

It's About Time

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1. Introduction

If I were to ask you: "What is the most important type of measurement technology? How would you answer this (without looking at the title of this paper.) Ah ha, you peeked. Yes, it is time. I'm sure some would argue that it's distance, or temperature, any other of many measurable quantities, based on their experience. Or perhaps you agree time is right up there in the importance scale. Hopefully, after reading this paper you will move the measurement of time up closer to the top.

I came across a really interesting and timely article in my latest Scientific American (reference 1, below) about this subject. OK, no more "time" jokes.

2. Old Times

*The world's first clocks were invented thousands of years ago, when the first human civilizations devised devices that tracked the sun's movement to divide the day into intervals. The earliest versions of sundials were made by the ancient Egyptians around 1500 B.C.E. Later, water clocks, first used by Egyptians and called clepsydras, meaning "water thieves," by the ancient Greeks, marked time by letting water drain out of vessels with a hole punched in the bottom. These instruments were perhaps the first to measure a duration of time independent of the movements of celestial bodies. Mechanical clocks driven by weights debuted in medieval European churches, and they ticked along at consistent rates, leading to the modern 24-hour day. The tolling of bells to mark the hour even gave us the word "clock," which has its roots in the Latin clocca, meaning "bell."*¹

As mechanical clocks became more precise, particularly with the development of the pendulum clock in the mid-17th century, timekeepers further divided the hour into minutes and seconds. (First applied to angular degrees, the word "minute" comes from the Latin prima minuta, meaning the "first small part," and "second" comes from secunda minuta, the "second small part.") For centuries towns maintained their own local clocks, adjusting them periodically so the strike of noon occurred just as the sundial indicated midday. It wasn't until the 19th century, when distant rail stations needed to maintain coordinated train schedules, that time zones were established and timekeeping was standardized around the world.

Clocks improved drastically in the 20th century after French physicists and brothers Jacques and Pierre Curie² discovered that applying an electric current to a crystal of quartz causes it to vibrate with a stable frequency. The first clock that used a quartz oscillator was developed by Warren Marrison and Joseph Horton of Bell Laboratories in 1927. The clock ran a current through quartz and used a circuit to divide the resulting frequency until it was low enough to drive a synchronous motor that controlled the clock's face. Today billions of quartz clocks are produced every year for wristwatches, mobile devices, computers, and other electronics.

¹ Jay Bennett, Scientific American, "Redefining Time," March 2025 Issue, <https://www.scientificamerican.com/article/worlds-most-accurate-clocks-could-redefine-time/>, access may be limited.

² Pierre's wife was Marie Curie. I just finished an excellent biography of Ms. Curie, linked below. <https://www.amazon.com/Elements-Marie-Curie-Radium-Science/dp/0802163823>

The key innovation that led to atomic clocks came from American physicist Isidor Isaac Rabi of Columbia University, who won the Nobel Prize in Physics in 1944 for developing a way to precisely measure atoms' resonance frequencies. His technique, called the molecular-beam magnetic resonance method, finely tuned a radio frequency to cause atoms' quantum states to transition. In 1939 Rabi suggested using this method to build a clock, and the next year his colleagues at Columbia applied his technique to determine the resonance frequency of cesium.

This element was viewed as an ideal reference atom for timekeeping. It's a soft, silvery metal that is liquid near room temperature, similar to mercury. Cesium is a relatively heavy element, meaning it moves more slowly than lighter elements and is therefore easier to observe. Its resonance frequency is also higher than those of other clock candidates of the time, such as rubidium and hydrogen, meaning it had the potential to create a more precise time standard. These properties eventually won cesium the role of defining the second nearly 40 years later.

3. Modern Times

But the first atomic clock was not a cesium clock. In 1949 Harold Lyons, a physicist at NIST's precursor, the National Bureau of Standards (NBS), built an atomic clock based on Rabi's magnetic resonance method using ammonia molecules. It looked like a computer rack with a series of gauges and dials on it, so Lyons affixed a clockface to the top for a public demonstration to indicate that his machine was, in fact, a clock. This first atomic clock, however, couldn't match the precision of the best quartz clocks of the time, and ammonia was abandoned when it became clear that cesium clocks would produce better results.

