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William J. H. Andrewes is a museum consultant and maker of precision sundials who has specialized in the history of time measurement for more than 35 years. He has worked at several scholarly institutions, including Harvard University. In addition to writing articles for popular and academic journals, Andrewes edited *The Quest for Longitude* and co-wrote *The Illustrated Longitude* with Dava Sobel.

INVENTION

A CHRONICLE OF TIMEKEEPING

Our conception of time depends on the way we measure it

By William J. H. Andrewes

HUMANKIND'S EFFORTS TO TELL TIME HAVE HELPED DRIVE THE EVOLUTION OF OUR TECHNOLOGY and science throughout history. The need to gauge the divisions of the day and night led the ancient Egyptians, Greeks and Romans to create sundials, water clocks and other early chronometric tools. Western Europeans adopted these technologies, but by the 13th century, demand for a dependable timekeeping instrument led medieval artisans to invent the mechanical clock. Although this new device satisfied the requirements of monastic and urban communities, it was too inaccurate and unreliable for scientific application until the pendulum was employed to govern its operation. The precision timekeepers that were subsequently developed resolved the critical problem of finding a ship's position at sea and went on to play key roles in the industrial revolution and the advance of Western civilization.

Today highly accurate timekeeping instruments set the beat for most of our electronic devices. Nearly all computers, for example, contain a quartz-crystal clock to regulate their operation. Moreover, not only do time signals beamed down from Global Positioning System satellites calibrate the functions of precision navigation equipment, they do so as well for cell phones, instant stock-trading systems and nationwide power-distribution grids. So integral have these time-based technologies become to our day-to-day lives that we recognize our dependency on them only when they fail to work.

RECKONING DATES

ACCORDING TO ARCHAEOLOGICAL EVIDENCE, the Babylonians, Egyptians and other early civilizations began to measure time at least 5,000 years ago, introducing calendars to organize and coordinate communal activities and public events, to schedule the shipment of goods and, in particular, to regulate cycles of planting and harvesting. They based their calendars on three natural cycles: the solar day, marked by the successive periods of light and darkness as the earth rotates on its axis; the lunar month, following the phases of the moon as it orbits the earth; and the solar year, defined by the changing seasons that accompany our planet's revolution around the sun.

Before the invention of artificial light, the moon had greater social impact. And, for those living near the equator in particular, its waxing and waning was more conspicuous than the passing of the seasons. Hence, the calendars

IN BRIEF

Devices for measuring time have been around for at least 5,000 years and today are essential for coordinating the operation of everything from cell phones to power-distribution grids.

The earliest mechanical clocks, invented just before 1300, told time by striking a bell.

By the early 1500s inventors had developed spring-driven mechanical clocks that were small enough to be portable.

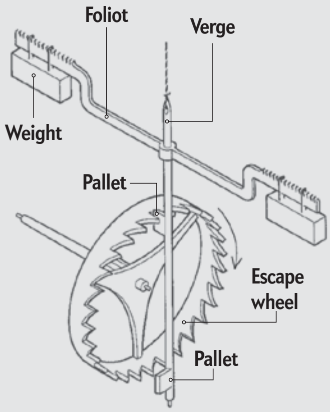
Modern quartz and atomic clocks have made it possible to keep extremely accurate time, which has opened the door to new applications.

ALAMY (*watch face*); SCIENTIFIC AMERICAN (*digital question marks*)

Development of Early Mechanical Clockworks

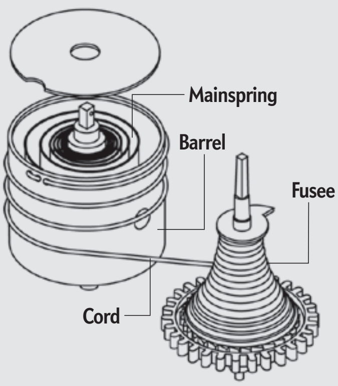
Verge and Foliot Escapement

The innovative component of the first mechanical clocks (circa 1300) was the escapement, a device that both controlled the escape wheel's rotation and transmitted the power needed to sustain the motion of the oscillator, which in turn regulated the speed at which the timekeeper operated. The escape wheel, a sawtoothed crown, is driven by a gear train powered by a weighted cord wound around the axle. The clockwise rotation of the escape wheel is obstructed by two pallets protruding from a vertical shaft, called a verge, which carries a bar known as a foliot. When the top pallet checks the escape wheel's rotation (causing a "tick"), the engaged wheel tooth gradually forces the pallet back until it is free to escape. The wheel's movement, however, is stopped almost immediately when the lower pallet arrests another tooth (causing a "tock") and then pushes the verge in the opposite direction. Driven by the escape wheel, the to-and-fro oscillation of the verge and foliot continues until the cord fully unwinds. The rate at which the mechanism operates can be adjusted by moving the weights on the foliot arms out (for slower) and in (for faster).



