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*

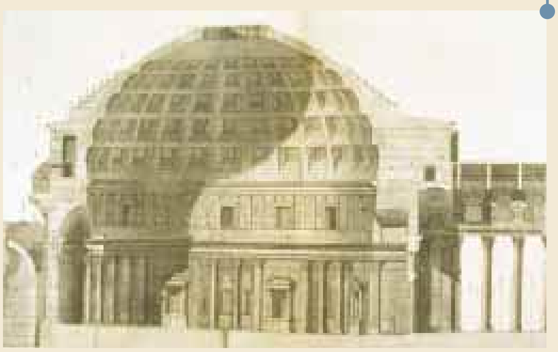
Agriculture appears to have developed simultaneously between 10,000 and 7000 B.C.E. in several parts of the world, as people who had been gathering wild plants began cultivating them (*left:* rock painting from Tassili N'Ajjer, Algeria, circa 6000–2000 B.C.E.). Cereals and legumes were among the earliest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

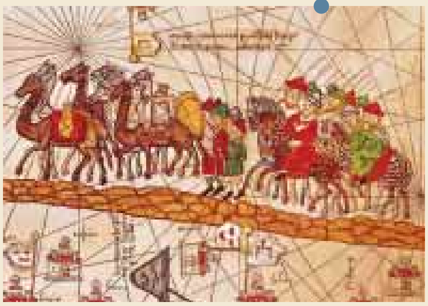
The earliest **stone tools,** discovered in eastern Africa, date to about 2.6 million years ago. Most are simple rock fragments from which *Homo habilis* removed flakes to form an edge. Sharper and more effective tools, such as this 700,000-year-old hand ax found at Olduvai Gorge in Tanzania, began to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

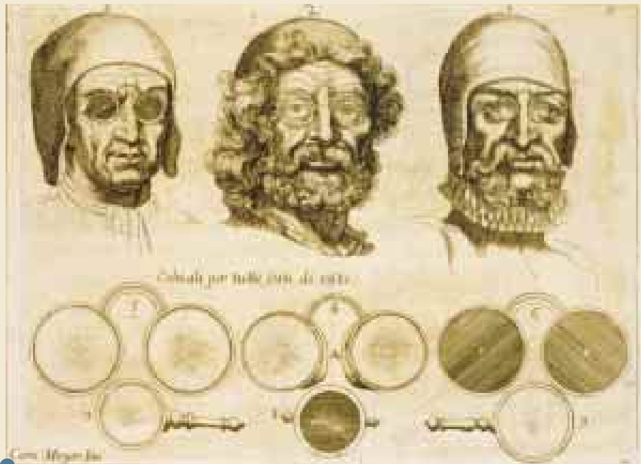
During its zenith around 200 C.E., the **Silk Road** was the longest road in the world, spanning an estimated 7,000 miles, from Xi'an in central China to the western Mediterranean. Venetian explorer Marco Polo utilized the road during his 13th-century C.E. travels (*below*). In addition to its important 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.

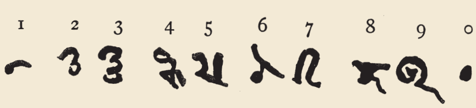
900 C.E.

950 C.E.

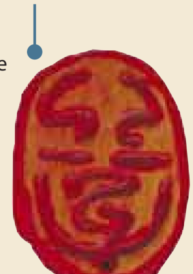
1040 C.E.

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.

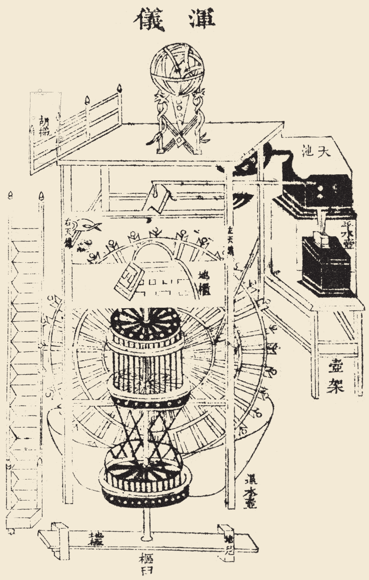
The origins of the familiar **numeral system** can be traced to the work of Hindu astronomers sometime before 650 C.E. The first book to explain clearly the Hindu decimal system, as well as the use of zero as a placeholder, was written during the ninth century C.E. by Muslim mathematician Muhammad ibn 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.



