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The Evolution of Time Measurement, Part 3: Atomic Clocks

Atomic clocks fundamentally altered the way that time is measured and kept. Before atomic clocks, the second was defined by dividing astronomical events, such as the solar day or the tropical year, into smaller parts. This changed in 1967, when the second was redefined as the duration of 9,192,631,770 energy transitions of the cesium atom [1]. The new definition meant that seconds were now measured by counting oscillations of atoms, and minutes and hours were now multiples of the second rather than divisions of the day. Atomic clocks also made it easier to measure time intervals shorter than one second. It is interesting to note that fractional second units, including the microsecond (10^{-6} s) and nanosecond (10^{-9} s), are based on the decimal system and not on the duodecimal or sexagesimal systems that were used to define minutes and hours.

The societal impact of atomic clocks has been immense. Many technologies that we take for granted rely on atomic clock accuracy, including mobile phones, Global Positioning System (GPS) satellite receivers, and the electric power grid. This makes it easy to forget that the first reliable atomic clocks appeared less than an average lifetime ago. We'll begin Part 3 of this series by looking at the origin of atomic clocks and some fundamental concepts. In the next installment, we'll move on to explore more recent advances in atomic timekeeping.

Origins of Atomic Clocks

The Scottish physicist James Clerk Maxwell was perhaps the first person to recognize that atoms could be used to keep time. In an era where the Earth's rotation was the timekeeping standard, Maxwell remarkably suggested to William Thomson (Lord Kelvin) that the "period of vibration of a piece of quartz crystal" would be a better absolute standard of time than the mean solar second, but would still depend "essentially on one particular piece of matter, and is therefore liable to accidents." Atoms would work even better as a natural standard of time. As Thomson wrote in the second edition of his *Elements of Natural Philosophy*, published in 1879 [2], [3]:

> *The recent discoveries … indicate to us natural standard pieces of matter such as atoms of hydrogen or sodium, ready made in infinite numbers, all absolutely alike in every physical property. The time of vibration of a sodium particle corresponding to any one of its modes of vibration is known to be absolutely independent of its position in the universe, and will probably remain the same so long as the particle itself exists.*

Atomic clock experiments didn't begin until about sixty years after Maxwell's suggestions. The early experiments were finally made possible by the rapid advances in quantum mechanics and microwave electronics that took place before, during, and after World War II. Most of the concepts that led to atomic clocks were developed by Isidor Isaac Rabi and his colleagues at Columbia University in the 1930s and 1940s [4], [5]. As early as 1939, Rabi had informally discussed applying his molecular beam magnetic resonance technique as a time standard with scientists at the National Bureau of Standards (NBS) [6]. His work earned him a Nobel Prize in 1944, but atomic clock research was mostly halted during World War II as scientists turned their attention to other areas. However, during the last year of the war, Rabi publicly discussed his plans for an atomic clock during a lecture at Columbia. The *New York Times* covered the story on January 21, 1945 (Fig. 1), with a lead sentence referring to the "most accurate clock in the universe" [7].

Basic Atomic Clock Principles

The basic principles of atomic clocks are fairly simple and were well understood by the early researchers. In short, because all atoms of a specific element are identical, they should produce the exact same frequency when they absorb energy or release energy. An atom could potentially serve as a "perfect" oscillator, and a clock referenced to an atomic oscillator would be far more accurate than all previous clocks.

The trick, of course, is being able to measure the undisturbed resonance frequency of an atom, which is derived from its quantized energy levels. The laws of quantum mechanics dictate that the energies of a bound system, such as an atom, have certain discrete values. An electromagnetic field at a particular frequency can boost an atom from one energy level to a higher one. Or, an atom at a high energy level can drop to a lower level by emitting energy. The resonance frequency (f_o) of an atomic oscillator is the difference between the two energy levels, E_1 and E_2, divided by Planck's constant, h:

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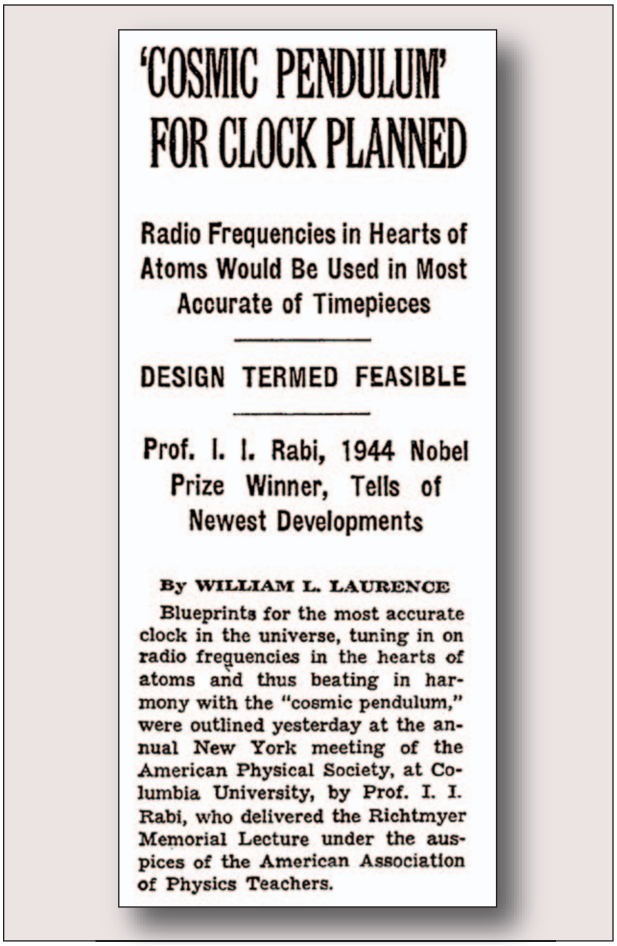

'COSMIC PENDULUM' FOR CLOCK PLANNED

Radio Frequencies in Hearts of Atoms Would Be Used in Most Accurate of Timepieces

DESIGN TERMED FEASIBLE

Prof. I. I. Rabi, 1944 Nobel Prize Winner, Tells of Newest Developments

By WILLIAM L. LAURENCE

Blueprints for the most accurate clock in the universe, tuning in on radio frequencies in the hearts of atoms and thus beating in harmony with the "cosmic pendulum," were outlined yesterday at the annual New York meeting of the American Physical Society, at Columbia University, by Prof. I. I. Rabi, who delivered the Richtmyer Memorial Lecture under the auspices of the American Association of Physics Teachers.

Fig. 1. The first public suggestion of an atomic clock, *New York Times*, January 21, 1945.

Fig. 2. The first atomic clock based on the ammonia molecule (1949). The inventor, Harold Lyons, is on the right; Edward Condon, then the director of NBS, is on the left. Courtesy of NIST.

$$f_o = \frac{E_2 - E_1}{h} . \tag{1}$$

Atoms absorb or emit energy over a small frequency range surrounding f_o, not at f_o alone. This spread of frequencies Δf_a is known as the resonance width, or linewidth. The ratio of the resonance frequency to the resonance width is known as the quality factor, Q, where

$$Q = \frac{f_o}{\Delta f_a} . \tag{2}$$

Because their resonance frequencies were so high, atomic clocks instantly had much higher Qs than previous clocks, which meant that they had the potential to become the world's most accurate timekeepers.

The First Atomic Clocks

It seems likely that Isidor Rabi expected cesium (^{133}Cs) atoms to be used in the first atomic clock [8]. His colleagues at Columbia first measured the cesium resonance frequency in 1940, estimating the frequency of the hyperfine transition as 9191.4 megacycles. This was relatively close to the number that would later define the second [9].

