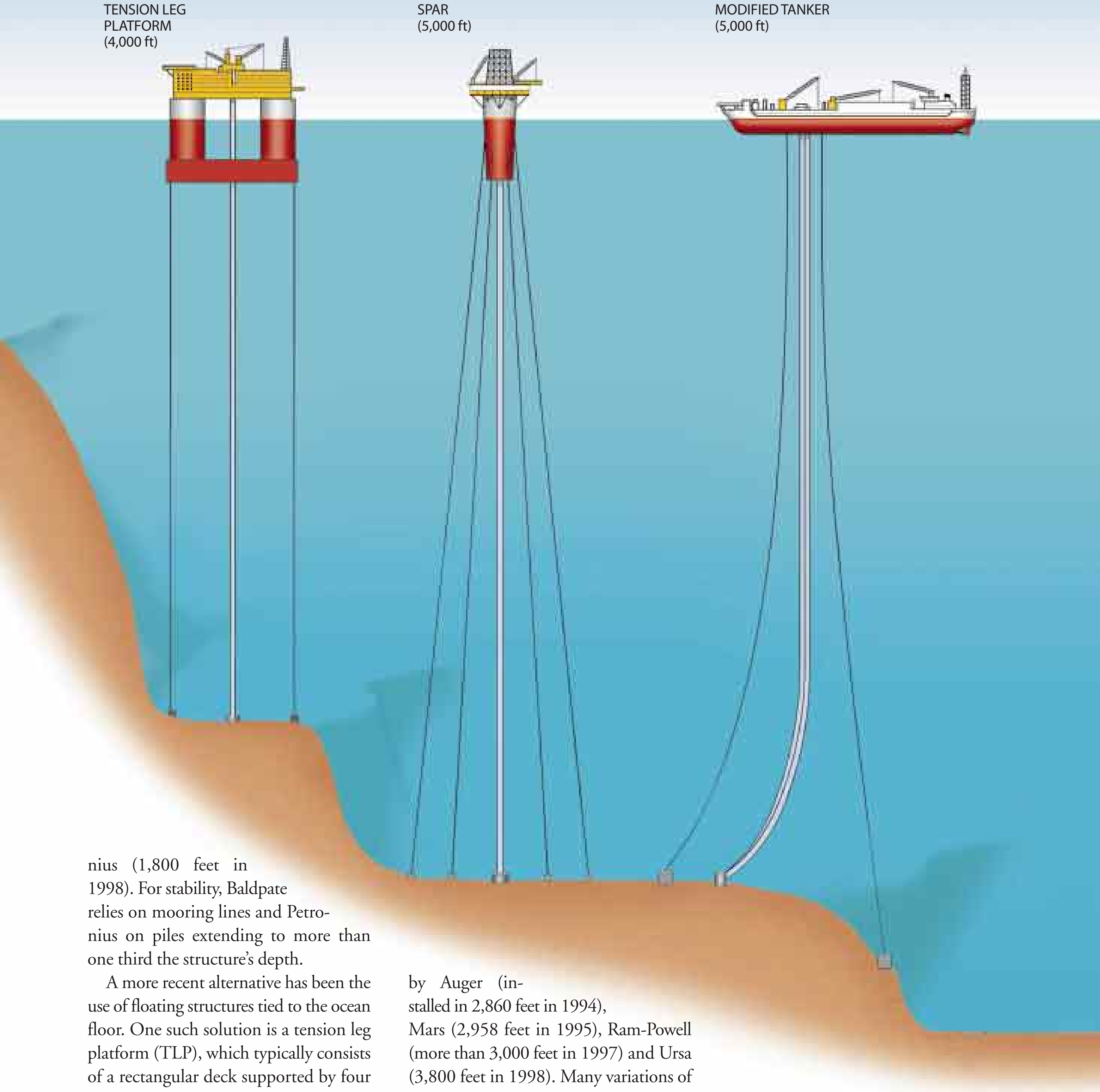
Waves and currents affect offshore structures differently. The action of waves is concentrated near the water surface, and the forces associated with them dissipate rapidly with depth. Current forces, on the other hand, subside much more slowly. Thus, although wave forces may be more significant for traditional jackets in shallow and intermediate waters, the relative importance of currents grows with greater depths. In the Gulf of Mexico, strong loop currents and the subeddies they spawn, as well as recently detected currents at great depths, are a major consideration.

To determine the wave and current forces requires knowledge of the water particle velocities and accelerations as well as the motions of the main structural elements and other basic components, including the pipes, risers, mooring lines and tethers. Obviously, the loads vary with time, so the accurate prediction of how the structure will react to them requires, in principle, complex dynamic analyses.

In the past, engineers typically neglected dynamic effects when designing shallow-water steel jackets. This omission was acceptable because the structures were very rigid against the dynamic forces. In engineering parlance, the natural period of a steel jacket in shallow waters is about one second or less. (In other words, the structure would have a tendency to vibrate with the beats spaced roughly one second apart, just as a guitar string of a specific length and material will emit a note of a certain pitch.) The period of the design waves, on the other hand, is normally around eight to 14 seconds, depending on the part of the world where the platform is installed.

But construction in deeper waters has led to taller—and inherently less stiff—structures that are much more susceptible to dynamic effects such as those caused by waves. For instance, the natural period of Shell's Cognac platform was reported to be roughly four seconds. For greater depths, the natural period of conventional steel jackets would approach that of the waves, and thus the dynamic effects would become amplified through resonance. (Think of a child soaring higher and higher on a swing because her parent pushes her in synchronicity with her motion.)

Because building a very rigid structure in deep water would be prohibitively expensive, engineers chose a different solution: making the platforms more flexible so that their periods far exceeded those of the waves. This approach led to Exxon's Lena (built in some 1,000 feet of water in 1983), Amerada Hess's Baldpate (1,700 feet in 1997) and Texaco's Petro-



GEORGE RETSECK

nius (1,800 feet in 1998). For stability, Baldpate relies on mooring lines and Petronius on piles extending to more than one third the structure's depth.

A more recent alternative has been the use of floating structures tied to the ocean floor. One such solution is a tension leg platform (TLP), which typically consists of a rectangular deck supported by four columns at the corners. Below the water surface, pontoons connect the columns, and four bunches of multiple vertical tendons, one for each column, secure the entire assembly to the sea bottom. The buoyancy of the structure creates tension in the tendons, and the structure behaves as an upside-down pendulum. TLPs have played an important role in the deep waters of the Gulf of Mexico, as evidenced by Auger (installed in 2,860 feet in 1994), Mars (2,958 feet in 1995), Ram-Powell (more than 3,000 feet in 1997) and Ursa (3,800 feet in 1998). Many variations of the classical TLP with different sizes and numbers of legs or tether bunches have been proposed and used recently, such as in British-Borneo's Morpeth field (1,700 feet in 1998).

Another variation is the spar concept, which consists of a cylindrical hull anchored with mooring lines that radiate from the center of the floating structure. Two spars have been installed in the Gulf of Mexico: Oryx's Neptune (1,900 feet in 1997) and Chevron's Genesis (2,600 feet in 1998), with several others under design or construction. Still another option is to use a semisubmersible structure (referred to as a floating production system) that has a hull like a TLP's but is held in place with catenary mooring lines. Also, modified tankers (called floating production storage and offloading systems) secured to the sea bottom with mooring lines are being used in many parts of the world but not in the Gulf of Mexico.

The new structures are very pliant, with natural periods much longer than those of ocean waves. Such flexibility, however, leads to other potential problems. Engineers must consider that a structure—particularly when it is limber—can vibrate at frequencies higher than the one associated with its natural period (just as overblowing into a flute results in higher notes). For TLPs, spars and other buoyant platforms, various nonlinear effects must be investigated.

EVEN SMALL WAVES CAUSE MOVEMENTS THAT CAN CONTRIBUTE TO FATIGUE FAILURE.

Vibrations can also be caused by vortex shedding, which occurs when waves and current move around an object, spawning vortices that can make the body undulate [*see illustration on opposite page*]. Even small waves cause periodic movements that can contribute to fatigue failure, similar to the way a metal paper clip will eventually snap if a part of it is bent back and forth repeatedly.

To study such effects, researchers must develop more accurate methodologies to compute the nonlinear wave kinematics, hydrodynamic forces and structural responses. Much has been accomplished recently in these fields, but numerous problems require further study.

In addition to computational analyses, scale models in wave tanks have been used to study structures that were later installed at great depths in the Gulf of Mexico and in the North Sea. Similar to wind-tunnel tests for aircraft, such experiments helped to validate proposed designs by yielding results that were then compared with analytical predictions. Tests of North Sea platforms led to the discovery of previously unknown phenomena, such as ringing and springing of TLPs, in which nonlinear effects cause the structure to vibrate vertically. Yet even model tests are limited in their ability to determine the true behavior of a platform in the ocean. Researchers are currently developing computer simulations that fully take into account nonlinear hydrodynamics to complement the wave-tank experiments.

A factor that must be considered in such analyses is damping—the ability of a structure to dissipate energy while vibrating, thus minimizing the effects of dynamic forces. But damping for offshore platforms is normally very small; it is mainly associated with vortex shedding around the hull, tethers and mooring lines. These effects are difficult to reproduce in lab experiments and to incorporate in computer models. Although numerical solutions are under development, much work remains before they can be validated and incorporated into wave-tank simulations.