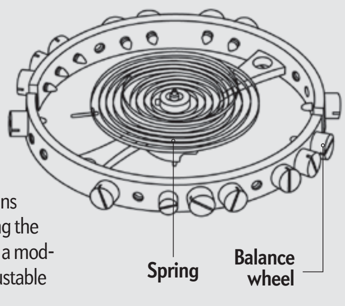
Fusee

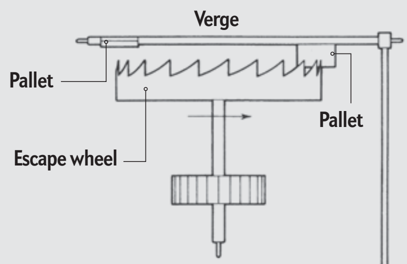
The use of coiled springs as the motive force for timekeepers was made practical by the invention of the fusee in the early to mid-1400s. Although a spring is a compact power source, its force varies, increasing as it is wound more tightly. The fusee, a cone-shaped grooved pulley, was devised to compensate for the variable strength of a timekeeper's mainspring. The barrel, which houses the spring, is connected to the fusee by a cord or chain. When the mainspring is fully wound, the cord pulls on the narrow end of the fusee, where a short torque arm produces relatively little leverage. As the clock runs, the cord is gradually drawn back onto the barrel. To compensate for the mainspring's diminishing strength, the cord's spiral track on the fusee increases in diameter. Thus, the force delivered to the gear wheels of the timekeeper remains constant despite the changing tension of its mainspring.

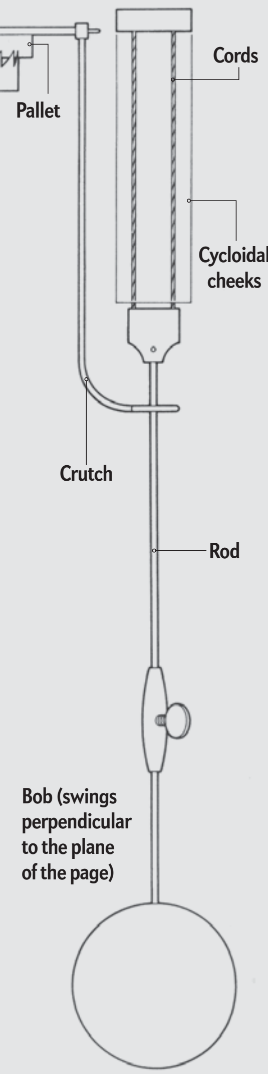


Spiral Balance Spring

In 1675 Huygens invented the spiral balance spring. Just as gravity controls the swinging oscillation of a pendulum in a clock, this spring regulates the rotary oscillation of a balance wheel in portable timepieces. A balance wheel is a rotor that spins one way and then the other, repeating the cycle over and over. Depicted here is a modern version, finely balanced with adjustable timing screws.





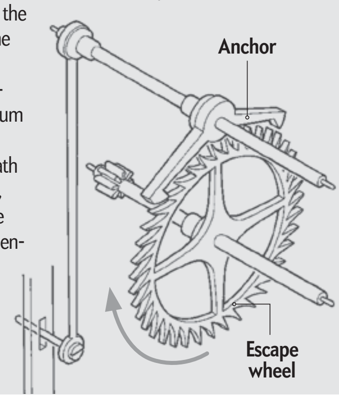


Pendulum Clock

Although Galileo and other 16th-century scientists knew about the potential of the pendulum as a timing instrument, Christiaan Huygens was the first to devise a pendulum clock. Huygens soon realized that a pendulum swinging in a small arc would perform its oscillations faster than one moving in a large arc. He overcame this problem by installing two curved "cycloidal cheeks" (*shown in side view*) at the pendulum's suspension point. Acting on the suspension cords, these curved stops reduced the effective length of the pendulum as its arc increased so that it maintained a cycloidal rather than a circular path. Thus, in theory, the pendulum completed every swing in the same time period, regardless of amplitude (swing distance). In Huygens's clock, the gravity-influenced motion of the pendulum replaced the purely mechanically driven oscillation of the horizontal foliot. Now it was the pendulum's beat that regulated the action of the verge escapement and the rotation of the wheels, which in turn delivered this far more reliable and accurate time measurement to the hands of the clock dial.

