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The Evolution of Time Measurement, Part 2: Quartz Clocks

Quartz clocks are the most common timekeepers of all. Billions of quartz oscillators are manufactured annually for use inside clocks, watches, mobile phones, computers, radios, and televisions. In this article, Part 2 of a five-part series, I discuss the evolution of quartz clocks, beginning with the discovery of piezoelectricity.

Piezoelectricity

It has long been known, perhaps even to ancient civilizations, that crystals of certain minerals have electrical properties. One often cited example involves tourmaline crystals, which were brought from Ceylon to Europe in large quantities to be sold as gemstones. In 1703, a Dutch observer noted that a heated tourmaline crystal would both attract and repel small particles of ash. Thereafter, tourmaline became known as the "electric stone" or the Ceylon magnet [1]. A century of experiments followed, and by 1824, the Scottish scientist David Brewster had observed similar properties in a number of different types of crystals. Brewster named the effect *pyroelectricity*, or the ability of certain materials to generate an electrical charge when they are heated or cooled [2].

While studying pyroelectricity in 1880, brothers Pierre and Jacques Curie demonstrated that crystals would also produce a charge when mechanical pressure was applied. Certain types of crystals would show positive and negative charges on portions of their surface when compressed in particular directions. The electrical charge was proportional to the pressure and would disappear when the pressure was withdrawn. This effect became known as *piezoelectricity*, or electricity resulting from pressure. Quartz (Fig. 1) and Rochelle salt (a less durable, water soluble crystal) exhibited the most piezoelectricity among the crystals tested by the Curie Brothers [3].

The Curies' initial experiment demonstrated only the *direct* piezoelectric effect, where the crystal converted physical pressure into electrical energy. In 1881, based on a theoretical suggestion by the French mathematician Gabriel Lippman, the Curies demonstrated that piezoelectricity had an *inverse* effect: if an electrical charge was applied to the crystal, it would physically strain and change its shape. Piezoelectric crystals were *transducers* that could convert energy from one form to another. Mechanical energy could be converted to electrical energy and vice versa, although some energy was lost during each conversion.

For nearly forty years after its discovery by the Curies, piezoelectricity remained little more than a scientific curiosity. It received even less attention than pyroelectricity, even though it was the chief cause of many pyroelectric effects [2]. Its first application resulted from the need to detect the presence of enemy submarines during World War I. By 1917, Paul Langevin in France and Alexander Nicolson in the United States had independently begun work on piezoelectric instruments that could transmit and receive sound waves underwater, determining the presence of submarines by "echo-ranging". Langevin's devices employed thin crystals of quartz glued between steel plates. He became known both as the inventor of

Fig. 1. A cluster of natural quartz crystals.

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sonar (originally an acronym for sound navigation and ranging) and the field of ultrasonics. Nicolson went on to develop other types of piezoelectric devices, including microphones, loudspeakers, and phonograph pickups [4]. He also constructed the first piezoelectric oscillator using Rochelle salt crystals [5]. The work of Langevin and Nicolson indirectly led to the quartz oscillator – a device that would soon play an important role in radio broadcasting.

Frequency Measurement and the Early Days of Radio

Time measurement has probably always been a topic of interest, or at least back to the beginnings of recorded history. In contrast, frequency measurement is a relatively recent topic, seldom discussed until the advent of radio broadcasting. Radio made frequency measurements essential because both receivers and transmitters had to be able to "tune" to the same frequency so that signals could reach their audience, and because stations that strayed from their assigned frequencies would interfere with other stations. Metrology laboratories, including the National Bureau of Standards (NBS) in the United States, began searching for ways to accurately measure frequency. John H. Dellinger led the NBS effort, and his 1923 paper entitled "Reducing the Guesswork in Tuning" [6] clearly explained the problem:

> The waves used by the broadcasting stations are spaced 10 kilocyles apart (3 meters at a wavelength of 300 meters). Thus one station is on 990 kilocycles, another on 1000, and another on 1,010 kilocycles. A variation of the frequency of 1 percent, for example, would be a variation of 10 kilocycles and could cause one station to be using exactly the wave that had been assigned to another. The whole success of American broadcasting is thus tied up with the placing of broadcasting stations on the correct frequencies to an accuracy approaching 99.9 percent. Since receiving sets are now available by which an individual can hear the stations from all over the United States on the same night, the importance of this accuracy is apparent.