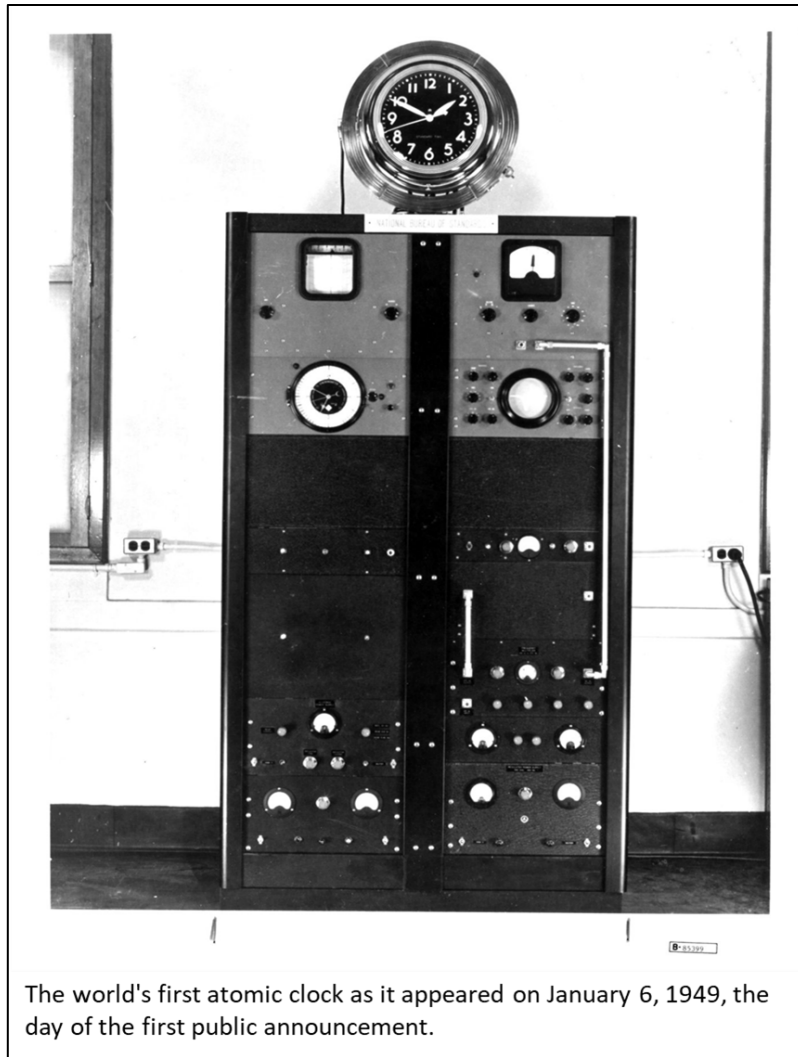
See the image on the next page.

Both the NBS and the National Physical Laboratory (NPL) in the U.K. developed cesium beam clocks in the 1950s. A key breakthrough came from Harvard University physicist Norman Ramsey, who found that it was possible to improve the measurements by using two pulses of microwaves to induce the atomic transitions rather than one. Cesium clocks continued to advance for the remainder of the century and, along with atomic clocks using different elements, became more precise and more compact.

At the time, the second was defined according to astronomical time. Known as the ephemeris second, it was equal to $1/31,556,925.9747$ of the tropical year (the time it takes for the sun to return to the same position in the sky) in 1900. Between 1955 and 1958, NPL scientists compared measurements from their cesium beam clock with the ephemeris second as measured by the U.S. Naval Observatory by tracking the position of the moon with respect to background stars.

4. Present Times

In August 1958 the second was calculated as 9,192,631,770 cycles of the cesium transition frequency-the same number that would be used for the new definition nine years later.