Anchor Escapement

Developed around 1670 in England, the anchor escapement is a lever-based device shaped like a ship's anchor. The motion of a pendulum rocks the anchor so that it catches and then releases each tooth of the escape wheel, which, in turn, provides an impulse to maintain the pendulum's oscillation. Unlike the verge escapement used in early pendulum clocks, the anchor escapement permitted the pendulum to travel in such a small arc that maintaining a cycloidal swing path became unnecessary. Moreover, this invention made practical the use of a long, seconds-beating pendulum and thus led to the development of a new, floor-standing case design, which became known as the longcase, or grandfather, clock.



DAVID PENNEY

developed at the lower latitudes were influenced more by the lunar cycle than by the solar year. In more northern climes, however, where seasonal agriculture was important, the solar year became more crucial. As the Roman Empire expanded northward, it organized its calendar for the most part around the solar year. Today's Gregorian calendar derives from the Babylonian, Egyptian, Jewish and Roman calendars.

The Egyptians formulated a civil calendar having 12 months of 30 days, with five days added to approximate the solar year. Each period of 10 days was marked by the appearance of special star groups (constellations) called decans. At the rise of the star Sirius just before sunrise, which occurred around the all-important annual flooding of the Nile, 12 decans could be seen spanning the heavens. The cosmic significance the Egyptians placed in the 12 decans led them to develop a system in which each interval of darkness (and later, each interval of daylight) was divided into a dozen equal parts. These periods became known as temporal hours because their duration varied according to the changing length of days and nights with the passing of the seasons. Summer hours were long, winter ones short; only at the spring and autumn equinoxes were the hours of daylight and darkness equal. Temporal hours, which were adopted by the Greeks and then the Romans (who spread them throughout Europe), remained in use for more than 2,500 years.

Ingenious inventors devised sundials, which indicate time by the length or direction of the sun's shadow, to track temporal hours during the day. The sundial's nocturnal counterpart, the water clock, was designed to measure temporal hours at night. One of the first water clocks was a basin with a small hole near the bottom through which the water dripped out. The falling water level denoted the passing hour as it dipped below hour lines inscribed on the inner surface. Although these devices performed satisfactorily around the Mediterranean, they could not always be depended on in the cloudy and often freezing weather of northern Europe.

THE PULSE OF TIME

THE EARLIEST RECORDED weight-driven mechanical clock was installed in 1283 at Dunstable Priory in Bedfordshire, England. That the Roman Catholic Church should have played a major role in the invention and development of clock technology is not surprising: the strict observance of prayer times by monastic orders occasioned the need for a more reliable instrument of time measurement. Further, the Church not only controlled education but also possessed the wherewithal to employ the most skillful craftsmen. Additionally, the growth of urban mercantile populations in Europe during the second half of the 13th century created demand for improved timekeeping devices. By 1300 artisans were building clocks for churches and cathedrals in France and Italy. Because the initial examples indicated the time by striking a bell (thereby alerting the surrounding community to its daily duties), the name for this new machine was adopted from the Latin word for "bell," *clocca*.

The revolutionary aspect of this new timekeeper was neither the descending weight that provided its motive force nor the gear wheels (which had been around for at least 1,300 years) that transferred the power; it was the part called the escapement. This device controlled the wheels' rotation and transmitted the power required to maintain the motion of the oscillator, the part that regulated the speed at which the timekeeper operated [*for an explanation of early clockworks, see box on opposite page*]. The inventor of the clock escapement is unknown.

UNIFORM HOURS

ALTHOUGH THE MECHANICAL CLOCK could be adjusted to maintain temporal hours, it was naturally suited to keeping equal ones. With uniform hours, however, arose the question of when to begin counting them, and so, in the early 14th century, a number of systems evolved. The schemes that divided the day into 24 equal parts varied according to the start of the count: Italian hours began at sunset, Babylonian hours at sunrise, astronomical hours at midday and "great clock" hours (used for some large public clocks in Germany) at midnight. Eventually these and competing systems were superseded by "small clock," or French, hours, which split the day, as we currently do, into two 12-hour periods commencing at midnight.