At the time of Dellinger's paper, 570 U. S. broadcast stations had already crowded into a 1000 kHz wide band and there was no satisfactory method for measuring frequency [7]. One common method involved using Lissajous figures on cathode-ray oscillographs to show the ratio of a radio frequency with respect to the audio frequency produced by a tuning fork. The best measurements involved wave meters, instruments that typically employed several inductance coils of different values and a variable capacitor. Each coil enabled the measurement of a range of wavelengths. Wave meters could barely meet the 99.9% (1×10^{-3}) accuracy requirement and were incapable of controlling frequency or meeting future measurement needs.

The quartz oscillator became the first reliable and accurate standard of radio frequency. The invention of the quartz oscillator is generally credited to Walter Cady, an American physicist who received his doctorate degree from the University of Berlin. After returning to the United States, Cady became a professor at Wesleyan University in Connecticut, a position he held for about 45 years. Like Langevin, Cady worked on anti-submarine systems during the war but afterwards focused on building a radio frequency standard. Like Nicolson, he began by experimenting with Rochelle salt crystals but turned his attention to quartz crystals in November 1919 [2]. When applying an AC voltage over a wide range of frequencies, Cady noticed that both Rochelle salt and quartz crystals would reach their maximum amplitude oscillation (resonance) over a very narrow range of frequencies. Quartz, however, had a sharper resonance curve than Rochelle salt. The quartz resonance curve was similar to that of a tuning fork, which was already used as a frequency standard for acoustic waves. Cady quickly realized that quartz could be made to oscillate at higher frequencies than a tuning fork, perhaps high enough to become a frequency standard for radio waves [8].

Cady applied for a patent for his "Piezo-Electric Resonator" in January 1920 [9], followed by a patent application for a "Method of Maintaining Electrical Currents of Constant Frequency" in May 1921 [10]. Fig. 2, from the second patent, is a schematic of what is considered to be the first quartz oscillator. The output of a three-stage amplifier was used to drive a rod-shaped quartz crystal (#12 in Fig. 2) at its natural frequency through one pair of electrodes that made use of the inverse piezoelectric effect. The amplifier was powered by the direct effect from the other pair of electrodes. The feedback to sustain oscillations in the electrical circuit was obtained only through the vibration of the quartz rod. Cady described it as "virtually a mechanically-tuned feed-back" circuit [11].

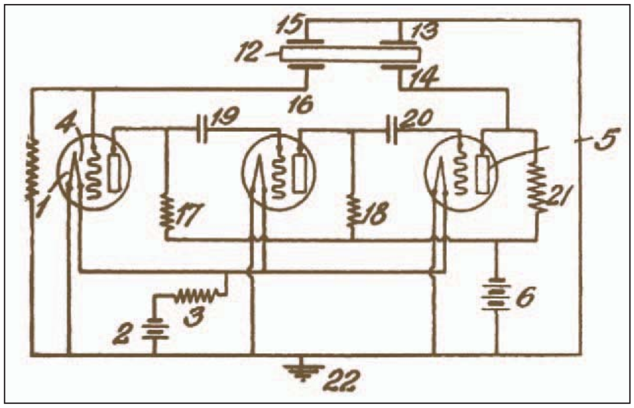

Fig. 2. Cady's original quartz oscillator circuit (from U. S. Patent 1,472,583).