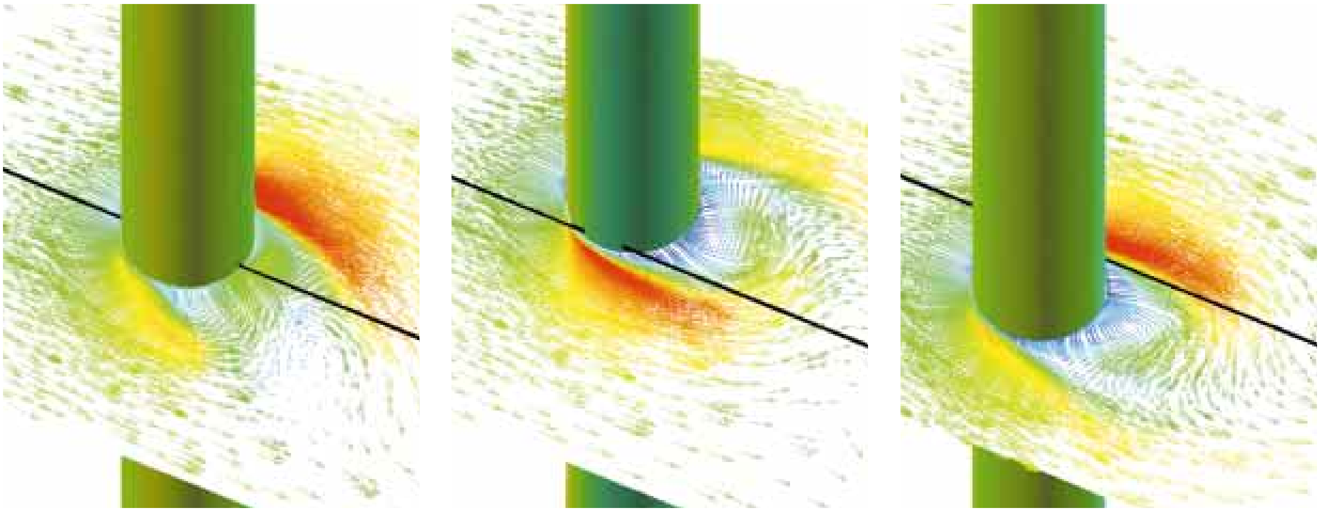
Most of the structural solutions for deep water consist of a large floating hull attached to the sea bottom by either vertical tethers or mooring lines, or both. They essentially consist of a combination of large-diameter bodies (hull), for which diffraction effects are important, and long slender members (tethers, mooring lines and pipes), for which drag (friction from moving water) must be considered. Although analysis of these different components is usually performed separately, an accurate prediction of the behavior of the complete platform requires the coupled analyses of all the components.

One approach for building TLPs and other deepwater floating platforms is to use composite materials that are resistant to corrosion and fatigue failure. These materials can be tailored to specific stiffnesses and strengths, resulting in weight reductions that then lead to greater overall economy. For one thing, a hull that is lighter can be made smaller with the resulting structure still buoyant even though it displaces less water. The size decrease has an advantage: waves will have less surface area to push on, and the structure will thus require less extensive mooring systems and anchor piles for stability. In fact, every pound reduction in weight of the hull of a TLP can ultimately bring down the total cost of the platform by $4 to $5.

Phenolic materials have already been used for the floor gratings, stairs, partitions and even bearing walls of TLPs, saving millions of dollars. More substantial cost reductions could be achieved if the tethers, mooring lines and risers (vertical pipes that transport the petroleum products up from the well) could also be made of composites consisting of a resin matrix with glass or carbon fibers, or a combination of both.

The main obstacle is a lack of knowledge about the long-term underwater behavior of these materials. Much research remains to be done to determine their aging and degradation, among other effects. The impracticality of having to wait 30 or 50 years to gain the necessary experience before using the new materials has motivated the development of instrumentation and nondestructive evaluation techniques that can monitor their performance as they are being used underwater. This capability is crucial because a composite pipe, for example, can suffer significant internal damage and deterioration before any external symptoms become visible.

Because of the difficulties of constructing offshore platforms in deep water, an increasingly popular alternative has been to install the well control equipment—called "Christmas trees" for historic reasons (on land the pipes and valves were stacked and resembled Christmas trees)—directly on the ocean floor. Such systems rely on long pipelines that connect to the shore or to existing platforms in shallower water. Examples include Petrobras's Marlim project off the coast of Brazil and Shell's Mensa in the



KARL W. SCHULZ AND JOHN KALLINDERIS *Offshore Technology Research Center*

A RIVER RUNS AROUND IT: When a fluid flows around an object, it can spawn alternating vortices (*shown in red, from left to right*). This phenomenon, called vortex shedding, can cause the object to undulate (the black line is stationary). The motion could then become amplified through resonance, leading to potential problems.

Gulf of Mexico, which was installed in 5,400 feet of water.

But the technology to pump mixed products (fluids as well as solids and gas) from a deepwater well needs additional investigation. One option is to separate the different components directly on the seabed. The success of such systems will depend on the development of equipment, including manifolds, control systems, actuators and meters, that can perform reliably at great depths.

The petroleum industry has already been considering the possibility of drilling in water as deep as 10,000 feet—nearly two miles. The task is daunting, given the extreme conditions. For starters, at a depth of 10,000 feet the water pressure is more than two tons per square inch, greater than 300 times the atmospheric pressure. Other complications include the potential presence of geohazards such as overpressured layers of sand that, when drilled through, erode the support around the casing, making further operations impossible. Additionally, at 10,000 feet the use of a drilling riser becomes problematic because of the pressures caused by the long mud columns inside the pipe. An alternative currently being explored is riserless operation, but the behavior of an unprotected rotating string for drilling under the combined action of waves and currents and the associated vortex-induced vibrations is largely unknown.

Additional research is also needed to maintain the position of the drilling vessel, particularly under strong winds and waves. To study such issues, Conoco recently deployed a new drill ship, the *Deepwater Pathfinder,* that boasts important innovations, including the use of satellite signals and six high-powered thrusters to maintain the vessel's position to within an average of less than seven feet without an anchor.

Of course, as drilling moves farther offshore, the potential for accidents continues to be a concern, and preventing such mishaps and mitigating their impact on the environment should they occur requires basic research in several specific areas. For example, to determine the effects of a blowout in very deep waters, scientists have been incorporating knowledge of ocean currents and other conditions into computer-simulation models to predict accurately the path of the oil and the extent of the spill. Furthermore, some of the most serious accidents, including the Piper Alpha disaster of 1988 and the *Exxon Valdez* incident of 1989, have highlighted the need to consider various human factors. Effective solutions will depend on cooperation between industry, research organizations, certification agencies (such as the American Bureau of Shipping) and regulatory bodies (the Minerals Management Service in the U.S., for instance).

In 1994 the daily production from deepwater drilling in the Gulf of Mexico was less than 100,000 barrels. By 1996 that figure had increased to 275,000, and it is expected to exceed one million by the end of 1999. This dramatic success in the Gulf of Mexico represents just the initial phase, and efforts will also intensify in other areas, including off the coasts of Brazil and West Africa. But this anticipated expansion—Marathon Oil recently announced an important find at 7,200 feet in the Gulf of Mexico—cannot occur without continued engineering innovation.

The technology needed for the safe production of oil in up to 3,000 feet of water is currently available, and the industry is able to reach water depths of 5,000 feet without any major foreseeable problems. Greater depths, though, will require no small amount of research and development, both at the basic and applied levels, to overcome a number of technical hurdles.

About the Author

JOSÉ M. ROESSET is director of the Offshore Technology Research Center, which is jointly operated by Texas A&M University and the University of Texas at Austin.

Designer Genomes

Life! I’ve created LIFE!” shrieks the crazed scientist, eyes wild, hair spiking every which way, deep in the throes of megalomania. The scene is recognizable at once as the melodramatic centerpiece of many a late-night sci-fi flick, both good and bad.

What’s more incredible is that such a scene may be playing itself out in a real lab sometime soon. The main difference—aside from the fact that most scientists now comb their hair—will be the creature on the table. Rather than a hulking monster made of body parts pilfered from a graveyard and stitched together by some scientist’s fawning lackey, the artificial organism will be a bacterium—a microscopic life-form 1,000 times smaller than the smallest grain of sand.

Spurring this revolution is a new kind of recipe book: in the past five years researchers have determined the complete genomes—the exact sequences of the thousands of nucleotide base pairs that make up the DNA—of 24 different organisms, including yeast and the common intestinal bacterium *Escherichia coli*. As they examine and compare these simple genome sequences, investigators are gaining a fuller understanding of the fundamental instructions for life. Many believe the day is not far off when they will be able to design and create entirely new organisms—new life—from scratch.

Of course, scientists have been engaged in some form of genetic engineering—introducing single genes into the DNA of microorganisms such as *E. coli*—since the 1970s. They have tweaked bacteria into producing human proteins, engineered corn plants that can make pesticides and grown tobacco plants that clean up mercury from the soil. What makes *genome* engineering different is the scale: researchers are now beginning to outfit microorganisms with new biochemical pathways involving dozens of genes packaged in long stretches of DNA, thereby altering extended segments of the microbes’ genomes. Information obtained from the federally sponsored Human Genome Project and other genome-sequencing efforts provides genome engineers with the necessary raw materials—genes and the DNA sequences that control them—as well as a better blueprint of how organisms are put together.

Genome engineering will enable scientists to design microbes that can perform just about any biochemical task—synthesizing increasingly complex molecules or breaking them down. Imagine bugs custom-made to whisk away the “bioorganic halogenated compounds that cover half of New Jersey,” says Roger Brent of the Molecular Sciences Institute in Berkeley, Calif.

Engineered microbes may even make molecular electronics a reality, suggests Gerald J. Sussman, a computer scientist and engineer at the Massachusetts Institute of Technology. When computer parts are reduced to the size of single molecules, industrious microbes could be directed to lay down complex electronic circuits. “Bacteria are like little workhorses for nanotechnology; they’re wonderful at manipulating things in the chemical and ultramicroscopic worlds,” Sussman says. “You could train them to become electricians and plumbers, hire them with sugar and harness them to build structures for you.”

How will genome engineers build these marvelous microbial machines? Many will simply modify an existing creature by adding a biochemical pathway cobbled together from other organisms. But even that is a daunting task. Tailoring an existing system to suit one’s needs requires quite a bit of knowledge about the pathway: Which steps are slowest? Where are the most likely bottlenecks? Genome engineers are turning to computer modeling to help design and test their systems [*see box on page 81*].