During the 1580s clockmakers received commissions for timekeepers showing minutes and seconds, but their mechanisms were insufficiently accurate for these fractions to be included on dials until the 1660s, when the pendulum clock was developed. Minutes and seconds derive from the sexagesimal partitions of the degree introduced by Babylonian astronomers. The word "minute" has its origins in the Latin *prima minuta,* the first small division; "second" comes from *secunda minuta,* the second small division. The sectioning of the day into 24 hours and of hours and minutes into 60 parts became so well established in Western culture that all efforts to change this arrangement failed. The most notable attempt took place in revolutionary France in the 1790s, when the government adopted the decimal system. Although the French successfully introduced the meter, liter and other base-10 measures, the bid to break the day into 10 hours, each consisting of 100 minutes split into 100 seconds, lasted only 16 months.

PORTABLE CLOCKS

FOR CENTURIES AFTER the invention of the mechanical clock, the periodic tolling of the bell in the town church or clock tower was enough to demarcate the day for most people. But by the 15th century a growing number of clocks were being made for domestic use. Those who could afford the luxury of owning a clock found it convenient to have one that could be moved from place to place. Innovators accomplished portability by replacing the weight with a coiled spring. The tension of a spring, however, is greater after it is wound. The contrivance that overcame this problem, known as a fusee (from *fusus,* the Latin term for "spindle"), was invented by an unknown mechanical genius probably between 1400 and 1450 [*see middle left illustration in box on opposite page*]. This cone-shaped device was connected by a cord to the barrel housing the spring: when the clock was wound, drawing the cord from the barrel onto the fusee, the diminishing diameter of the spiral of the fusee compensated for the increasing pull of the spring. Thus, the fusee equalized the force of the spring on the wheels of the timekeeper.

The importance of the fusee should not be underestimated: it made possible the development of the portable clock as well as the subsequent evolution of the pocket watch. Many high-grade, spring-driven timepieces, such as marine chronometers, continued to incorporate this device until after World War II.

INNOVATIVE CLOCKWORKS

IN THE 16TH CENTURY Danish astronomer Tycho Brahe and his contemporaries tried to use clocks for scientific purposes, yet even the best ones were still too unreliable. Astronomers in particular needed a better tool for timing the transit of stars and thereby creating more accurate maps of the heavens. The pendulum proved to be the key to boosting the accuracy and dependability of timekeepers. Galileo, the Italian physicist and astronomer, and others before him experimented with pendulums, but a 27-year-old Dutch astronomer and mathematician named Christiaan Huygens devised the first pendulum clock on Christmas Day in 1656. Huygens recognized the commercial as well as the scientific significance of his invention immediately, and within six months a local maker in the Hague had been granted a license to manufacture pendulum clocks.

Huygens saw that a pendulum traversing a circular arc completed small oscillations faster than large ones. Therefore, any variation in the extent of the pendulum's swing would cause the clock to gain or lose time. Realizing that maintaining a constant amplitude (amount of travel) from swing to swing was impossible, Huygens devised a pendulum suspension that caused the bob to move in a cycloid-shaped arc rather than a circular one. In theory, this enabled it to oscillate in the same time regardless of its amplitude [*see top right illustration in box on page 52*]. Pendulum clocks were about 100 times as accurate as their predecessors, reducing a typical gain or loss of 15 minutes a day to about a minute a week. News of the invention spread rapidly, and by 1660 English and French artisans were developing their own versions of this new timekeeper.

The advent of the pendulum not only heightened demand for clocks but also resulted in their development as furniture. National styles soon began to emerge: English makers designed the case to fit around the clock movement; in contrast, the French placed greater emphasis on the shape and decoration of the case. Huygens, however, had little interest in these fashions, devoting much of his time to improving the device both for astronomical use and for solving the problem of finding longitude at sea.

In 1675 Huygens devised another fundamental improvement, the spiral balance spring. Just as gravity controls the swinging oscillation of a pendulum in clocks, this spring regulates the rotary oscillation of a balance wheel in portable timepieces. A balance wheel is a finely balanced disk that rotates fully one way and then the other, repeating the cycle over and over [*see bottom left illustration in box on page 52*]. The spiral balance spring revolutionized the accuracy of watches, enabling them to keep time to within a minute a day. This advance sparked an almost immediate rise in the market for watches, which were now no longer typically worn on a chain around the neck but were carried in a pocket. It also increased the demand for portable sundials by which watches could be set to time.