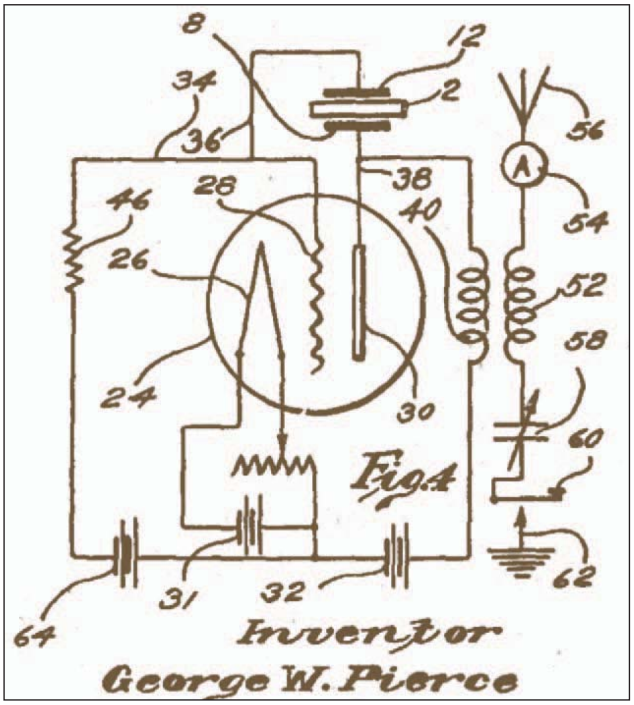

Fig. 3. The Pierce oscillator circuit in a wireless telegraphy system (from U. S. Patent 1,789,496).

George W. Pierce, a friend of Cady's and an electrical engineering professor at Harvard, improved upon Cady's work. He demonstrated that plates of quartz cut a certain way could be made to vibrate at specific frequencies that were proportional to the thickness of the plates. Cutting, grinding, and mounting quartz crystals to generate specific frequencies soon became a huge area of research, development, and production. Pierce also simplified and improved the circuit (Fig. 3). He used just one vacuum tube instead of Cady's three and connected just one pair of electrodes to the crystal (#2 in Fig. 3). Pierce's circuit could sustain oscillation with a constant frequency determined by the crystal alone and could oscillate at much higher frequencies [12]. In his 1924 patent application, Pierce claimed that he had "utilized harmonics of the device at 20,000 kilocycles per second" [13]. The higher frequencies were just what the radio industry needed, and within months, Pierce-type oscillators were used to construct crystal-controlled radio transmitters. The work of Cady and Pierce was synergistic; Cady proved the concept of the quartz oscillator, and Pierce made its use practical by designing a reliable and easy-to-use circuit [8]. The Pierce circuit remains the most common type of piezoelectric oscillator circuit to this day.

Radio engineers instantly recognized the value of the quartz oscillator, but it was several years before the standards of measurement were changed. Cady had sent four crystal oscillators to NBS for calibration in April 1920, shortly after filing his patent application. John Dellinger's group was in charge of the calibrations, and later that same year, Dellinger wrote in an NBS annual report of "a remarkable new type of wave meter consisting of a quartz crystal" [7]. Even so, NBS was still referencing its frequency measurements to wave meters when it began broadcasting standard wavelength signals from radio station WWV in March 1923.

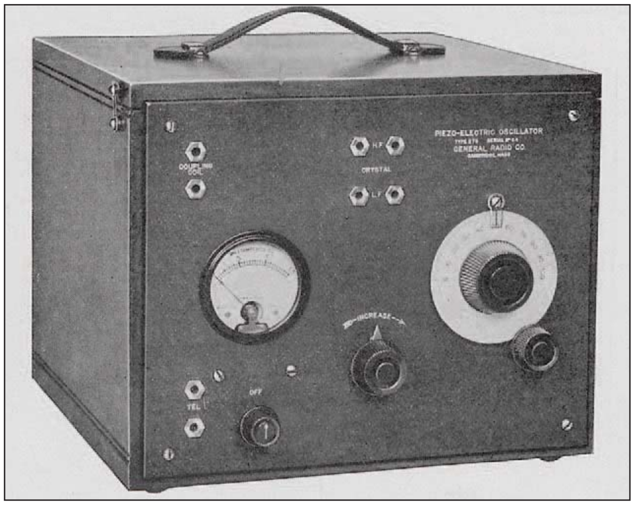

Fig. 4. The first commercial quartz oscillator, the General Radio Type 275.