The world's first atomic clock as it appeared on January 6, 1949, the day of the first public announcement.

Since then, atomic clocks have continued to progress, particularly with the development of cesium fountain clocks in the 1980s. But by 2006 newer clocks were beating them.

In addition to the clocks at NIST, some of the most advanced timekeepers in the world can be found at the University of Colorado Boulder, down the street in another lab pushing the frontier of timekeeping. JILA, a joint venture of NIST and the university, houses four "optical lattice clocks" that are among the global record holders for accuracy. (The lab was previously called the Joint Institute for Laboratory Astrophysics and now is simply known by the acronym.)

These state-of-the-art instruments are housed in large rectangular boxes with sliding doors that double as dry-erase boards, each covered in equations and diagrams. Components twinkle in the dim light of the lab as lasers and readouts pulse with light.

Each clock works by firing two lasers at each other to create an interference pattern called an optical lattice, a grid with areas of high and low intensity. Pancake-shaped clouds of thousands of neutral strontium atoms become trapped in the high-intensity parts of the lattice, suspended in place.

Another laser then induces an electron transition in the atoms, pushing the outer electrons up an entire orbital level. This is a larger transition than occurs in the cesium atoms, where the electrons only move up one "hyperfine" level. But as in the cesium clock, detectors look for photons released when the electrons settle back to their original states to confirm that the laser is at the correct frequency to make the electrons hop. Compared with the cesium transition, which occurs at about nine billion hertz, the strontium transition requires a much higher frequency: 429,228,004,229,873.65 Hz.

Each of the four clocks in the lab serves a different purpose, measuring interactions between the atoms or effects from the environment—such as gravity, temperature fluctuations or wayward electromagnetic fields—in an attempt to reduce these sources of uncertainty. Optical clocks are so sensitive that the slightest disturbance, even someone slamming a nearby door, will shift the target transition frequency.

Author's comment: The JILA optical lattice clock is so accurate it would neither gain nor lose one second in about 5 billion years, if it could operate that long.³

5. Future Times

The key limiting factor in an optical lattice clock is blackbody radiation, says Jun Ye, lead researcher of the JILA lab. This radiation is the thermal energy released by any body of mass because of its temperature alone. To compensate for this effect, Ye and his team built a new thermal-control system inside the vacuum chamber of one of the clocks, a "fairly heroic effort" that Ye attributes to his students. The project allowed them to measure the transition frequency of strontium with a systematic uncertainty of 8.1×10^{-19} , the most accurate clock measurement ever made. This strontium optical lattice clock and other, similar models are now among the leading candidates to redefine the second.

The other main contenders are called single-ion clocks. Some of the best examples can be found at NIST and at the German PTB lab. This type suspends one charged ion (in this case, an atom with one or more electrons removed so that it carries a positive charge) within a trap of electromagnetic fields and then induces an atomic transition with a laser. Currently the most accurate of these clocks uses an aluminum ion.

Single-ion clocks avoid the noise that light lattices introduce to a system, Huntemann⁴ says, and "there is generally a smaller sensitivity to external fields," including fields in the experiment as well as the environment. Optical lattice clocks, however, scrutinize thousands of atoms at once, improving accuracy...