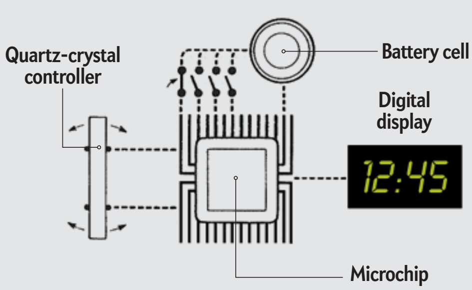
At about the same time, Huygens heard of an important English invention. The anchor escapement, unlike the verge escapement he had been using in his pendulum clocks, allowed the pendulum to swing in such a small arc that maintaining a cycloidal pathway became unnecessary. Moreover, this escapement made practical the use of a long, seconds-beating pendulum and thus led to the development of a new case design. The longcase clock, commonly

PRECISION TIMEKEEPERS

Two Modern Clocks

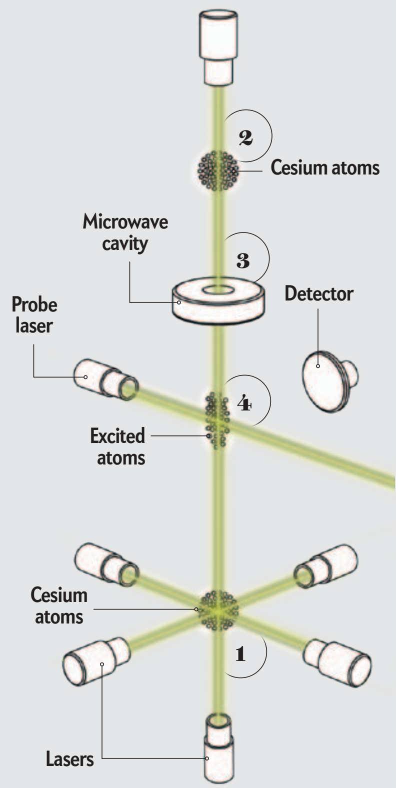
Quartz Movement

By the end of the 1960s watchmakers had taken a step away from the traditional oscillating balance wheel with the development of an electronic transistor-based oscillator comprising a tiny tuning fork whose vibrations were converted into the movement of the hands. With the simultaneous rise of cheap, low-power integrated circuits and light-emitting diodes (LEDs), the search for a more accurate timing element was on. Watchmakers soon adopted the quartz-crystal resonator from radio transmitters. Quartz crystals are piezoelectric: they vibrate when subjected to a changing electric voltage, and vice versa. When driven by a voltage at its harmonic frequency, the crystal oscillates resonantly, ringing like a bell. The output of the oscillator is then converted to pulses suitable for the watch's digital circuits, which operate an LED display or electrically actuated hands.



Cesium Fountain (Atomic) Clock

Cesium fountain clocks derive their timing reference from the frequency of an electron spin-flip transition that occurs in a cesium 133 atom when probed by tuned microwaves. In a vacuum chamber, six lasers slow the movements of gaseous cesium atoms, forming a small cloud ①. A change in the operating frequency of the upper and lower lasers launches the atomic cloud, fountainlike ②, up through a magnetically shielded microwave cavity ③. As gravity pulls the cloud back down through the cavity, the electrons in the atoms interact with the microwaves for a second time. The microwaves flip the spins of the electrons, changing their quantum-mechanical energy states. After the cloud falls farther, a probe laser causes the cesium to fluoresce, revealing whether its electrons have flipped their spins, a reaction that is monitored by a detector ④. The detector's output signal is then used to make the slight correction needed to tune the microwave emitter to a precise resonant frequency that can serve as the time beat for a clock.



DAVID PENNEY (*left*); ALAN DANIELS (*right*) known since 1876 as the grandfather clock (after a song by American Henry Clay Work), began to emerge as one of the most popular English styles. Longcase clocks with anchor escapements and long pendulums can keep time to within a few seconds a week. The celebrated English clockmaker Thomas Tompion—and, subsequently, his successor, George Graham—later modified the anchor escapement to operate without recoil. This enhanced design, called the deadbeat escapement, became the most widespread type used in precision timekeeping for the next 150 years.

SOLVING THE LONGITUDE PROBLEM

WHEN THE ROYAL OBSERVATORY, Greenwich, was founded in England in 1675, part of its charter was to find "the so-much-desired longitude of places." The first Astronomer Royal, John Flamsteed, used clocks fitted with anchor and deadbeat escapements to time the exact moments that stars crossed the celestial meridian, an imaginary line that connects the poles of the celestial sphere and defines the due-south point in the night sky. This allowed him to gather more accurate information on star positions than had hitherto been possible by making angular measurements with sextants or quadrants alone.