By 1924, radio engineers could actually buy a quartz oscillator that Cady and Pierce had helped design, the General Radio Type 275 (Fig. 4). The instrument measured 10 in × 11 in × 8 in (25.4 cm x 27.9 cm x 20.3 cm) and weighed nineteen lbs (8.6 kg). It sold for $145 with one quartz plate ground to a frequency specified by the purchaser [14]. The WWV broadcasts were finally referenced to a 50-kHz quartz crystal oscillator located at the transmitter site in early 1927, quickly boosting its accuracy from parts per thousand to parts per million. This was fortuitous, because the new Federal Communications Commission (FCC), created by Congress in 1927, required all radio broadcasters to stay within 500 Hz of their assigned frequency [7]. The requirement was tightened to 50 Hz in 1932 (5×10^{-5} at 1000 kHz). However, by then it was no longer an issue, because by 1929, the U. S. national frequency standard, the group of four 100-kHz quartz oscillators shown in Fig. 5, had reached an accuracy of 1×10^{-7} [15]. A year earlier General Radio began selling a quartz frequency standard, the Model C-21-H, that was accurate to within 1×10^{-6} [16]. The quartz oscillator had made it easy for the radio industry to obtain the accuracy it needed, solving a serious measurement problem in less than a decade.

The First Quartz Clocks

When the quartz oscillator was invented, the mechanical clocks that served as standards for time measurements counted very slow frequencies. For example, some chronometers would beat twice a second (2 Hz), and some clocks with long pendulums

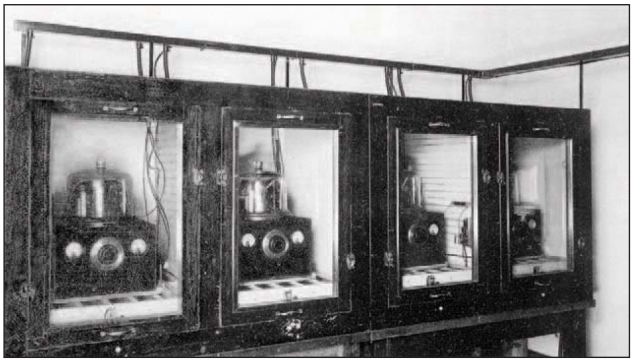

Fig. 5. The U.S. national frequency standard in 1929, a group of four quartz oscillators.

completed just one-half oscillation per second (0.5 Hz). In contrast, quartz oscillators ran at frequencies of thousands of hertz. Keeping time with quartz required a way to measure and count these much higher frequencies [17].

The invention of the quartz clock is generally credited to William Marrison. Born in Canada in 1896, Marrison worked on radio communications in the Royal Flying Corps during World War I. After the war, he received a masters degree from Harvard and went to work in New York City, first for Western Electric and then at Bell Telephone Laboratories. At Bell, he worked on quartz frequency standards with his supervisor and colleague Joseph W. Horton. In October 1927, the two presented a paper where they described two new clocks: one referenced to the 100 Hz frequency of an electric tuning fork, the other to the 50 kHz frequency of a quartz crystal [18]. This was the first published account of a quartz clock, although Marrison's notes suggest that he conceived of the idea in November 1924 [19].

Over a period of several years, Marrison refined his quartz clock to use a 100 kHz oscillator and a frequency divider that, as Marrison wrote, functioned as a "reducing gear". The frequency was divided twice, each time by a factor of 10, so that one cycle in the output of the divider corresponded to 100 vibrations of the crystal. The resulting frequency of 1 kHz was used to control the speed of a small 1000-cycle synchronous motor, thus locking the motor's frequency to the frequency of the crystal. Marrison noted that when the crystal produced "its nominal frequency exactly, the clock keeps accurate time" but that the frequency of the crystal could vary due to external conditions such as pressure, temperature, and vibration. Fig. 6 shows the crystal oscillator (left) and the back of the clock face with the synchronous motor exposed (right).