“We want to learn to program cells the same way as we program computers,” says Adam P. Arkin, a physical chemist at Lawrence Berkeley National Laboratory. Some genome engineers have started by building the biological equivalent of the most basic

As efforts accelerate to catalogue the lengthy stretches of DNA responsible for life, scientists are getting closer to being able to build living cells from scratch

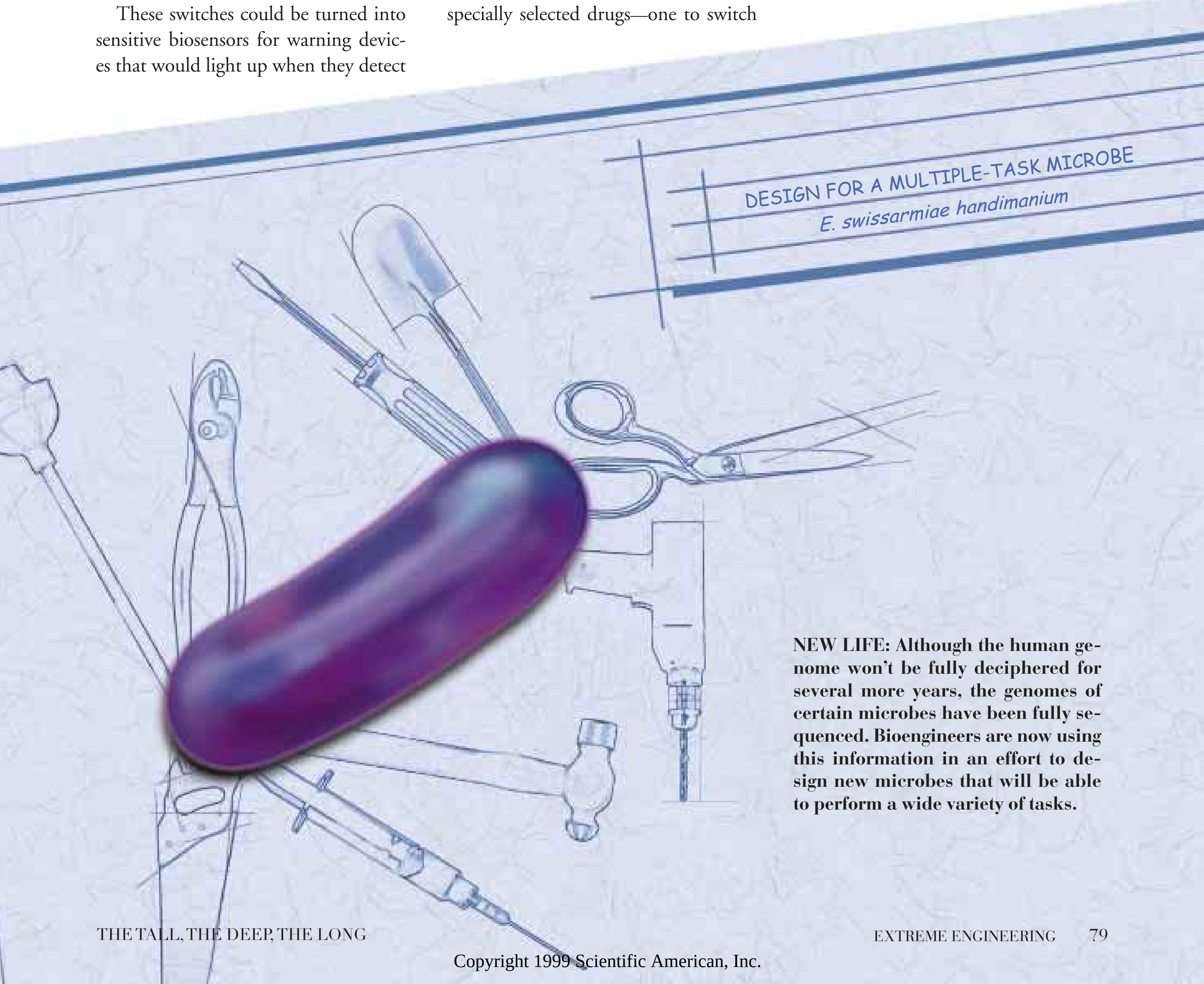
by Karen Hopkin

switch in a computer—a digital flip-flop. Such a cellular toggle switch—made of DNA and some well-characterized regulatory proteins—might be devised to turn on a specific gene when exposed to a particular chemical.

These switches could be turned into sensitive biosensors for warning devices that would light up when they detect bioterrorist weapons such as botulin toxin or anthrax spores, according to James J. Collins, a physicist and bioengineer at Boston University. They could also be used in gene therapy: implanted genes might be controlled with single doses of specially selected drugs—one to switch the gene on, another to switch it off.

"It sounds simple," says Eric Eisenstadt of the Office of Naval Research (ONR), an agency that sponsors such projects. "But believe it or not, it isn't that easy to

LAURIE GRACE



NEW LIFE: Although the human genome won't be fully deciphered for several more years, the genomes of certain microbes have been fully sequenced. Bioengineers are now using this information in an effort to design new microbes that will be able to perform a wide variety of tasks.

do.” Selecting the appropriate genes—and configuring them to produce the desired response—is tricky business. Even so, Eisenstadt predicts that such genetic switches will be the “first baby steps” on the way to designing new regulatory pathways and eventually novel organisms.

Genome engineers trying to make such switches at least have a pattern to copy; nature serves as both teacher and supplier. “Cells switch genes on and off all the time,” observes M.I.T.’s Thomas F. Knight, Jr., a computer scientist turned bioengineer. By taking advantage of nature’s designs, genome engineers are starting off with circuits and components that have been “evolutionarily validated” as parts that work well, Brent adds.

Some researchers are harnessing the powers of evolution even more directly. They are using the principle of natural selection (in this case, survival of the fittest) to generate improved enzymes and perhaps whole organisms. In a process described as DNA shuffling, Willem P. C. Stemmer and his colleagues at Maxygen in Redwood City, Calif., isolate the genes for a particular enzyme from a handful of microbes. They break the genes into fragments and randomly introduce mutations to provide added variety. Then they shuffle and stitch the fragments back together.

By then screening for the mutant enzyme that is the fastest or most stable, investigators wind up with a hybrid that might be thousands of times more efficient than any of its parent enzymes, says Maxygen’s Jeremy Minshull. Stemmer and his colleagues plan to apply a similar technique to shuffling not just single genes but whole genomes, which should yield bacteria optimized for whatever properties they desire—the ability to detoxify New Jersey, for example.

Andrew D. Ellington and his associates at the University of Texas use selective pressures to steer bacteria toward something even more unnatural—accepting and using amino acids that do not occur in nature and that are normally poisonous to living organisms. Ellington hopes that these funky bugs, which he calls Un-coli, will perform novel chemical reactions. Such as? “We don’t know,” he chirps with glee. “That’s what makes this fun.”

VICTORIA ROBERTS

“Our daughter cell may have my ability to take up inorganic ions, but she’s got your wonderful talents at amino acid metabolism.”

FUNCTION OF ESSENTIAL GENES	NUMBER OF GENES
TRANSLATION: Assembly of amino acids into a protein, based on the blueprint provided by the sequence of nucleotides in a molecule of messenger RNA	95
ENERGY: Production of enzymes necessary to allow the microbe to extract energy from nutrients such as simple sugars	34
NUCLEOTIDE METABOLISM: Synthesis or recycling of the four chemical bases that make up a strand of DNA or RNA	23
REPLICATION: Creation of a duplicate copy of the bacterial DNA chromosome, without which the microorganism could not reproduce	18
CHAPERONES: Production of molecules that guide, or “chaperone,” the correct assembly of newly produced proteins	13
TRANSCRIPTION: Conversion of a strand of DNA into a sequence of RNA, from which a protein could be manufactured	9
RECOMBINATION AND REPAIR: Detection and repair of breaks or errors that can occur in replicating DNA for reproduction	8
COENZYME METABOLISM: Synthesis and use of small-molecule co-factors that help some proteins to perform their tasks	8
EXOPOLYSACCHARIDES: Production of complex sugars that form part of the cell wall or external capsule	8
AMINO ACID METABOLISM: Synthesis or scavenging of the amino acids that are the building blocks of proteins	7
LIPID METABOLISM: Production of lipids that store energy and form the bulk of the cell membrane	6
UPTAKE OF INORGANIC IONS: Production of the channels that permit the cell to respond to changes in its environment and to import salts and metals	5
SECRETION AND RECEPTORS: Synthesis of molecules that enable cells to export proteins and respond to external signals such as the presence of nutrients	5
OTHER CONSERVED PROTEINS: Synthesis of additional proteins or RNAs with essential but as yet unknown functions	18

BASIC GENES: By comparing the genomes of the microbes *Hemophilus influenzae* (1,700 genes) and *Mycoplasma genitalium* (500 genes), scientists may have determined the 257 genes essential for life, at least for microbes.

Adapted from “A Minimal Gene Set for Cellular Life Derived by Comparison of Complete Bacterial Genomes,” by Arcady R. Mushegian and Eugene V. Koonin, in *Proceedings of the National Academy of Sciences USA*, Sept. 17, 1996.

Rather than tinkering with existing bacteria, other scientists are talking seriously about building a creature from scratch, the ultimate engineering feat. Their approach is to start small, and several groups of investigators are trying to determine the minimal set of genes necessary for a cell to survive and reproduce.

One way to ascertain which genes are essential for life is to examine those present in microbes that have been fully sequenced and see which ones nature has elected to preserve. Eugene V. Koonin and Arcady R. Mushegian of the National Institutes of Health’s National Center for Biotechnology Information have done just that. They compared two fully sequenced microbes: *Hemophilus influenzae,* with 1,700 genes, and *Mycoplasma genitalium,* with 500 genes—the smallest bacterial genome sequenced to date.

Koonin and Mushegian conclude that only 250 or so genes are required for life. J. Craig Venter and his colleagues at the Institute for Genomic Research (TIGR)—the team that sequenced *H. influenzae* and *M. genitalium*—venture that it’s closer to 300. An organism with these 250 or 300 genes—whatever they are—would be able to perform the dozen or so functions required for life: manufacturing cellular components such as DNA, RNA, proteins and fatty acids; generating energy; repairing damage; transporting salts and other molecules; responding to chemical cues in their environment; and replicating. Although each of these functions requires multiple genes, the whole shebang could be carried in a genome some 300,000 nucleotide bases in length—about half the size of *M. genitalium*’s.

To determine which genes are truly indispensable, some researchers have been deleting them one by one. Venter’s TIGR team is knocking genes out of *M. genitalium.* Other groups are performing similar elimination experiments in *E. coli* and yeast. Pharmaceutical companies are using *E. coli* mutants generated by George M. Church of Harvard Medical School to identify new targets for antibiotics—genes that appear to be essential for bacteria but are not found in humans.

Knowing which genes are necessary is one thing, but how do you turn that information into life? Today’s DNA synthesizers are not capable of whipping up genome-size chunks of DNA. But researchers are working on techniques for synthesizing large rings of DNA that hold the genes for a single biochemical function—say, all the enzymes necessary to produce ATP, the molecule that cells use for energy. Glen A. Evans and his colleagues at the University of Texas Southwestern Medical Center can churn out DNA 10,000 to 20,000 nucleotide bases in length; they’d like to make pieces 10 times as long.