Although navigators could find their latitude (their position north or south of the equator) at sea by measuring the altitude of the sun or the polestar above the horizon, the heavens did not provide such a straightforward solution for finding longitude. Storms and currents often confounded attempts to keep track of distance and direction traveled across oceans. The resulting navigational errors cost seafaring nations dearly, not only in prolonged voyages but also in loss of lives, ships and cargo.

The severity of this predicament was brought home to the British government in 1707, when an admiral of the fleet and more than 1,600 sailors perished in the wrecks of four Royal Navy ships off the coast of the Scilly Isles. Thus, in 1714, through an act of Parliament, Britain offered substantial prizes for practical solutions to finding longitude at sea. The largest prize, £20,000 (roughly 200 times the annual wage of a skilled engineer of the time), would be given to the inventor of an instrument that could determine a ship's longitude to within half a degree, or 30 nautical miles, when reckoned at the end of a voyage to a port in the West Indies, whose longitude could be accurately ascertained using proved land-based methods.

The great reward attracted a deluge of harebrained schemes. Hence, the Board of Longitude, the committee appointed to review promising ideas, held no meetings for more than 20 years. Two approaches, however, had long been known to be theoretically sound. The first, called the lunar-distance method, involved precise observations of the moon's position in relation to the stars to determine the time at a reference point from which longitude could be measured; the other required a very accurate clock to make the same determination. Because the earth rotates every 24 hours, or 15 degrees in an hour, a two-hour time difference represents a 30-degree difference in longitude. The seemingly overwhelming obstacles to keeping accurate time at sea—among them the often violent motions of ships, extreme changes in temperature and variations in gravity at different latitudes—led British physicist Isaac Newton and his followers to believe that the lunar-distance method, though problematic, was the only viable solution.

Newton was wrong, however. In 1737 the board finally met for the first time to discuss the work of a most unlikely candidate, a Yorkshire carpenter named John Harrison. Harrison's large and rather cumbersome longitude timekeeper had been used on a voyage to Lisbon and on the return trip had proved its worth by correcting the navigator's dead reckoning of the ship's longitude by 68 miles. Its maker, however, was dissatisfied. Instead of asking the board for a West Indies trial, he requested and received financial support to construct an improved machine.

After two years of work, still displeased with his second effort, Harrison embarked on a third, laboring on it for 19 years. But by the time it was ready for testing, he realized that his fourth marine timekeeper, a five-inch-diameter watch he had been developing simultaneously, was better. On a voyage to Jamaica in 1761, Harrison's oversize watch performed well enough to win the prize, but the board refused to give him his due without further proof. A second sea trial in 1764 confirmed his success. Harrison was reluctantly granted £10,000. Only when King George III intervened in 1773 did he receive the remaining prize money. Harrison's breakthrough inspired further developments. By 1790 the marine chronometer was so refined that its fundamental design never needed to be changed.

MASS-PRODUCED TIMEPIECES

AT THE TURN OF THE 19TH CENTURY, clocks and watches were relatively accurate, but they remained expensive. Recognizing the potential market for a low-cost timekeeper, two investors in Waterbury, Conn., took action. In 1807 they gave Eli Terry, a clockmaker in nearby Plymouth, a three-year contract to manufacture 4,000 longcase clock movements from wood. A substantial down payment made it possible for Terry to devote the first year to fabricating machinery for mass production. By manufacturing interchangeable parts, he completed the work within the terms of the contract.

A few years later Terry designed a wooden-movement shelf clock using the same volume-production techniques. Unlike the longcase design, which required the buyer to purchase a case separately, Terry's shelf clock was completely self-contained. The customer needed only to place it on a level shelf and wind it up. For the relatively modest sum of $15, many average people could now afford a clock. This achievement led to the establishment of what was to become the renowned Connecticut clockmaking industry.