Marrison compared his clock to U. S. Naval Observatory time signals during December 1929 and January 1930. The clock was accurate to within 0.2 s per day or less (about 2 × 10^{-6}). However, its time error was gradually changing by a total of 0.14 s over a period of about 47 days (about 3 ms per day on average). He correctly attributed this to the "aging effect" of the crystal [20]. We can deduce from his measurements that the frequency of the crystal was changing by a few millihertz each day on average (a 1.16 mHz frequency change at 100 kHz would result in a 1 ms time change).

The first commercial quartz clocks were sold by General Radio. Horton had left Bell Labs to join General Radio in 1928, becoming their chief engineer. He designed a series of *Syncro-Clocks* that avoided infringing on Marrison's patents by utilizing a different frequency divider circuit [8]. These clocks, introduced in the early 1930s, didn't come with oscillators. They were intended to be used with quartz frequency standards that often filled large equipment racks. The technology rapidly advanced, however, and quartz clocks became smaller and more accurate. The first "portable" quartz clock was probably the Model CFQ produced by Rohde & Schwarz in Germany beginning in 1938 (Fig. 7). Weighing 46 kg, it was accurate to within ±0.004 s per day (5 × 10^{-8}). By then, quartz clocks were the world's most accurate timekeepers and had essentially made pendulum

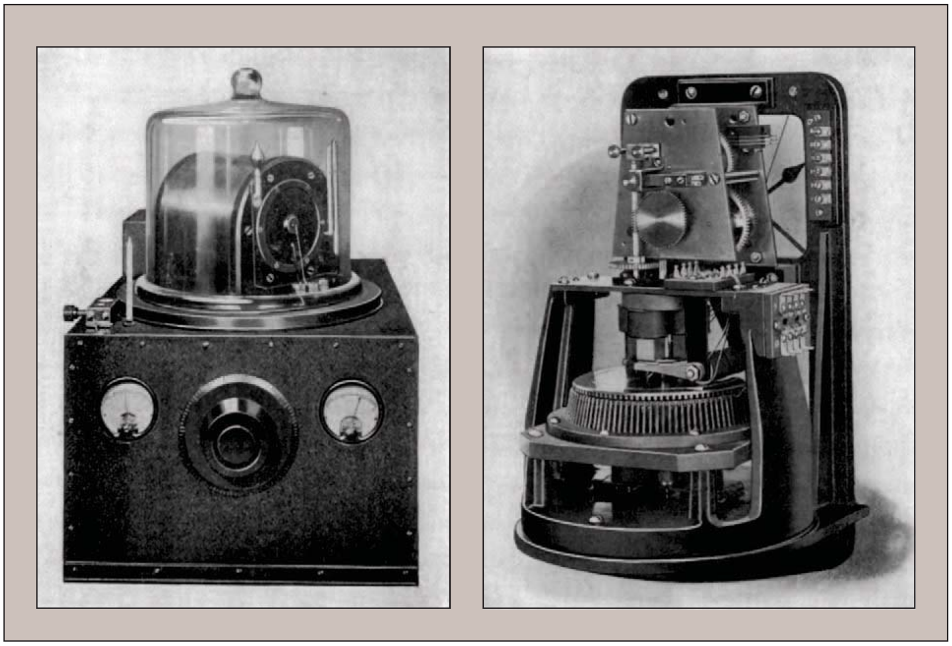

Fig. 6. The crystal oscillator (left) and motor and display assembly (right) of Marrison's quartz clock.

clocks (including the Shortt pendulum described in Part 1 of this series) obsolete.

Fig. 7. Rohde & Schwarz Model CFQ, the first portable quartz crystal clock (courtesy of Rohde & Schwarz).