As fate would have it, however, the world's first working atomic clock was based not on cesium atoms but instead used the 23.8 GHz inversion transition of the ammonia molecule as its source of resonance. The ammonia clock (Fig. 2) was developed at NBS by Harold Lyons and his associates. It consisted of a quartz oscillator, electronically stabilized by the ammonia absorption line, and frequency dividers that produced a 50 Hz output signal. Lyons first operated the device on August 12, 1948, although it was not publicly demonstrated until January 1949. The heart of the system, an eight meter long waveguide absorption cell filled with ammonia, was wrapped around an analog clock mounted on top of the equipment cabinets. The analog clock was there for esthetics only, to make the unwieldy instrument look like a conventional clock. Two versions of the ammonia clock were built, with the best reported accuracy about 2 ms per day (2×10^{-8}). Work on a third version was halted when it became apparent that atomic beam techniques were likely to provide a significant increase in accuracy [8], [10], [11], [12]. The ammonia clock failed to outperform the best quartz clocks of its time and never served as a time standard, but it offered a glimpse of what the future would bring.

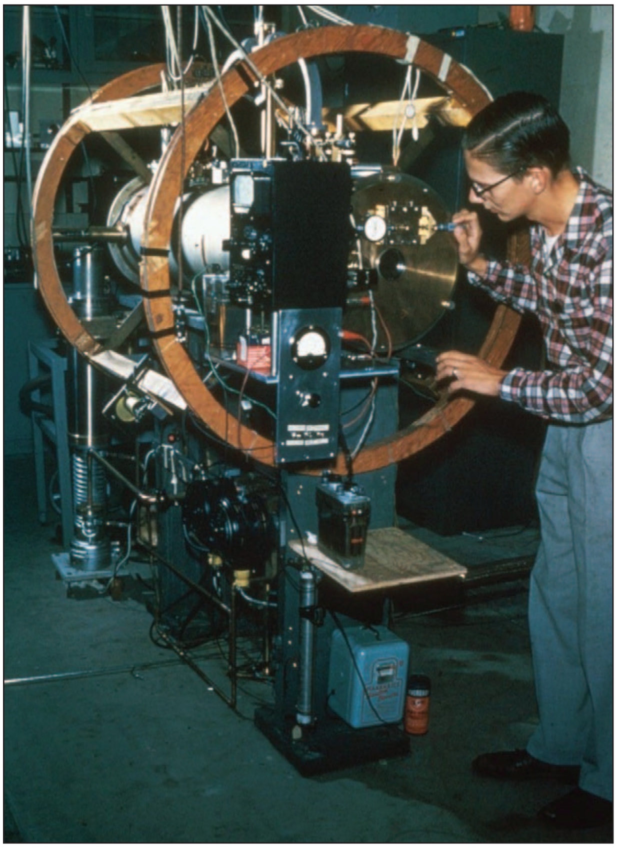

Fig. 3. Roger Beehler of NBS with NBS-1. Courtesy of NIST.

The NBS group, led by Lyons and Jesse Sherwood, turned their attention from ammonia to cesium clocks in 1950 [13]. Cesium had several properties that made it a good choice as the source of atomic resonance. Somewhat similar to mercury, cesium is a soft, silvery-white ductile metal. It becomes a liquid at about 28.4 °C (slightly warmer than room temperature). Cesium atoms are relatively heavy (133 amu) and move at a relatively slow speed of about 130 m/s at room temperature. This allows cesium atoms to be observed for a longer period than hydrogen atoms, for example, which travel at a speed of about 1600 m/s at room temperature. Cesium also has a higher resonance frequency (~9.2 GHz) than other atoms that were later utilized in atomic clocks, such as rubidium (~6.8 GHz) and hydrogen (~1.4 GHz).