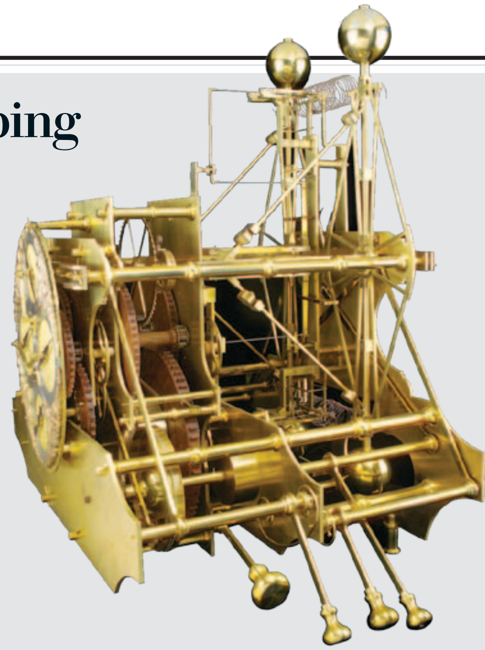
Before the expansion of railroads in the 19th century, towns in the U.S. and Europe used the sun to determine local time. For example, because noon occurs in Boston about three minutes before it does in Worcester, Mass., Boston's clocks were set about three minutes ahead of those in Worcester. The expanding railroad network, however, needed a uniform time standard for all the stations along the line. Astronomical observatories began to distribute the precise time to the railroad companies by telegraph. The first public time service, introduced in 1851, was based on clock beats wired from the Harvard College Observatory in Cambridge, Mass. The Royal Observatory introduced its time service the next year, creating a single standard time for Britain.

The U.S. established four time zones in 1883. By the next year the governments of all nations had recognized the benefits of a worldwide standard of time for navigation and trade. At the 1884 International Meridian Conference in Washington, D.C., the globe was divided into 24 time zones. Delegates chose the Royal Observatory as the prime meridian (zero degrees lon-

Clocks That Revolutionized Timekeeping

Hemispherical Sundial (Italy, circa A.D. 100)
The shadow's direction on this ingenious Roman sundial shows the time of day (just after the eighth hour of daylight), while its length indicates the time of year (summer solstice).

Pendulum Clock (the Netherlands, 1657)
Dutch scientist Christiaan Huygens granted Salomon Coster the right to make the first pendulum clocks of his design, revolutionizing the European clockmaking industry.



H1 Sea Clock (England, 1735)
John Harrison finally solved the centuries-old problem of finding longitude at sea in 1759 with his fourth marine timekeeper. This is an exact replica of his first sea clock, called H1.

gitude, the line from which all other longitudes are measured) in part because two thirds of the world's shipping already used Greenwich time for navigation.

WATCHES FOR THE MASSES

MANY CLOCKMAKERS of this era realized that the market for watches would far exceed that for clocks if production costs could be reduced. The problem of mass-fabricating interchangeable parts for watches, however, was considerably more complicated because the precision demanded in making the necessary miniaturized components was so much greater. Although improvements in quantity manufacture had been instituted in Europe since the late 18th century, European watchmakers' fears of saturating the market and threatening their workers' jobs by abandoning traditional practices stifled most thoughts of introducing machinery for the production of interchangeable watch parts.

Disturbed that American watchmakers seemed unable to compete with their counterparts in Europe, which controlled the market in the late 1840s, a watchmaker in Maine named Aaron L. Dennison met with Edward Howard, who had established a successful clock- and scale-making business in Roxbury, Mass., to discuss mass-production methods for watches. Howard and his partner gave Dennison space to experiment and develop machinery for the project. By the fall of 1852, 20 watches had been completed under Dennison's supervision. His workmen finished 100 watches by the following spring, and 1,000 more were produced a year later. By that time the manufacturing facilities in Roxbury were proving too small, so the newly named Boston Watch Company moved to Waltham, Mass., where by the end of 1854 it was assembling 36 watches a week.

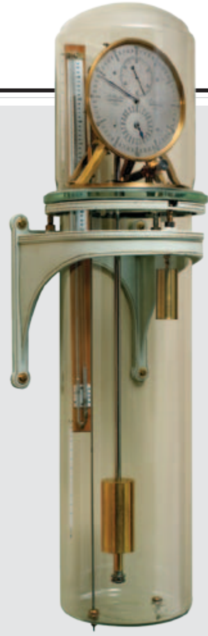
The American Waltham Watch Company, as it eventually became known, benefited greatly from a huge demand for watches during the Civil War, when Union Army forces used them to synchronize operations. Improvements in fabrication techniques further boosted output and reduced prices significantly. Meanwhile other U.S. companies formed in the hope of capturing part of the burgeoning trade. The Swiss, who had previously dominated the industry, grew concerned when their exports plummeted in the 1870s. The investigator they sent to Massachusetts discovered that not only was productivity higher at the Waltham factory but production costs were less. Even some of the lower-grade American watches could be expected to keep reasonably good time. The watch was at last a commodity accessible to the masses.

Because women had worn bracelet watches in the 19th century, wristwatches were long considered feminine accoutrements. During World War I, however, the pocket watch was modified so that it could be strapped to the wrist, where it could be viewed more readily on the battlefield. With the help of a substantial marketing campaign, the masculine fashion for wristwatches caught on after the war. Self-winding mechanical wristwatches made their appearance during the 1920s.