Growing Quartz Crystals

Quartz is the second most common mineral on Earth after feldspar. Even so, it became so important to radio communications and timekeeping that a shortage was feared, and the United States government declared quartz a critical national resource during World War II. Thirty million or more quartz crystal units were produced from 1942 to 1945 for use in Allied radios. Nearly all of the quartz used by the Allies during the war was mined in Brazil, but the available quantities were uncertain and delivery was slow. When the war ended, the U. S. Army Signal Corps and private industry invested heavily in research aimed at finding a substitute for natural quartz.

The task of growing synthetic, or "cultured", quartz crystals had been pursued for years before World War II with unsatisfactory results. The key players in the post war effort were Bell Telephone Laboratories and Brush Development Company, led by the American physicist Charles Sawyer. Both Bell and Brush focused on the hydrothermal method of crystal growth. This method grew crystals under high pressure and high temperature in an enclosure called an autoclave, using natural quartz as a nutrient supply to "seed" the growth of synthetic quartz. This method worked but had two problems: the growth of the crystals was either too slow, or it could not be sustained for more than one day. However, the postwar research refined the method, and by the end of 1948, Brush had grown a flawless 1.5 in (3.8 cm) diameter quartz crystal, the largest grown up to then in a laboratory. Bell Telephone laboratories made further advances by developing new, higher-pressure autoclaves that allowed even larger crystals to be grown at a predictable rate [8], [21].

Funded by the Signal Corps, Brush Development built the world's first manufacturing plant for synthetic quartz in Bedford, Ohio in 1953. After Brush merged with another company, Charles Sawyer founded a new company, called Sawyer Research Products. Along with other manufacturers, Sawyer soon began selling synthetic quartz, not only to the military but to private industry. New markets for quartz oscillators emerged, including color television. Every color TV required a quartz oscillator to generate a 3.579545 MHz color burst frequency that was used to superimpose color onto the standard black-and-white signal. This market was slow to develop, but when the color television industry reached high volume sales during the 1960s, most TV sets included oscillators made of synthetic rather than natural quartz [8].

By 1971, synthetic quartz had become more common than natural quartz in electronics applications, and today nearly all quartz oscillators contain synthetic crystals. The quartz crystal and quartz oscillator marketplace was estimated as US $4.1 billion in 2008. It continues to grow due to the recent explosion of portable electronic devices. For example, a typical mobile phone contains five quartz oscillators. Some serve as timing references, while others regulate the

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transmit and receive frequencies [22]. The hydrothermal method of growing synthetic crystals has been continuously refined, but the basic methods developed during the post-war effort are still in use [8], [21].

The Limits of Quartz Oscillator Performance

By the early 1950s, quartz oscillators could generate frequencies accurate to within 1×10^{-10} [23]. This was 10,000,000 times better accuracy than the original radio requirements specified by Dellinger [2] and about 200,000 times better than today's FCC requirements for AM and FM stations [24]. Quartz oscillators have certainly become far more reliable (some have run for decades without failing), much smaller, and far less expensive but not significantly more accurate than they were in the 1950s. Even today's best quartz oscillators require regular adjustments to maintain frequency accurately to within 1×10^{-10}.

There are several factors that limit the accuracy of quartz oscillators. Their frequency is determined by the cut and size of the crystal. Crystals can be cut and trimmed very precisely to accurately produce specific frequencies, but unlike atoms (discussed in the next installment of this series), no two crystals can be exactly alike or produce exactly the same frequency. Therefore, the inherent accuracy of a quartz clock will always be limited, as will its ability to agree with other quartz clocks.

Temperature is often the most serious external environment problem. The most effective method for controlling temperature is to encase the crystal in a temperature-controlled oven, a technique that dates back to the 1930s [25].