The Drawing Board of Life

When engineers set out to build digital circuits,” observes Roger Brent of the Molecular Sciences Institute in Berkeley, Calif., “they don’t touch soldering iron to circuit board until they’ve modeled the system computationally.” Like good engineers, biologists who aim to design new metabolic pathways—or novel organisms—are coming to recognize the value of a good computer simulation.

One such model has already yielded some provocative predictions. The institute’s Drew Endy has been perfecting a computer program that simulates the life cycle of T7—a virus that attacks *E. coli.* Endy’s program is based on detailed knowledge of T7’s biology—such as when and how strongly each of the virus’s roughly 50 genes is turned on and which RNA and proteins result. In his model, Endy divided the virus’s genome into its individual genes and the DNA elements that control them. He then shuffled all the pieces and asked whether these new viruses could survive in his virtual world. Most didn’t do too well: they failed to produce as many progeny as the original parent virus in the same amount of time. But a few did better than the real-world T7, which suggests that the virus’s genome may not be configured for optimum reproduction.

Why didn’t evolution select the better breeder? According to Endy, the real T7 may work better in varying environments than its computer model cousins. For instance, when Endy makes food scarce in his model, he finds that almost none of the mixed-up viruses fare as well as the T7 that nature engineered, in terms of the number of offspring. “This cries out to be tested experimentally,” Brent notes. A new DNA synthesizer should allow Brent and Endy to generate these jumbled genomes and put their predictions to the test. *—K.H.*

With the proper genes in hand, all that would remain would be for scientists to stuff the pieces of DNA into an empty cell sac—most likely an animal cell from which the nucleus had been removed. The proteins left in the gutted cell, Evans and others hope, would begin making the molecules necessary to jump-start this new form of life.

Of course, producing novel life-forms will raise many concerns, from ecological to ethical. Potential problems have already surfaced in the genetically engineered plants of today. For example, corn that produces its own insecticide may kill harmless bugs (like monarch butterflies). Minimal-genome microbes, however, might not even be able to survive outside the lab. “I doubt this minimal lifeform will be lurching around frightening villagers,” comments Thomas H. Murray of the Hastings Center for Bioethics.

Then there is the philosophical question: If scientists can actually create life, are they playing God? “People usually raise that point as a way to forestall discussion of the real issues,” says David Magnus of the University of Pennsylvania Center for Bioethics. He and his colleagues have been considering the ethical implications of synthesizing cells from the ground up—an event he guesses will grab headlines in the next five years. After two years of contemplation, the group has concluded that the potential benefits of engineering life—which Magnus says include better gene therapy techniques and an enhanced understanding of cell biology—outweigh the possible dangers. But these issues, he asserts, should be addressed by scientists and society.

That discussion had better start soon, because genome engineers are closer than even most scientists realize to making creatures unlike anything ever seen on Earth. What this brave new bioengineered world will look like is hard to say. “But it’s going to be awesome,” ONR’s Eisenstadt predicts. “I mean, it’s life.”

About the Author

KAREN HOPKIN is a recipient of the M.I.T. Knight Science Journalism Fellowship. She has no immediate plans to move to New Jersey.

Bridging Borders in Scandinavia

by Peter Lundhus

High above the Flinte Channel off the coast of Sweden, the final 140-meter (459-foot) segment of the Øresund Bridge snapped into place this past August. After four years the 16-kilometer (9.9-mile) Øresund Bridge and Tunnel project—commonly known as the Øresund Fixed Link—is nearly finished. With the exception of the soaring twin concrete pylons that support the cable-stayed bridge, every massive, multiton part of the Fixed Link was cast or built elsewhere, floated out to the site and (like the colorful snap-together Lego blocks invented in nearby Denmark) assembled, piece by piece, on the spot.

The $3-billion Fixed Link is one of the largest infrastructure projects in European history. Its completion in mid-2000 will fulfill the age-old ambition of linking Denmark and Sweden across the Øresund Strait, by connecting the Danish capital of Copenhagen and the Swedish regional capital of Malmö.

The project entails three major structures: the world's longest underwater combined railway and motorway tunnel, more than four kilometers long; a 7.8-kilometer bridge with a cable-stayed section as its centerpiece; and an artificial island four kilometers long in the middle of the strait where the bridge and tunnel meet. Skillful prefabrication was the key to this project. It minimized the need for dangerous, difficult offshore work, made it possible to construct the bridge and tunnel parts in a controlled environment, and yielded a low rate of on-the-job accidents.

Continued on page 85

The Øresund Bridge and Tunnel will join Denmark and Sweden on July 1, 2000. Prefabrication of the project's complex components facilitated construction

SØREN MADSEN

CONSTRUCTION OF ØRESUND BRIDGE
near Malmö, Sweden

A SENSE OF SCALE: Workmen inside the tunnel are dwarfed by a steel bulkhead that seals one of the tunnel element's four large tubes designed for a railway or motorway.

SØREN MADSEN

Continued from page 82

The tunnel segment of the Fixed Link, which stretches from the Danish coast to the artificial island (informally referred to as Peberholm), has five parallel tubes—two each for the railway and motorway, and a small tunnel that serves as an escape gallery. The tunnel consists of 20 prefabricated concrete elements; each element is made of eight separate sections. Workers at a specially built factory 12 kilometers north of the tunnel site cast the concrete sections indoors—each in a single 30-hour cycle—and then joined them together to form the tunnel elements. A single element is 176 meters long, 42 meters wide and nearly nine meters high; it weighs about 57,000 metric tons.

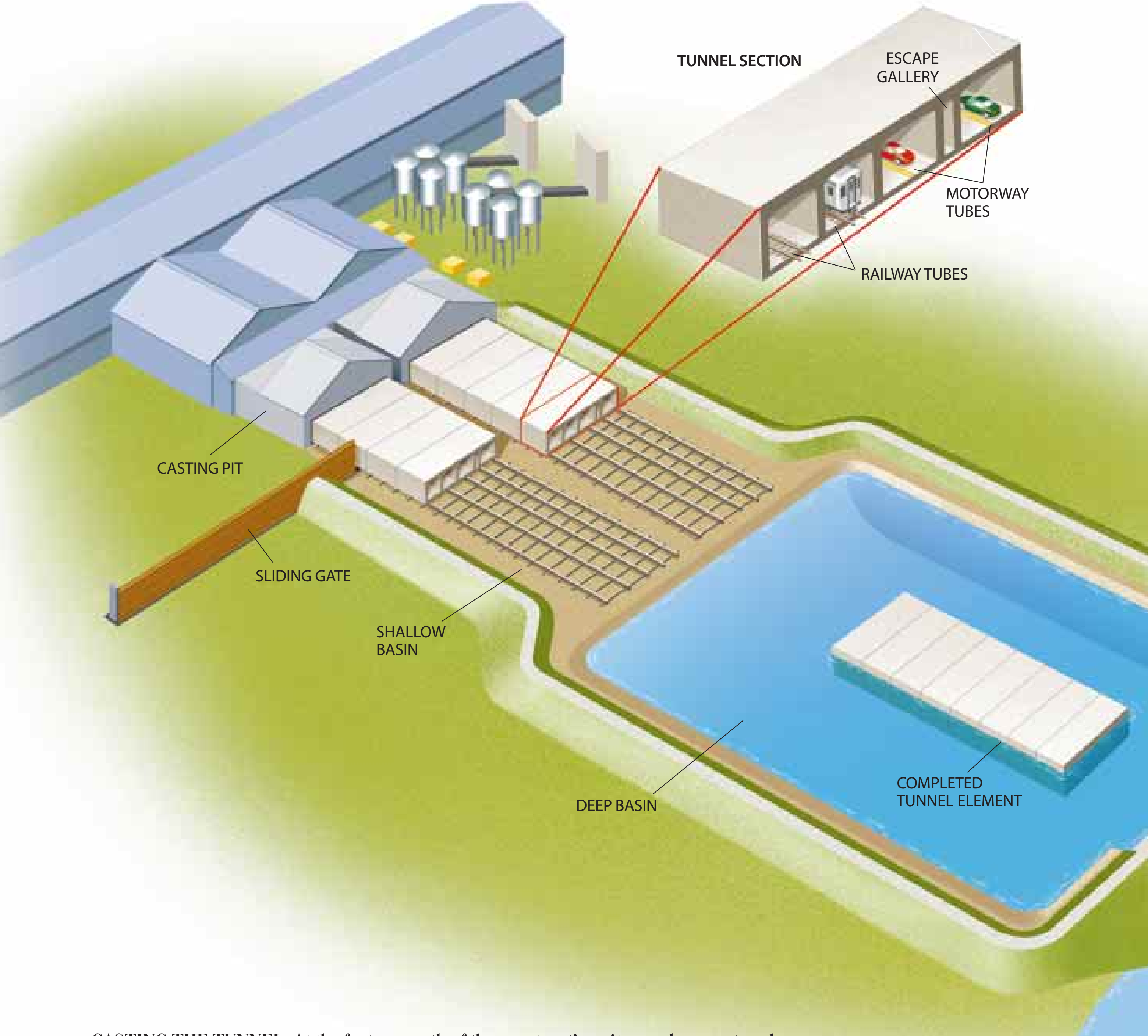
The ends of the completed tunnel elements were then sealed with huge steel bulkheads, and tugboats towed each assembly to the construction site. The final segment was positioned in the tunnel trench on January 6, 1999. On January 26, workers opened the bulkhead door between the last two elements, connecting Copenhagen on the Danish coast with Peberholm island.

For the bridge from Peberholm island to Malmö, the engineering team chose a cable-stayed design for the 1,092-meter center section. In this scheme the bridge deck is supported mainly by arrays of straight cables anchored directly to the vertical pylons—not carried by two or more main cables, as is the case with a traditional suspension bridge. This allows the freedom to design without the massive anchor blocks at the ends of the main cables yet still creates a very strong bridge that can accommodate the weight of the combined railway and motorway link. Notably, the Øresund bridge will carry the heaviest load of any cable-stayed bridge built to date.