HIGH-PRECISION CLOCKS

AT THE END OF THE 19TH CENTURY, Sigmund Riefler, based in Munich, developed a radical new design of regulator—a highly accurate timekeeper that served as a standard for controlling others. Housed in a partial vacuum to minimize the effects of barometric pressure and equipped with a pendulum largely unaffected by temperature variations, Riefler's regulators attained an accuracy of a tenth of a second a

Shelf Clock (U.S., circa 1816)
Eli Terry designed a shelf clock with interchangeable parts, giving birth to the Connecticut clockmaking industry, and granted patent rights to Seth Thomas, who made this example, one of the earliest mass-produced clocks.



Glass-Tank Regulator (Germany, 1895)
Sigmund Riefler made a significant improvement in timekeeping when he designed a clock that operated in a partial vacuum. Combined with a pendulum made from a metal alloy with very low thermal expansion, this Riefler regulator could keep time to a 10th of a second per day.

STEPHEN PITKIN

day and were thus adopted by nearly every astronomical observatory.

Further progress came several decades later, when English railroad engineer William H. Shortt designed a so-called free pendulum clock that reputedly kept time to within about a second a year. Shortt's system incorporated two pendulum clocks, one a "master" (housed in an evacuated tank) and the other a "slave" (which contained the time dials). Every 30 seconds the slave clock gave an electromagnetic impulse to, and was in turn regulated by, the master clock pendulum, which was thus nearly free from mechanical disturbances.

Although Shortt clocks began to displace Rieflers as observatory regulators during the 1920s, their superiority was short-lived. In 1928 Warren A. Marrison, an engineer at Bell Laboratories, then in New York City, discovered an extremely uniform and reliable frequency source that was as revolutionary for timekeeping as the pendulum had been 272 years earlier. Developed originally for use in radio broadcasting, the quartz crystal vibrates at a highly regular rate when excited by an electric current [*see left illustration in box on page 54*]. The first quartz clocks installed at the Royal Observatory in 1939 varied by only two thousandths of a second a day. By the end of World War II, this accuracy had improved to the equivalent of a second every 30 years.

Quartz-crystal technology did not remain the premier frequency standard for long either, however. By 1948 Harold Lyons and his associates at the National Bureau of Standards in Washington, D.C., had based the first atomic clock on a far more precise and stable source of timekeeping: an atom's natural resonant frequency, the periodic oscillation between two of its energy states [*see right illustration in box on page 54*]. Subsequent experiments in both the U.S. and England in the 1950s led to the development of the cesium-beam atomic clock. Today the averaged times of cesium clocks in various parts of the world provide the standard frequency for Coordinated Universal Time, which has an accuracy of better than one nanosecond a day.

Up to the mid-20th century, the sidereal day, the period of the earth's rotation on its axis in relation to the stars, was used to determine standard time. This practice had been retained even though it had been suspected since the late 18th century that our planet's axial rotation was not entirely constant. The rise of cesium clocks capable of measuring discrepancies in the earth's spin, however, meant that a change was necessary. A new definition of the second, based on the resonant frequency of the cesium atom, was adopted as the new standard unit of time in 1967.

The precise measurement of time is of such fundamental importance to science and technology that the search for ever greater accuracy continues. The performance of atomic clocks had been improving by a factor of at least 10 per decade for about 50 years. But over the past decade improvements in atomic clock accuracy have dramatically accelerated. Recent advances in laser science—particularly the Nobel Prize–winning development of femtosecond laser frequency combs—and atomic physics have enabled the development of many new types of optical atomic clocks, some based on transitions in single ions in electromagnetic traps and some based on collections of cold neutral atoms held in lattices formed by laser light. Several of these atomic clocks are already stable to within a few hundred femtoseconds per day and continue to rapidly improve.

At this level of performance, formerly negligible effects become important and measurable. For example, the best atomic clocks can now measure changes in gravity over the distance of a stair step, tiny magnetic fields generated by heart and brain activity, and other quantities such as temperature and acceleration. Companies are now manufacturing "chip-scale" atomic clocks the size of a quarter. In addition to keeping time with increasing accuracy, new generations of atomic clocks will be used as exquisite sensors for myriad applications and will become ever smaller and more portable.

Although our ability to measure time will surely improve in the future, nothing will change the fact that it is the one thing of which we will never have enough. SA

MORE TO EXPLORE

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