Even if a crystal were perfectly cut and trimmed, its frequency would still change due to external and internal environmental effects. Temperature is often the most serious external environment problem. The most effective method for controlling temperature is to encase the crystal in a temperature-controlled oven, a technique that dates back to the 1930s [25]. *Oven-controlled crystal oscillators* (OCXOs) keep the crystal temperature constant when the temperature outside the instrument varies and are the most stable type of quartz oscillator. Changes that occur inside the instrument are harder to prevent. As Marrison observed in his early experiments, they produce an effect known as *aging*, which results in a frequency change that can be either positive or negative. A reversal in the direction of the aging occasionally occurs, and the aging rate usually slows down as the instrument gets older. The rate at which a quartz oscillator ages is usually related to the way that the crystal is packaged and mounted. The aging rate will be more predictable if the crystal's packaging keeps it free from contamination from humidity and from the buildup of foreign materials [26]. Even with the best packaging, however, some change in frequency due to aging is inevitable. Because so many factors limit their accuracy, quartz clocks are no longer used as standards by timing laboratories. However, they are accurate enough for everyday timekeeping and are found literally everywhere, including inside the everyday wristwatch.

The Quartz Watch

Until the latter part of the 1950s, all wristwatches were mechanical clocks driven by a mainspring and had to be wound daily by the person who wore them. This changed in January 1957 when the world's first battery-powered watch, the Hamilton Electric 500, was introduced by the Hamilton Watch company of Lancaster, Pennsylvania [27]. The watch ran at the same frequency as a typical mechanical watch, 5 Hz, derived from tiny electrical contacts that opened and closed five times per second.

When electric watches first appeared, watch industry experts already knew that new technology, including the recent invention of the transistor, had made it possible to build a quartz watch. A quartz watch would also be battery powered but would be many times more accurate than a simple electric watch. Seven different programs to build a quartz watch were launched between 1955 and 1969 [28]. Before any of them succeeded, however, the Bulova Watch Company of New York introduced its *Accutron* watch in October 1960. Designed by a Swiss electrical engineer named Max Hetzel, the watch substituted a tuning fork for the traditional balance wheel found in mechanical watches. The tuning fork was powered by a one-transistor oscillation circuit that ran at a frequency of 360 Hz, making the watch hum instead of tick. The Accutron was accurate to within 2 seconds per day, or about ten times more accurate than the best mechanical watches [27], [28].

The Accutron captured the public's imagination and posed a serious threat to the Swiss watch industry, which had made well over half of the world's watches during the 1950s. To combat the threat, the Centre Electronique Horloger (CEH) in Neuchâtel, Switzerland was formed in 1962 with the intent of developing a quartz watch that would surpass the accuracy of the Accutron. The group was founded by Roger Wellinger, a Swiss-American electronics specialist, and the team eventually grew to more than 90 people. Two key members of the team were Armin Frei and Rolf Lochinger. Both had received

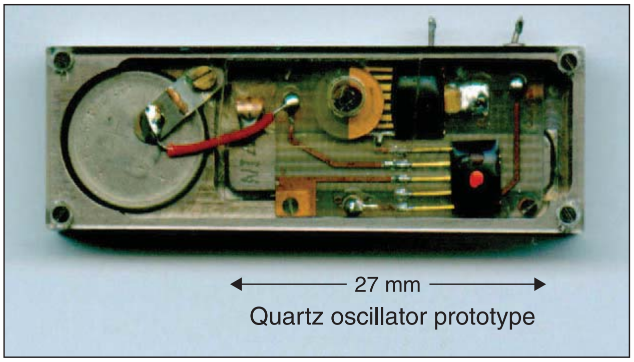

Fig. 8. The 8192 Hz oscillator used in the first quartz watch.

their Ph.D. degrees from the Swiss Federal Institute of Technology and worked for some years in the United States before returning to Switzerland. Beginning in May 1965, Frei focused on developing a miniature quartz oscillator, and Lochinger began developing frequency dividers and driver circuits for the stepping motors that would move the watch hands [28], [29].