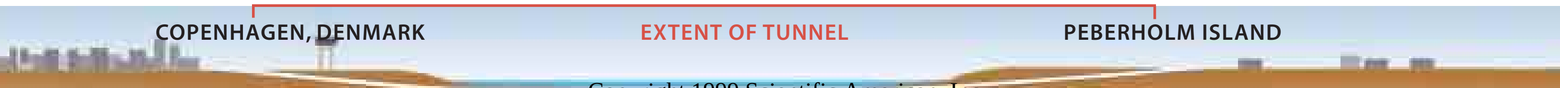
Like the tunnel, the Øresund bridge was highly prefabricated. A factory on the east coast of Sweden produced the eight steel girders for the cable-stayed bridge. These girders were then transported by barge to Malmö for final assembly. The two approach bridges on either side of the high center span consist of 49 girders, each weighing some 6,000 metric tons. These segments were manufactured and assembled in Spain. Workers used the specially designed floating crane known as the *Svanen* ("Swan") to carry the bridge segments to the construction site and lower each one into place [*see top photograph on page 88*].

Construction of the Fixed Link involved a major dredging and reclamation effort of several million cubic meters of seabed material. The tunnel trench required the dredging of 2.2 million cubic meters of material. An additional 1.8 million cubic meters of seafloor was excavated during so-called compensation dredging, which repositioned and deepened the shipping routes of the Flinte and Drogden channels and also avoided blocking the movement of water, salt and dissolved oxygen through Øresund Strait to the Baltic Sea. Fortunately, the construction team was able to reuse all the dredged material from the ocean floor, primarily for creating the artificial island of Peberholm.

The Øresund Fixed Link will enable the 3.5 million inhabitants of the Copenhagen-Malmö area—whose commercial activities were limited by the lengthy ferry crossing of the strait—to develop this cross-border region into a major northern European center for business, transport, research and education.



CASTING THE TUNNEL: At the factory north of the construction site, workers cast each 176-meter, 57,000-metric-ton tunnel element in eight individual 22-meter sections (*above*). As each section was joined to the next, hydraulic jacks pushed the lengthening element out of the casting pit and onto a ramp in a dry, shallow basin adjacent to a water-filled deep basin. Once all eight sections had been cast and linked to form one complete element, each of the element's five tunnel tubes were sealed with watertight steel bulkheads [*see photograph on preceding page*], creating a buoyant, air-filled concrete vessel. The sliding gate at the rear of the shallow basin was then closed and the basin was flooded with around 10 meters of water, until the tunnel element began to float. The element was pulled out into the deep basin and parked to await towing to the tunnel site. Workers then drained the shallow basin, making room for the next element.



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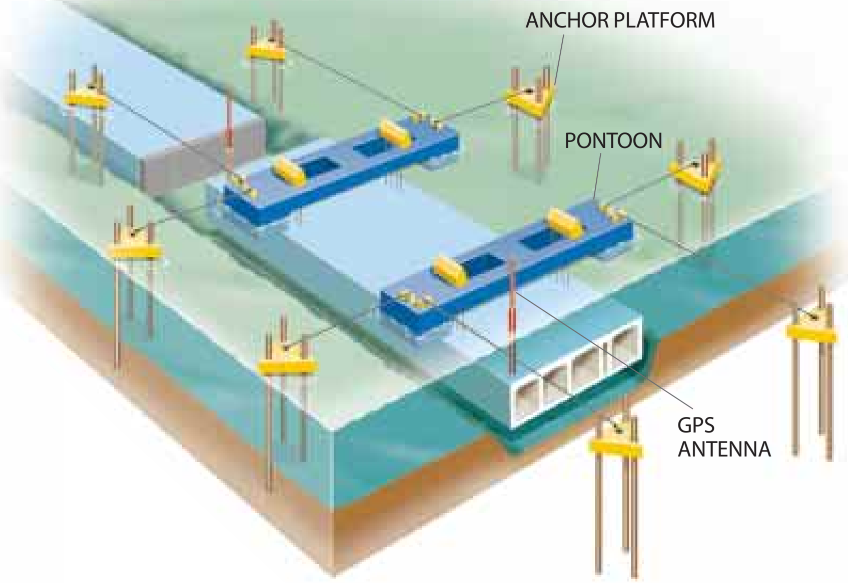
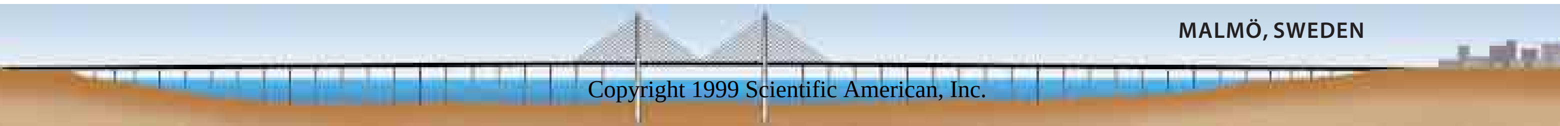


TOWING THE TUNNEL: Once one of the enormous tunnel elements—equipped with pontoons and floating almost completely immersed—had been moved to the deep basin, tugboats towed the piece to the tunnel site. When the element reached the site (*photograph above*), engineers positioned it above the tunnel trench and secured it to eight anchor platforms in the seabed (*above*). Next, they pumped water into the ballast tanks within the tunnel and lowered it into the trench. The final, precise positioning took place with the aid of the Global Positioning System (GPS), which allowed workers to position the element in the trench with an accuracy to within five centimeters. To connect the pieces of the tunnel, engineers pulled the newly immersed element against the previous one, where a set of rubber gaskets was installed between the two. As the two elements came together, a small reservoir of water was trapped between them. When the water was pumped out of the reservoir, the water pressure outside compressed the gaskets and sealed the joint. Workers then removed the giant steel bulkheads between the elements and ballasted the recent arrival with concrete so it would remain in place.

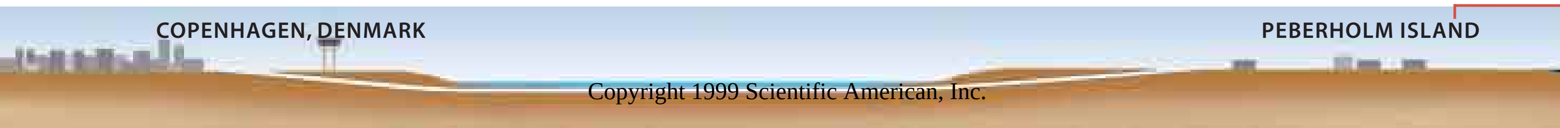
ILLUSTRATIONS BY GEORGE RETSECK



PIERRE MENS

BUILDING THE BRIDGE: The giant *Svanen* ("Swan") crane places one of the final girders that make up the high center span of the bridge (*above*). Apart from the soaring main pylons, which were cast in place (two of them can be seen here with cranes attached to their tops), all other bridge components—the caissons, the pillar shafts of the approach bridge, the cable-stayed bridge girders—were lowered into place by the *Svanen* crane. Specially modified for the Øresund project, the *Svanen* has a maximum lifting capacity of 8,700 metric tons. The versatile crane can position the heaviest concrete and steel elements with the utmost precision, constructing the bridge much the way a child builds with a Lego kit. The upper concrete deck of the bridge carries the motorway, and the lower deck contains the railway tracks (*right*).

PIERRE MENS

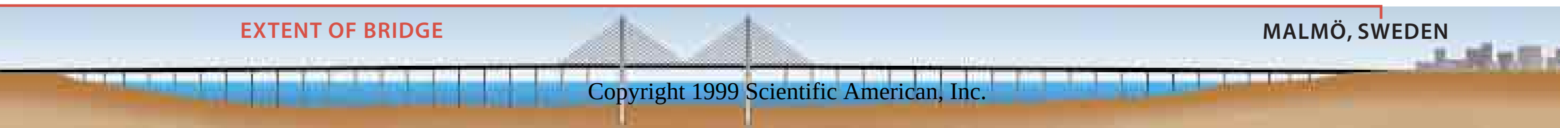


ANCHORING THE BRIDGE: Pylons consisting of twin concrete towers support the cable-stayed bridge. These towers rise 204 meters above sea level, making them the tallest concrete structures in Sweden. The cables on the bridge follow the classical cable-stayed harp pattern and are anchored to the bridge girders of the 500-meter main span at 20-meter intervals and to the pylons every 12 meters (*below*). The foundations for the pylons and the approach bridge piers are 20,000-metric-ton prefabricated concrete caissons more than 20 meters high. Just as with so many other parts of the project, these pieces were cast in a dry dock in Malmö Harbor and then towed to the bridge site for installation below the waterline. The pylon legs were built on top of the caissons using climbing formwork and prefabricated reinforcing steel cages, visible on the tops of the incomplete set of towers at left in the photograph below.

PIERRE MENS

About the Author

PETER LUNDHUS has been technical director for the Øresund Fixed Link since its inception. In 1988 he joined the Great Belt company, which, in 1998, completed the Great Belt Link in Denmark, the predecessor to the Øresund Fixed Link. Lundhus received a master of science degree in civil engineering from the Technical University of Denmark in 1965.