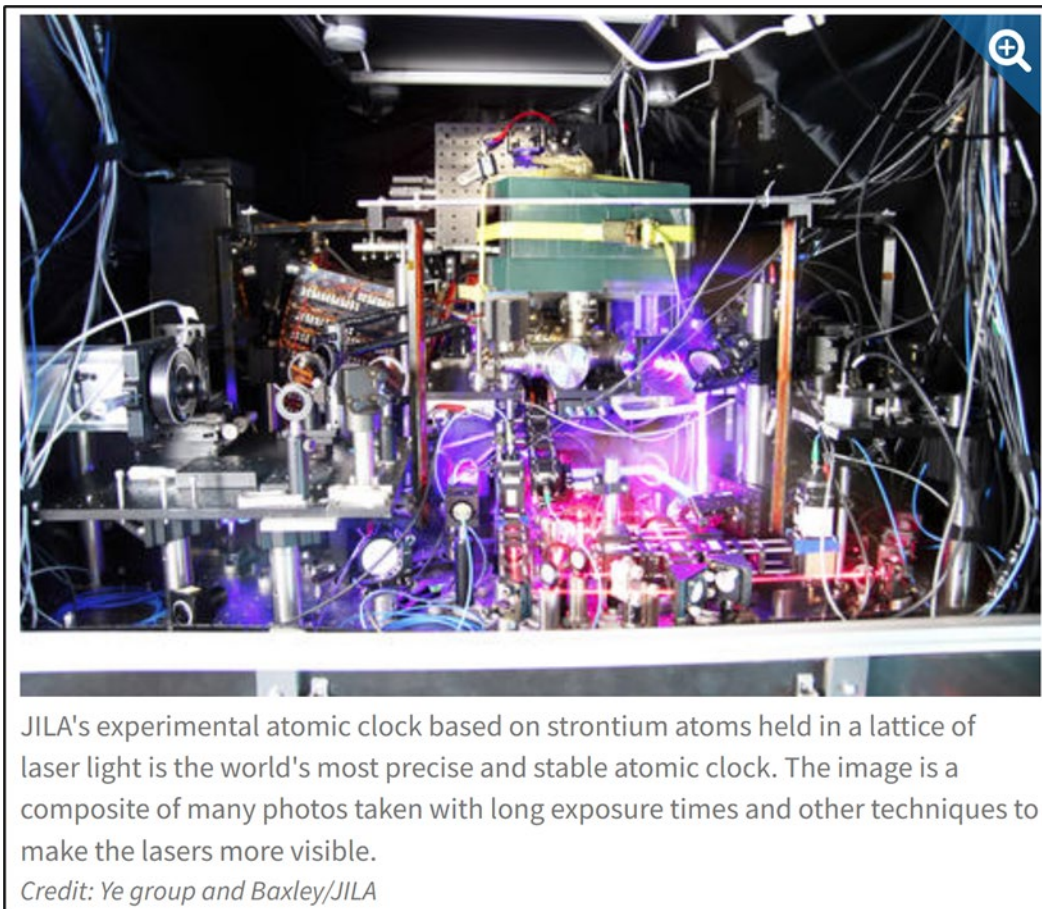
Ion clocks and optical lattice clocks have been trading the accuracy record back and forth for the past two decades. They have even demonstrated how time passes faster at higher elevations—a prediction from Einstein's general theory of relativity, which showed that time dilates, or stretches, closer to large masses (in this case, Earth). In a 2022 experiment, parts of a strontium optical lattice clock at JILA separated by just a millimeter in height measured a time difference on the order of 0.0000000000000000001 (10^{-19}). This tiny aberration would have been too small for a cesium clock to detect.

³ <https://www.nist.gov/news-events/news/2014/01/jila-strontium-atomic-clock-sets-new-records-both-precision-and-stability>

⁴ Nils Huntemann, Scientist at PTB, the national metrology institute of Germany.

If scientists choose to redefine the second, they must decide not only which clock to use but also which atomic transition: that of strontium atoms or ytterbium or aluminum ions- or something else. One possible solution is to base the definition on not just one atomic transition but the average of all the transitions from different kinds of optical clocks. If an ensemble of clocks, each with its own statistical weighting, is used to redefine the second, then future clocks could be added to the definition as needed.

Last year Ye⁵ and his team demonstrated the viability of a nuclear clock based on thorium. This type of clock uses a nuclear transition – a shift in the quantum state of atomic nuclei-rather than an electron transition. Because nuclei are less sensitive to external interference than electrons are, nuclear clocks may become even more accurate than optical clocks once the technology is refined.



Final author's comment: Times up.

⁵ Jun Ye, lead researcher of the JILA lab. See section 5.