Frei had a miniature quartz oscillator working by early 1966 (Fig. 8). Frei also developed a driver circuit that consumed less than 4 µA of power (with the red dot) and a circuit for fine tuning the quartz frequency (the black integrated circuit (IC) with no dot). The resonator was a 24 mm bar-shaped quartz crystal hidden inside the 27 mm oscillator case. To keep the electronics simple, the oscillator frequency had to be a power of two in order to produce a pulse with a period of one second at the end of the divider chain. Frei chose a frequency of 8192 Hz, or 2^{13} Hz. This meant that by using 13 binary flip-flop stages, the frequency could be reduced to 1 Hz, and a stepping motor could be used to drive the second hand. This scheme was utilized in the first quartz oscillator movement produced by CEH, known as Beta 1. However, the divider stages placed a large load on the battery, limiting its lifetime to less than one year. For this reason, CEH produced a second movement, Beta 2, which used the same oscillator but had only five divider stages. Beta 2 only divided the quartz frequency to 256 Hz and utilized a vibrating motor and ratchet wheel to move the second hand. Its only advantage over Beta 1 was that it used less power [29].

The first Beta 1 prototype was assembled in July 1967 and qualifies as the first quartz watch. The first Beta 2 prototype was assembled about one month later [29]. During August 1967, six Beta 2 and five Beta 1 movements were tested at the Observatory in Neuchâtel and were found to be accurate to within 0.1 to 0.2 s per day [28], or about 1×10^{-6}; a remarkable feat for a clock small enough to wear on your wrist. Because its battery could last more than one year, CEH elected to manufacture the Beta 2 movement instead of Beta 1, calling the commercial version of the movement Beta-21. About 20 Swiss firms introduced watches with Beta-21 movements on April 10, 1970 [29].

Fig. 9. The first commercial quartz watch, the Seiko Astron (courtesy of Seiko).

About four months earlier, the Swiss watchmakers had been beaten to the marketplace by the Japanese company Seiko, which introduced a quartz watch called the Astron (Fig. 9) on Christmas Day of 1969. The Astron also ran at 8192 Hz, but its design differed from Beta 1 and Beta 2, and it was slightly less accurate. It used a quartz tuning fork oscillator rather than a bar. Like the Beta 1, it used 13 binary divider stages and a stepping motor to drive its second hand. However, the Swiss had manufactured their own ICs, and Seiko had designed a hybrid circuit that included 76 transistors, 29 condensers and 84 resistors, each hand-soldered to the watch movement [27]. A team of 20 people, led by Tsuneya Nakamura, worked on the design of the Astron. The first commercially available quartz watch, the Astron, sold for US $1250, which in 1969 was equivalent to the price of an economy car.

Due to their high cost and some manufacturing issues, sales of the first quartz watches were small, but the technology rapidly improved. The problem of excessive battery consumption was solved by the use of low power complementary metal oxide semiconductor (CMOS) components. Frank Wanlass of Fairchild Semiconductor in the United States had invented CMOS logic in 1963, and CMOS components found their way into quartz watches by about 1970. The approach used by the Beta 21 movement was quickly abandoned, and dividing to 1 Hz and using a stepper motor became standard practice. By 1972, the Swiss watch company Girard-Perregaux had introduced a quartz watch movement called the GP350 that ran at a frequency of 32768 Hz (2^{15} Hz) and included a 15-stage CMOS divider circuit. Over 50,000 GP350 movements were sold, and the 32768 Hz frequency became the standard for the quartz watch industry [28]. Today, even the least expensive quartz watches are usually accurate to within 0.5 s per day (5×10^{-6}) and their batteries can last for several years. The best quartz watches can keep time to within about 10 s per year, or about 3×10^{-7}.

The quartz watch was one of the most significant inventions of the 20th century, and it quickly surpassed the mechanical watch in popularity. It was estimated that about 1.2 billion watch movements were manufactured in 2005, and about 99% were quartz controlled [28]. It would be impossible to overstate the importance of quartz clocks to time measurement and timekeeping. We rely on quartz clocks to regulate our everyday lives. Even so, a few technologies require more accuracy than quartz clocks can provide. The never ending quest for more accurate time led to the development of atomic clocks, which I will explore in Part 3 of this series of articles.

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