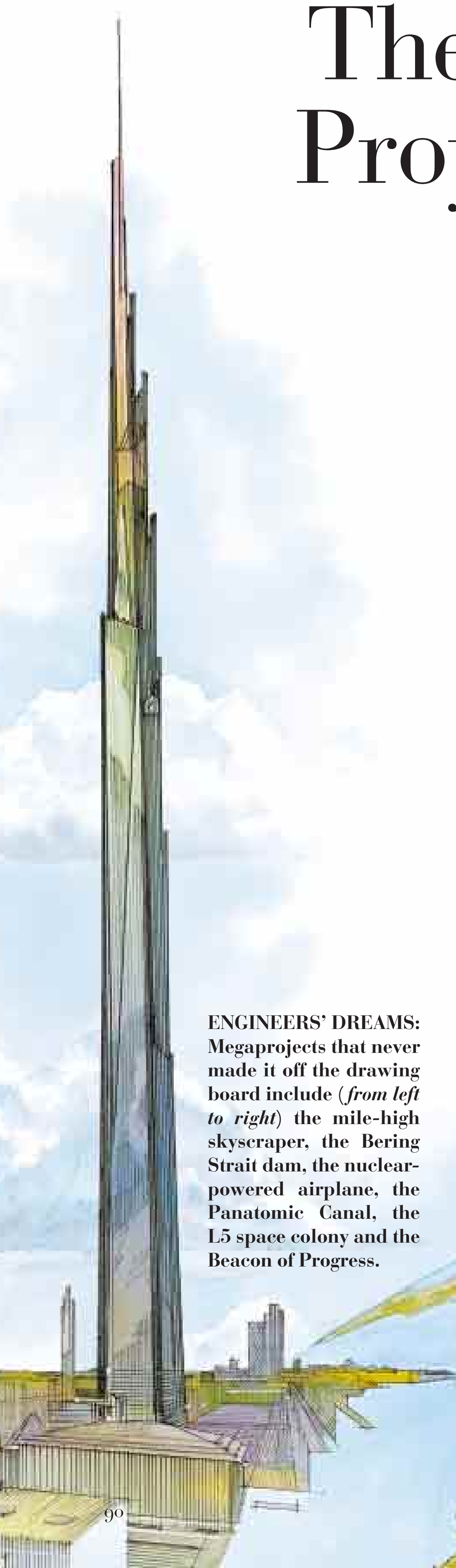
The GREATEST Projects Never Built

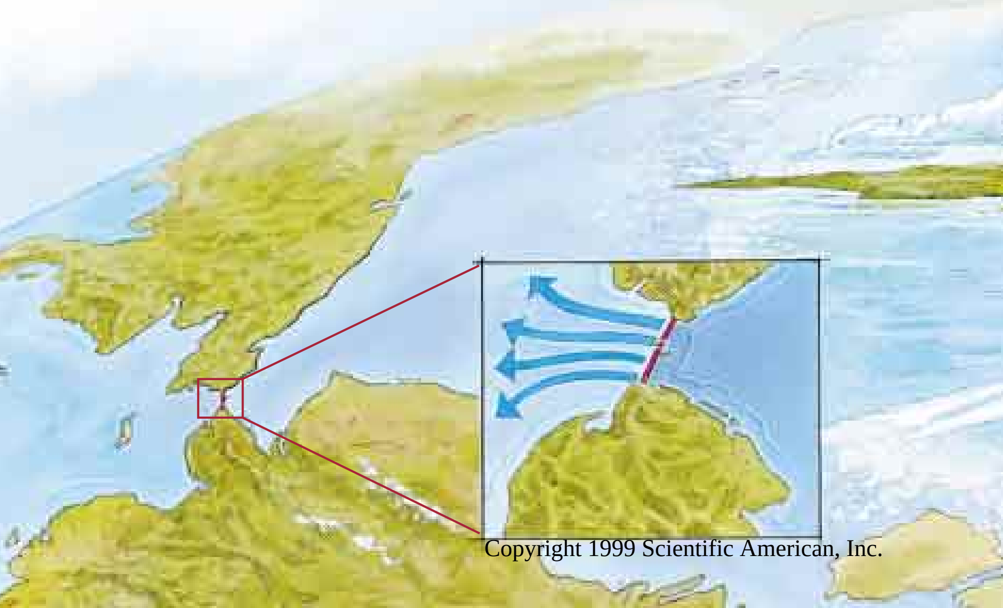
Many well-laid engineering plans went astray—and in some cases, it was lucky they did

by Mark Alpert

To the ancient Babylonians, it must have sounded like a wonderful idea. "Let us build us a city and a tower, whose top may reach unto heaven; and let us make us a name, lest we be scattered abroad upon the face of the whole earth." At least that's how the Book of Genesis tells the story. The construction started well: the builders had plenty of brick, mortar and laborers. What they didn't count on was the wrath of the Lord. Outraged by the ambitions of the early engineers, the Almighty killed the project by forcing the workers to speak in different languages. The Tower of Babel became the first in a long line of marvelous structures that, for one reason or another, were never built.

In the past century alone, visionary architects and engineers have proposed a host of stupendously impractical projects. Some prominent examples are the mile-high skyscraper, the nuclear-powered airplane, the Superconducting Super Collider and the L5 space station. Divine anger didn't kill any of these plans—they were done in by extravagant costs, unforeseen construction problems, shifts in political backing and the often belated realization, "Hey, do we really need this thing?" The history of these proposals suggests a basic lesson that should be taught in all engineering and architecture schools: just because something *can* be built does not necessarily mean that it *will* or *should* be built.





ENGINEERS' DREAMS: Megaprojects that never made it off the drawing board include (*from left to right*) the mile-high skyscraper, the Bering Strait dam, the nuclear-powered airplane, the Panatomic Canal, the L5 space colony and the Beacon of Progress.

Consider, for instance, the Beacon of Progress. In 1900 Désiré Despradelle, an architecture professor at the Massachusetts Institute of Technology, proposed the construction of a 1,500-foot-high (457-meter-high) obelisk in Chicago overlooking Lake Michigan. The Beacon of Progress, which would have been nearly three times as tall as the Washington Monument, was an elaborate expression of the French-born Despradelle's love for America. He planned to adorn the obelisk with statues of lions, eagles and female figures representing the 13 original colonies. Despradelle and his students worked on the design for several years, and it won numerous awards. Their plan, however, had a glaring flaw: the obelisk's base could not have supported the immense weight of the granite monument. The Chicago Architectural Club exhibited drawings of the Beacon of Progress, but the city's builders politely declined to take up the project.

Half a century later America's greatest architect envisioned an even more grandiose structure. In 1956 Frank Lloyd Wright, then in his late 80s, presented his plans for the Illinois, a 528-story skyscraper that would have towered a full mile above Chicago. Shaped like a giant rapier, the steel-and-aluminum building would have provided office space for 100,000 workers, parking for 15,000 cars and landing decks for 150 helicopters. In fact, the skyscraper could have housed the entire government workforce of the state of Illinois.

Toledo architect Byron L. West, who attended Wright's presentation as a graduate student at the Illinois Institute of Technology, recalls that the audience was intrigued by the proposal. "Because he was Frank Lloyd Wright, they took him seriously," West says. "But I was with a group of architecture students, and we were a little skeptical." The next day West and his fellow students calculated how long it would take Chicago's elevated rail system to deliver 100,000 workers to Wright's proposed skyscraper. Assuming a fully loaded eight-car train arrived at the building every five minutes, the answer was 10 hours. Another problem was elevators—the Illinois would have required hundreds. All those elevator shafts would have taken up a lot of space, sharply reducing the proportion of income-

BARRY ROSS

generating square footage in the building. Needless to say, funding for the Illinois never materialized.

Thinking big is also a predilection of civil engineers, who often delight in drawing up blueprints for gargantuan dams, canals and bridges. In 1928 German engineer and architect Herman Sörgel described a remarkable plan to increase the landmass of Europe and Africa by draining much of the Mediterranean Sea. Sörgel proposed building a dam across the Strait of Gibraltar to block the current from the Atlantic Ocean. Water levels in the Mediterranean would drop by about 40 inches a year; after a century or so 90,000 square miles (233,000 square kilometers) of new land would appear above the surface. Much of the Adriatic and Aegean seabeds would become valuable real estate. There would be some drawbacks, of course: most of the present Mediterranean ports would be stranded miles from the water's edge, and sea levels in the rest of the world would rise by three feet. But that, according to Sörgel, was simply the price of progress.

In 1957 Pyotr Borisov conceived a similar transformation for the Arctic Ocean. The Soviet engineer argued that the Russian climate could be greatly improved by constructing a dam across the Bering Strait, the narrow stretch of ocean between Siberia and Alaska. Powerful pumps at the dam would spew billions of gallons of cold Arctic water into the Pacific Ocean. The flow would draw warmer Atlantic water into the polar region and eventually melt the Arctic ice cap, which would in turn warm the vast Russian tundra. Borisov acknowledged that his plan would affect the climates of other countries as well—and not all for the better—but he didn't see this as a fatal flaw. In retrospect, it's lucky that Russia sold Alaska to the U.S. in 1867. If the Russians had held on to the territory, they would have been free to build the Bering Strait dam, and the cold war might have taken on a whole new meaning.

JUST BECAUSE SOMETHING *CAN* BE BUILT DOES NOT NECESSARILY MEAN IT *WILL* OR *SHOULD* BE BUILT.

None of these schemes progressed beyond the design stage, and no one spent any serious money to determine whether they were feasible. Unfortunately, the same cannot be said for the nuclear-powered airplane. After World War II, U.S. Air Force officials became convinced that they needed a longer-range bomber. A nuclear-powered aircraft, they reasoned, would require only a small amount of uranium fuel and thus could stay aloft for weeks. Its range would be limited, it was said, "only by sandwiches and coffee for the crew." So the air force set out to build a nuclear turbojet engine. In a conventional jet engine, incoming air is mixed with fuel and burned; in the nuclear version, the air would be heated by a reactor.

The engineers quickly ran into a problem: the reactor needed massive shielding to protect the plane's crew and equipment from radiation. An early design called for nearly 50 tons of shielding, which is more than half the weight of an unloaded B-52. And all of it would be for naught in the event of an accident; if the nuclear-powered aircraft crashed, it would splatter radioactive material over a wide area. Citing these concerns, the air force recommended canceling the study, but Congress kept it alive. The politicians were determined to beat the Russians, who were vainly trying to build their own atomic plane. By the early 1960s, though, the air force had come up with a better way to deliver warheads—via intercontinental missiles—and President John F. Kennedy finally killed the program, which had cost taxpayers a total of $1 billion.

The nuclear foolishness didn't end there, though. In the late 1950s the U.S. Atomic Energy Commission (AEC) launched Project Plowshare to explore the possibility of using atomic blasts for peaceful pursuits. Some scientists envisioned detonating a string of atom bombs to excavate a canal that would replace the one in Panama (the proposed waterway was dubbed the Panatomic Canal). Others considered employing the weapons to dig out harbors in Alaska or to release petroleum from oil tar sands in Canada. The AEC even tested the concept by setting off a series of underground nuclear explosions in Nevada, Colorado and New Mexico. The countries of Central America, however, turned down the Panatomic Canal, and in the 1970s Project Plowshare died a quiet death. About $160 million had been wasted on the idea.

Not all the great unfinished projects of the 20th century were so wrongheaded. Some efforts had admirable goals and were technologically feasible but simply grew too expensive. A good example is the Superconducting Super Collider, a humongous particle accelerator that was slated for the small town of Waxahachie, Tex. Conceived in the early 1980s by the U.S. Department of Energy, the Super Collider was designed to smash protons together at unprecedented speeds and allow researchers to examine the subatomic debris. The beams of protons were to be accelerated by thousands of superconducting magnets situated along a circular tunnel with a circumference of 54 miles (87 kilometers). Particle physicists hailed the proposal, saying the Super Collider would be a powerful tool for studying the fundamental building blocks of matter. Initial estimates put the project's cost at roughly $4 billion.