The first cesium clock built by Lyons and Sherwood utilized Rabi's magnetic resonance technique. Sherwood

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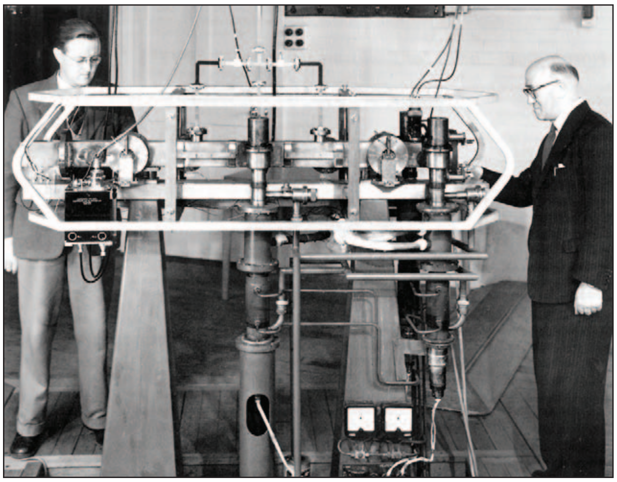

Fig. 4. Louis Essen (right) and Jack Parry (left) with the original NPL cesium clock. Courtesy of NPL.

reported initial results at a 1952 meeting of the American Physical Society, but the resonance width of the clock was too wide to serve as an accurate time standard [14]. As we saw in (2), the Q of an oscillator can be increased by either increasing the resonance frequency or narrowing the resonance width [15]. Once cesium was selected as the atom of choice, the resonance frequency could not be changed, so the focus turned to making the resonance width as narrow as possible. Narrowing the resonance width required a better way of interrogating the cesium atoms.

Rabi's original magnetic resonance technique interrogated the atoms with one microwave pulse. Methods were developed to increase the Q by applying longer microwave pulses, but these schemes didn't work as expected due to subtle technical side effects: the long interaction period between the atoms and microwave field subjected the frequency of the clock to Doppler shifts and other uncertainties. A breakthrough occurred in 1949 when Norman Ramsey of Harvard University invented the separated oscillatory field method, an improvement that would be critically important to future atomic clock designs. Ramsey's new method interrogated the atoms with two short microwave pulses, separated by some distance. Applying the oscillating field in two steps accomplished the goal of narrowing the resonance width. It also reduced the sensitivity to microwave power fluctuations and magnetic fields by factors of 10 to 100 or more and eliminated most of the Doppler effect. In short, Ramsey's work made it possible to build much more accurate atomic clocks [16], [17]. His achievements in atomic clock development earned him a share of the Nobel Prize some four decades later, in 1989.

The NBS team quickly modified their clock to employ Ramsey's new technique of separated oscillating fields and reduced the resonance width to just 300 Hz. Encouraged by these results, Lyons predicted that the clock would eventually be accurate to 1×10^{-10} (~10 µs/day) [12], [18]. His prediction eventually came true, but it happened much later than expected. In 1953, NBS interrupted their atomic clock program, a decision made partially for budgetary reasons and partially because the agency elected to focus on other areas. By 1955, both Lyons and Sherwood had left NBS, and the cesium clock was taken apart and moved from Washington, DC to a new laboratory in Boulder, Colorado [19], [20]. The clock was reassembled by a new team of researchers in Boulder but did not become a working time standard until 1958. Then known as NBS-1 (Fig. 3), the clock finally achieved Lyon's predicted accuracy [12].

The disruption of the NBS program caused the NBS to lose its large early lead in the cesium clock race and allowed the National Physical Laboratory (NPL) in England to become the clear winner. The NPL effort was led by Louis Essen, who had previously worked on quartz clocks and measurements of the speed of light before becoming interested in atomic timekeeping. Beginning about 1949, Essen made several trips to the United States where he met with early atomic clock researchers, including Rabi and his colleagues at Columbia and Jerrold Zacharias of the Massachusetts Institute of Technology (MIT). Essen was anxious to apply their work to timekeeping and appealed to the NPL director to start a new program to build an atomic clock. After several delays, work on a cesium clock began at NPL in 1953 and progressed rapidly enough for a working time standard to be placed in operation in June 1955 (Fig. 4). The original reported accuracy was 1×10^{-9} (0.1 ms/day) [21], [22]. The NPL cesium clock was to play a key role in the redefinition of the second, a topic we will explore in the next installment of this series.

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