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.

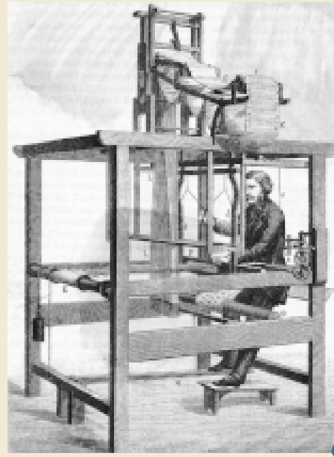


Gunpowder was probably discovered around 950 C.E. by Taoist alchemists, but the incendiary mixture was used almost exclusively in fireworks until it arrived in Europe sometime in the 13th century. Early cannons developed in the 1300s most likely fired only arrows, but by the mid-1400s cannonballs had 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.

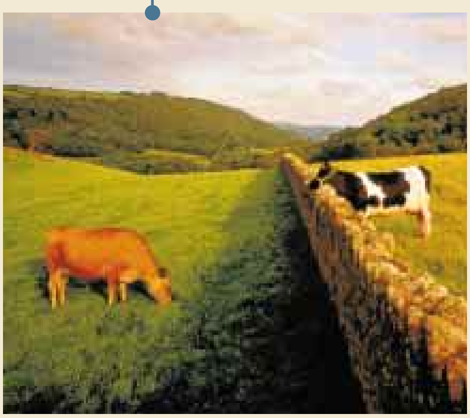
An early form of **vaccination**—in which patients were inoculated with a mild form of smallpox—was practiced in many Eastern countries before the 18th century. This somewhat risky means of securing immunity was popularized in England during the 1720s by writer and traveler Lady Mary Wortley Montagu, 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

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.

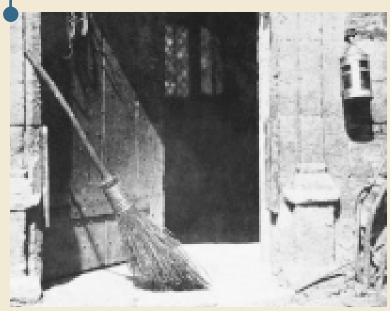


For many years under the feudal system, farmers in Europe operated under an open-field system, in which fields were open to all at certain times of the year for grazing livestock. But during the 1700s and mid-1800s, English farmers saw vast areas of collectively owned land drawn into individual lots 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.

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].

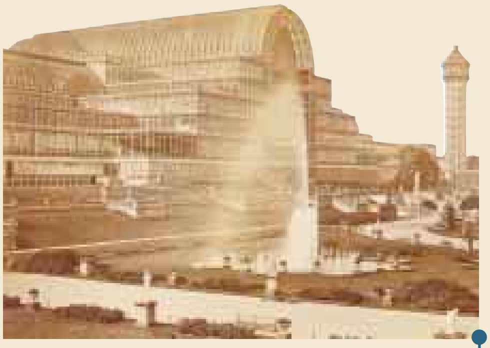
SCHOOL OF AFRICAN AND ORIENTAL STUDIES, LONDON/BRIDGEMAN ART LIBRARY (Design for a Chinese water clock, by Su Sung); A. McPHAIL *Tony Stone Images* (*fence*); CORBIS (*vaccine; refrigerator*); CULVER PICTURES (*bridge; Crystal Palace*); CORBIS/BETTMANN (*loom*); CORBIS/HISTORICAL PICTURE ARCHIVE (*calotype*);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

1830s



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].

1851



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].

1859

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].

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).

1860

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.

1866

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

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.*