Presidents Ronald Reagan and George Bush strongly supported the Super Collider, and in the early 1990s contractors began tunneling under the Texas prairie. By that point, however, design changes and unexpected expenses had almost tripled the accelerator's price. Many politicians outside Texas saw the Super Collider as a pork-barrel science project that

BARRY ROSS

MEDITERRANEAN MADNESS: In 1928 German engineer Herman Sörgel proposed building dams to drain the Mediterranean Sea. Europe and Africa would have gained territory (*light green*), but their ports would have been landlocked.

would drain funding from smaller but equally important research efforts. So in 1993 Congress axed the program, even though $2 billion had already been spent. The partially built tunnel was abandoned, and today only a few filled-in access shafts mark its presence. The disappointed physicists learned a hard lesson: big science doesn't always sell. Many set their sights on the more modest Large Hadron Collider, the $6-billion particle accelerator now being constructed outside Geneva.

The construction of manned outposts in space is also seen, at least by some scientists and politicians, as a worthy goal. In 1975 the National Aeronautics and Space Administration sponsored an engineering study to design a permanent orbital community. Basing its plan on earlier concepts, the group proposed a space station in the shape of a giant wheel, more than a mile across. The station would orbit Earth in a stable position called the L5 Lagrangian point, which is equidistant from Earth and its moon. Much of the station's raw materials would come from the moon, including oxides, metallic ores and lunar soil for farming. The station's 10,000 colonists would live along the rim of the wheel, which would revolve once a minute to simulate Earth's gravity. The estimated cost of the station was $200 billion in 1975 dollars, equivalent to some $500 billion today.

Over the past quarter of a century, this grand blueprint has been scaled down dramatically. The International Space Station currently being built by NASA and its partners is designed to hold a crew of only seven astronauts. The station's price tag, however, remains enormous: $100 billion, according to the latest estimates. One problem with space construction is that it costs so much to boost the building materials into orbit. Another difficulty is the lack of an economic need for large structures in space. NASA has studied building solar-power collectors that would transmit power to Earth, and space enthusiasts have envisioned orbital hotels that would carry hundreds of tourists. But neither of these ideas is currently feasible. In the near future, at least, space colonies will exist only in science fiction.

What about the other unfinished projects still lying on humanity's drawing board? Although a Bering Strait dam seems out of the question, some engineers are pushing for the construction of a bridge or tunnel between Siberia and Alaska. And even Frank Lloyd Wright's mile-high skyscraper may someday become a reality thanks to the development of self-propelled elevator cars, which could take up less space than conventional elevators because several can travel in the same shaft. Indeed, many feats of engineering that once seemed beyond humankind's reach have ultimately been achieved. Consider the tunnel under the English Channel, which had been a dream of engineers since the 18th century. The dream finally came true in 1994, when the Chunnel linked England and France with a high-speed railway. Unfortunately, the project went way over budget, costing $17 billion. The Chunnel's revenues could not cover the interest on its debt, and the owners of the tunnel narrowly escaped bankruptcy in 1997. In other words, the Chunnel was an engineering success but a financial failure. The moral for ambitious architects and engineers: be careful what you wish for, because you just might get it. SA

About the Author

MARK ALPERT is an editor at *Scientific American.* In his spare time he is trying to build a nuclear-powered coffee machine.

The Hubris of Extreme Engineering

by Henry Petroski

Wright brothers at Kitty Hawk, N.C., 1903

> “Engineers can come to **believe in themselves** and their creations beyond reasonable limits. When failures do occur, they naturally cause setbacks but usually do not force the abandonment of dreams for ever grander and more ambitious projects.”

The ancient Greek mathematician and engineer Archimedes claimed that he could move Earth with a large lever, if only he could locate a fulcrum and a place to stand. Many centuries later Galileo was more circumspect about what engineers can do, for he recognized that what worked on a small scale did not necessarily succeed on a larger one. By then, Renaissance engineers knew that levers, like stone obelisks and wooden ships, could be scaled up only so much before they broke under their own weight. Unfortunately, what Galileo learned has not always been remembered, nor is it likely always to be respected in the new millennium.

With the introduction of iron as a structural material, it was possible for engineers not only to dream of larger and larger structures but also to realize them. The first iron bridge, completed in 1779, spanned 100 feet (30 meters) across the Severn River in western England. Within decades, spans exceeding 500 feet were being envisioned, and soon the railroad created the need for ever longer iron bridges.

Isambard Kingdom Brunel, the great Victorian engineer known as the “Little Giant,” was famous for his expansive thinking. Although his contemporaries saw his Great Western Railway serving the countryside to Land’s End (the westernmost point of England), Brunel saw it continuing on across the Atlantic in the form of a steamship carrying passengers and cargo to America. His ship, the *Great Western,* became one of the first to disprove the conventional scientific wisdom of the time—that no ship could be built large enough to carry all the coal it needed for such a voyage.

If the Atlantic could be crossed, then why not greater expanses of sea? Brunel designed his *Great Eastern* steamship to be large enough to transport all the coal it would need to voyage from England to Australia. At 692 feet, the ship had to be constructed parallel to the water because the shipyard could not accommodate the conventional stern-first orientation for assembly and launching. The launch itself took three embarrassing months when the massive vessel got stuck on the incline into the water. Although the ship was structurally sound, it proved too large for most harbors and ended up a white elephant, eventually cut up for scrap. A larger ship was not to be built for almost half a century, until the 704-foot *Oceanic* was completed in 1899.

This pattern has repeated itself—for instance, the supersonic Concorde, first built in the mid-1970s, is a technologically sweet aircraft but has seen only limited service because its sonic boom is not welcome over residential areas around airports. Other supersonic projects have been abandoned as a result. Clearly, the designs of engineers must be more than just strong enough and fast enough; they must also be compatible with the existing phys-

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CORBIS/HOLTON-DEUTSCH COLLECTION

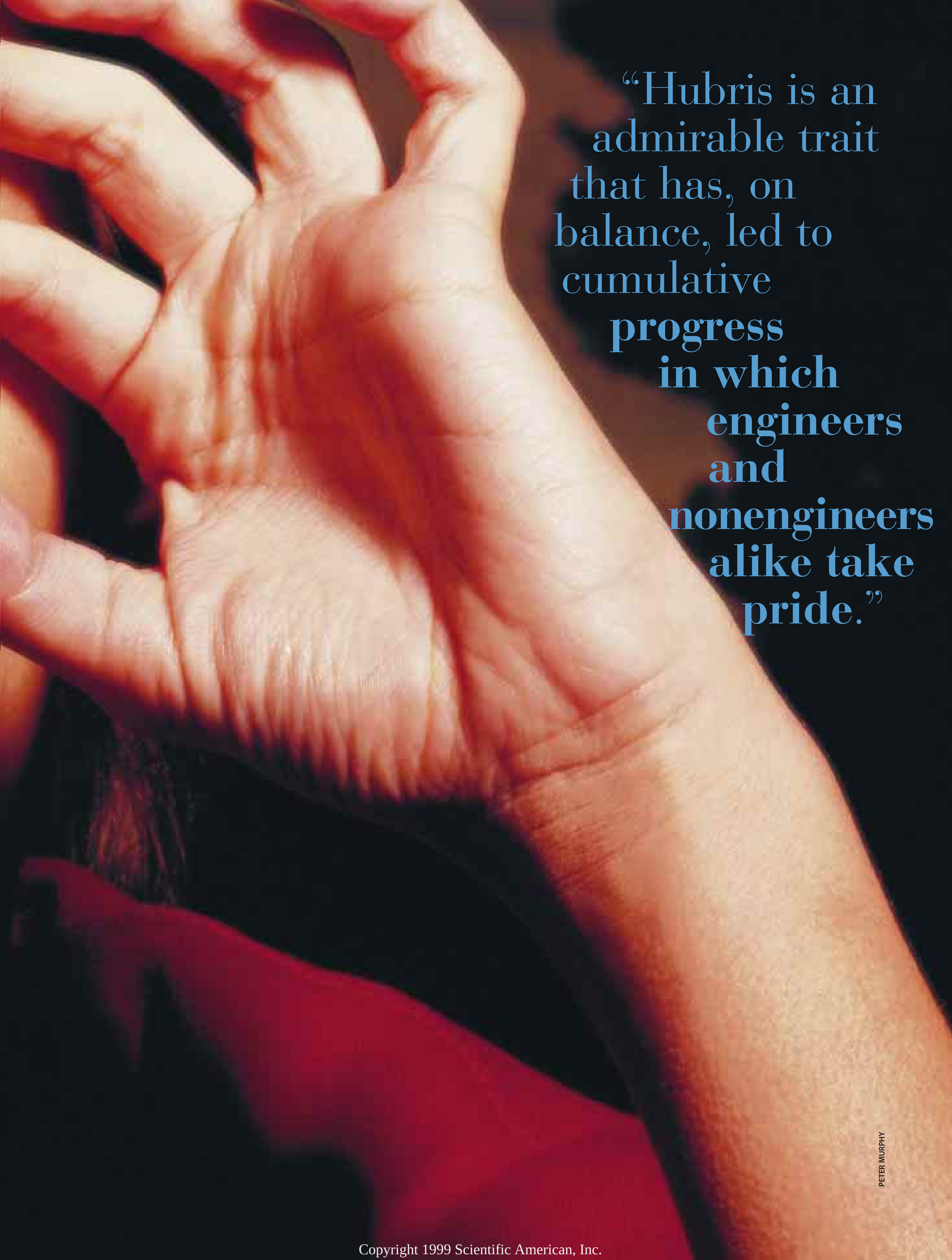
YANN ARTHUS-BERTRAND *Corbis*

"**Colossal accidents** happen when

Abandoned town near Chornobyl, November 1998

overconfidence and complacency prevail."

