BUILDING BLOCKS

The Jantar Mantar, Samrat Yantra (Giant sundial) in Jaipur. GETTY IMAGES

How time has been kept throughout history: from sundials to atomic clocks

The world has come from keeping time with the Sun and the moon to atoms and their nuclei. Some physicists have even started work on the next-to-next generation of devices, called nuclear clocks

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Time is an inalienable part of our reality. Scientists don't understand it fully at the universe's largest and smallest scales, but fortunately for humans, a panoply of natural philosophers and inventors have allowed us to keep step with its inexorable march – with clocks.

What is a clock?

Clocks are devices that measure the passage of time and display it. Their modern versions have the following parts – a power source, resonator, and counter.

A clock measures the amount of time that has passed by tracking something that happens in repeating fashion, at a fixed frequency. In many modern clocks, for example, this is a quartz crystal. More rudimentary devices often depended on natural events instead. The sundials in use in ancient times allowed people to 'tell' time by casting shadows of changing lengths against sunlight. In water clocks, water would slowly fill a vessel, with its levels at different times indicating how much time had passed. The hourglass served a similar purpose, using sand instead of water.

How did mechanical clocks work?

Until the Middle Ages, engineers around the world improved the water clock with additional water tanks, gear wheels, pulleys, and even attached musical instruments to the point where they were practically developing rudimentary analog computers.

One of the first major revolutions in timekeeping that paved the way for modern clocks was the invention of the verge escapement mechanism in the 13th century, which first opened the door to mechanical clocks. The fundamental element here was a gear that, through a combination of mechanical arrangements, could only move in fixed intervals. The gear was called an escape wheel if it was circular. A second gear, called the balance wheel, was enmeshed with the first such that when the escape wheel moved forward one gear tooth at a time, the balance wheel would oscillate back and forth. This oscillation would drive the 'hands' of a clock on a clockface as long as some force was applied on the balance wheel to keep it moving.

Between the 15th and 18th centuries, clockmakers developed and improved on spring-driven clocks. These devices replaced the suspended weight that applied the force on the balance wheel in the previous designs with a coiled spring. To keep these clocks from becoming inaccurate as the spring unwound, clockmakers also developed mechanisms like the fusee, which ensured the spring always delivered a uniform force. The idea to couple a balance spring with the balance wheel also led to the advent of pocket watches.

After every 'tick' motion before the 'tock' motion towards the other side, the balance spring would return the balance wheel to its neutral position. As a result, the clocks lost a few minutes a day versus a few hours a day before.

Finally, in the mid-17th century, the Dutch inventor Christiaan Huygens invented the pendulum clock. While the clock itself used the by-then familiar escapement mechanism, Huygens made an important contribution by working out a formula to convert the pendulum's swings to the amount of time passed.

How did clocks change shipping?

The marine chronometer came the next century. For a ship to accurately know where it was on the face of the earth, it needed to know its latitude, longitude, and altitude. The latitude could be computed based on the Sun's position in the sky and the altitude could be assumed to be sea level, leaving the longitude – which requires an accurate clock onboard each vessel. Pendulum clocks couldn't serve this purpose because the ship's rocking motion rendered them inaccurate.

A carpenter named John Harrison built a working marine chronometer in 1761 and delivered it to the British government for its longitude prize, worth GBP 20,000 at the time. This device featured mechanisms to ensure the clock's operation wasn't affected by the ship's rocking, the force of gravity, and some temperature changes.

Thus, time flew until modernity dawned. The better clocks of the 19th century were electric clocks, that is, whose energy source was a battery or an electric motor rather than suspended weights or springs, although the former and latter were attached to improve the efficiency of existing designs. And at long last came the 20th century.

How do quartz clocks work?

Two important types of clocks in operation today are the quartz clock and the atomic clock. The fundamental setup of both these instruments is similar: they have a power source, a resonator, and a counter. In quartz clocks, the resonator is a quartz crystal. The power source sends electrical signals to a quartz crystal, whose crystal structure oscillates due to the piezoelectric effect. The signal's energy can be tuned to make the crystal oscillate at its resonant frequency, making it the resonator. The counter counts the number of periodic oscillations and converts them into seconds (depending on the crystal's period). A digital display shows the counter's results.

Such quartz clocks are inexpensive to make and easy to operate, and their invention led to watches and wall-clocks becoming very common from the mid-20th century.

What are atomic clocks?

An atomic clock may seem futuristic in comparison.

The power source is a laser and the resonator is a group of atoms of the same isotope. The laser imparts just enough energy for the atom to jump from its low energy state to a specific higher energy state. And when the atom jumps back down, it releases radiation with a well-established frequency. For example, the caesium atomic clock uses caesium-133 atoms as the resonator. When these atoms excite and then de-excite, they release radiation of frequency 9,192,631,770 Hz. So when the counter detects 9,192,631,770 full waves of the radiation, it will record that one second has passed.

Atomic clocks are distinguished by their resonator; each such clock is called a time standard. For example, India's time standard is a caesium atomic clock at the National Physical Laboratory, New Delhi, which maintains the Indian Standard Time. Many countries are currently developing next-generation optical clocks. This is because the higher the frequency of the radiation emitted in the clock, the more stable the clock will be. That emitted in a caesium atomic clock is in the microwave range (gigahertz), and the resulting clock loses or gains a second only once in 20 million years or so. The radiation in the next-generation clocks is in the optical range (hundreds of terahertz) – thus the clocks' name. These devices use strontium or ytterbium atoms as resonators and don't miss a second in more than 10 billion years.

Some physicists have even started work on the next-to-next generation of devices, called nuclear clocks: their resonators are the nuclei of specific atoms rather than the whole atom. Atomic clocks need to make sure the resonator atoms aren't affected by energy from other sources, like a stray electromagnetic field; an atom's nucleus, however, is located well within each atom, surrounded by electrons, and thus could be a more stable resonator.

Since April this year, researchers around the world have reported three major developments in building functional nuclear clocks: a laser to excite thorium-229 nuclei to a specific higher energy state, a way to link a thorium-229 nuclear clock with an optical clock, and a precise estimate of the excitation energy. The nucleus's de-excitation emission has a frequency of 2,020 terahertz, alluding to an ultra-high precision.