The Motorola 7400 Power PC microprocessor, currently the fastest on the market



"Hubris is an admirable trait that has, on balance, led to cumulative **progress in which engineers and nonengineers alike take pride.**"

PETER MURPHY

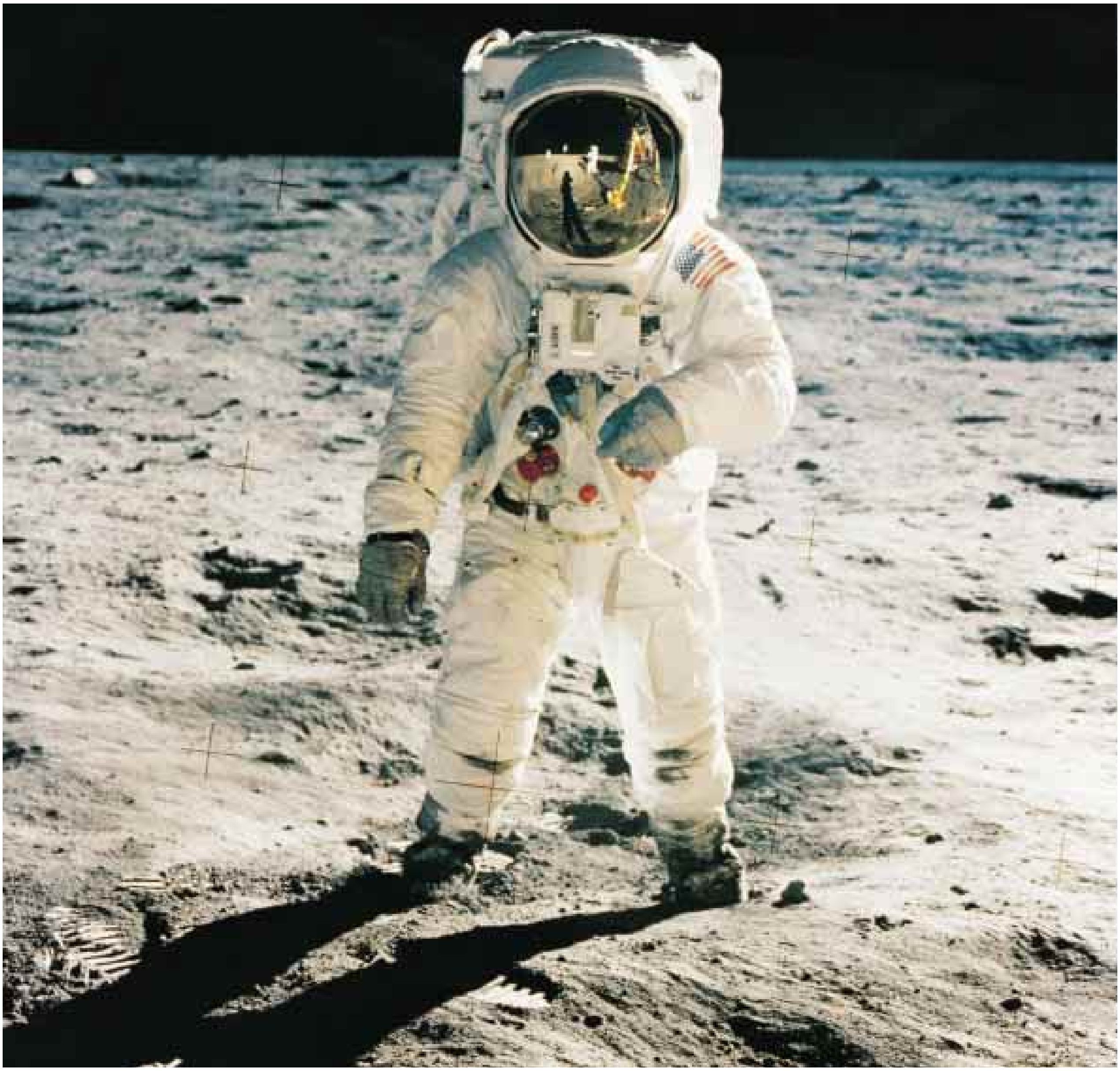
“Clearly, the designs of engineers
enough and fast enough; they must
existing physical, political and

FRANK POLICH *Associated Press*

Demolition of public housing projects in Chicago, December 12, 1998

must be more than just strong also be compatible with the **social infrastructure.**”

“It is as much a part of the human spirit to build longer and to fly faster



NEIL A. ARMSTRONG/NASA

Astronaut Edwin “Buzz” Aldrin on the moon, July 20, 1969

as it is to **probe the universe further** and the atom deeper than our ancestors did.”

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ical, political and social infrastructure.

When Gustav Lindenthal, who had built an impressive bridge in Pittsburgh in the early 1880s, proposed an enormous suspension bridge across the Hudson River at New York City in 1885, there were plenty of naysayers (as there always are with great projects). At 3,500 feet, the bridge's span was to be over twice that of the Brooklyn Bridge, then the longest in the world. And some people, perhaps recalling Galileo's caveats, raised the legitimate question of whether such a long span could even support itself. Yet Lindenthal held on to his dream for almost 40 years, modifying it as times and circumstances changed. Its price tag also changed with the times, rising to as high as $500 million when land acquisition and terminal facilities were included, a price that no one seemed willing to pay. To his critics who said that such a massive bridge could not be built, Lindenthal responded that "it was possible to bridge the Atlantic Ocean, but impossible to finance such an undertaking."

Although Lindenthal's great bridge was never built as he had dreamed it, a more modest crossing of the Hudson was engineered by his assistant Othmar Ammann, whom Lindenthal accused of not thinking monumentally enough and of being a disloyal protégé. But if Ammann's bridge did not live up to Lindenthal's aesthetic expectations, it did to more practical ones: at one tenth the cost of Lindenthal's monstrosity, the George Washington Bridge, which opened to traffic in 1931, was such a technological and financial success that in the following decade it served as a sleek model for suspension bridges built across the U.S., including the Golden Gate Bridge in San Francisco.

The ill-fated Tacoma Narrows Bridge, another descendant of Ammann's George Washington Bridge, was completed in 1940 across an arm of Puget Sound south of Seattle. At the time it was the third longest bridge in the world and narrower than any before it. The bridge had been designed according to a theory developed by Leon Moisseiff, who had served as consulting engineer to the project, as he had to virtually all large suspension bridges built after 1900. When a lesser-known engineer questioned the design as too slender, Moisseiff stood by his theory, assuring people that the bridge would be safe.

Only three months after it opened, however, the Tacoma Narrows Bridge collapsed in a 42-mile-an-hour wind. The physical phenomenon of aerodynamic instability, which had not revealed itself in heavier and wider bridges, dominated the behavior of the Tacoma Narrows. In the aftermath of this disaster, mid-20th-century engineers responded by proposing more comprehensive theories of bridge behavior. Today suspension bridges more than twice as long as the Tacoma Narrows are built safely, in no small part due to the lessons learned from the initial catastrophe. The recently completed Akashi-Kaikyo Bridge in Japan spans 6,529 feet—a mile and a quarter—between its towers.

This is not to say, though, that the hubris of bridge engineers will never again draw them into the same trap that led to failures in the past. In the 1990s, after decades of successful experience with cable-stayed bridges, beginning with those built in Germany after the war, significantly longer spans began to be built. Even though cable-stayed bridges were originally meant to span no more than 1,200 feet, with longer crossings expected to be suspension bridges, two modern cable-stayed bridges—the Pont de Normandie in France and the Tatara Bridge in Japan—now extend over as great distances as the Tacoma Narrows suspension bridge did.

How far cable-stayed bridges can be scaled up before they, too, reach their limit depends on how well engineers understand the behavior of their structures. Already some concern has arisen, because excessive movement has been observed in the taut cables of cable-stayed bridges in Sydney, Australia, and elsewhere during strong wind and rain. Thus far such problems have been conquered by retrofitting the bridges with damping devices, which prevent the movements from growing out of control, but the hubris of bridge engineers that drives them to build longer spans in the face of these warning signs may yet lead to uncontrollable conditions.

Engineers also manifest their hubris in other types of projects. Willy Ley, in his 1954 book *Engineers' Dreams,* described some of the grandest schemes imagined by engineers up until that time: damming the Congo River to create the largest lake in Africa; draining the Mediterranean Sea to reclaim land for crowded Europe; building a tunnel between England and France. This last dream was, of course, realized when the Channel Tunnel opened in 1994, more than two centuries after the idea was first articulated by French engineer Nicolas Desmaret. Whereas the Congo is not likely to be dammed in the foreseeable future, the Three Gorges Dam in China will soon back up water on the Yangtze River and displace more than a million people. Today the decision whether to dam a river is often more political than technical. Engineers can dream, but it takes political savvy and resolve, not to mention money, to move the machinery that moves the earth.

The ultimate triumph of mega-engineering schemes, from gigantic ships to monumental skyscrapers, is also frequently limited by issues tangential to the main idea, by details that can seem decidedly low-tech or even nontechnical—matters such as politics, aesthetics and safety. When engineers ignore these factors or treat them as undeserving of the same careful analysis as the main technological challenge, disaster can result. The sinking of the *Titanic* might not have been nearly as great a tragedy had the ship's vulnerability been acknowledged by having enough lifeboats on board. The Three Mile Island and Chornobyl accidents might not have progressed to the point that they did had nuclear power generation not come to be viewed as so commonplace as to breed a casual and careless attitude among some operators. The space shuttle *Challenger* might not have exploded had managers

Chrysler Building,
New York City,
completed 1930

JOSEPH POBERESKIN *Tony Stone Images*

> “Just as by standing on the shoulders of giants we can become even bigger giants, so it is that by climbing on the spires of skyscrapers, **engineers can reach for ever taller skyscrapers.**”

heeded engineers’ warnings about the behavior of O-rings in cold weather, rather than becoming emboldened by the two dozen successful space shuttle missions that preceded Flight 51L. In short, colossal accidents happen when overconfidence and complacency prevail.

Engineers and managers of technology, being human, can come to believe in themselves and their creations beyond reasonable limits. When failures do occur, they naturally cause setbacks but usually do not force the abandonment of dreams for ever grander and more ambitious projects. As soon as the cause of a failed effort is sufficiently understood and the sting of its tragedy sufficiently remote, engineers want to pick up where they left off in their pursuit of greater goals. This is as it should be in engineering—as in life—for it is as much a part of the human spirit to build longer and to fly faster as it is to probe the universe further and the atom deeper than our ancestors did. Just as by standing on the shoulders of giants we can become even bigger giants, so it is that by climbing on the spires of skyscrapers, engineers can reach for ever taller skyscrapers. If this be hubris, it is an admirable trait that has, on balance, led to cumulative progress in which engineers and nonengineers alike take pride. SA

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HENRY PETROSKI is Aleksandar S. Vesić Professor of Civil Engineering and professor of history at Duke University. He is the author of *To Engineer Is Human* and *Engineers of Dreams,* among other titles. His latest work, *The Book on the Bookshelf,* is about the care and housing of books themselves.