recalibration

Michael A. Lombardi

First in a Series on the Evolution of Time Measurement: Celestial, Flow, and Mechanical Clocks

Time is elusive. We are comfortable with the concept of time, but in many ways it defies understanding. We cannot see, hear, or touch time; we can only observe its effects. Although we are unable to grasp time with our traditional senses, we can clearly "feel" the passage of time as we watch night turn to day, the seasons change, or a child grow up. We are also aware that we can't stop or reverse the continuous flow of time, a fact that becomes more obvious as we get older. Defining time seems impossible, and attempts to do so by philosophers and scientists fall far short of their goal.

In spite of its elusiveness, we can measure time exceptionally well. In fact, we can measure time with more resolution and less uncertainty than any other physical quantity. Timekeeping, however, is fundamentally different and more challenging than other measurements because it requires continuity. For example, we can turn on a voltmeter whenever we need to measure voltage. When the measurement is finished, we can turn off the voltmeter until we need it again. In contrast, the "meters" we use to measure and "keep" time, called clocks, can never be turned off. Because the passage of time never stops, a stopped clock is useless. To become useful again, it must be restarted and synchronized with another clock that continued to measure time during its absence.

It is helpful to note that time, as we know it, is an agreed upon standard. Before we could keep time, we had to first define the units of time interval. These units could then be measured and counted. This is exactly what a clock does — it measures and counts time intervals to mark the passage of time. In this article, the first of a four-part series, I will discuss how time measurement has evolved throughout history. I'll begin by describing some early clocks and the first attempts to measure and keep time.

Sundials and the Concept of the Hour

The day, or the period of one rotation of the Earth upon its axis, is a natural unit of time interval. In fact, until the early part of the 20th century, the Earth was thought to be a perfect clock. It seems likely that the first attempts to measure time involved simply counting sunrises or sunsets to record the number of elapsed days. This resulted in calendars, which historians tell us are many centuries older than the first clocks. The first instruments that we now recognize as clocks could measure intervals shorter than one day by dividing the day into smaller parts.

Most historians credit the Egyptians with being the first civilization to use clocks. Their first clocks were probably nothing more than sticks placed in the ground that indicated time by both the length and direction of their shadow. As early as 1500 BC, the Egyptians had developed a more advanced shadow clock (Fig. 1). This T-shaped instrument was placed in a sunlit area on the ground. In the morning, the crosspiece (AA) was set to face east and then rotated in the afternoon to face west. The long arm (BB) was calibrated into six parts with a scale that formed what was probably the first representation of what we now call the hour. The morning and afternoon hours combined to form the twelve-hour day, reflecting Egypt's early use of the duodecimal (base 12) number system. The number twelve was important for at least two reasons. It equaled the number of lunar cycles in a year and the number of joints in four fingers (excluding the thumb), making it possible to count to twelve with one hand [1].

Shadow clocks and the circular sundials that followed keep *apparent solar time*, based on the apparent motion of the Sun as observed from Earth. The Earth has a non-circular orbit and a tilt in its axis, so the Sun appears to move fastest when it is closest to the Earth. To a sundial, noon is the instant when the Sun reaches its highest point in the sky, but the Sun actually reaches its high point at different times during the course of year, varying from the average time by as much as sixteen minutes. For these reasons, the time kept by sundials varies throughout the seasons.

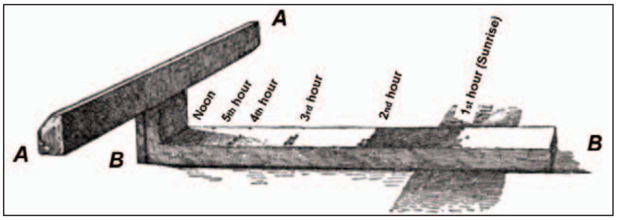

Fig. 1. Early Egyptian Shadow Clock (circa 1500 BC).

1094-6969/11/$25.00©2011IEEE

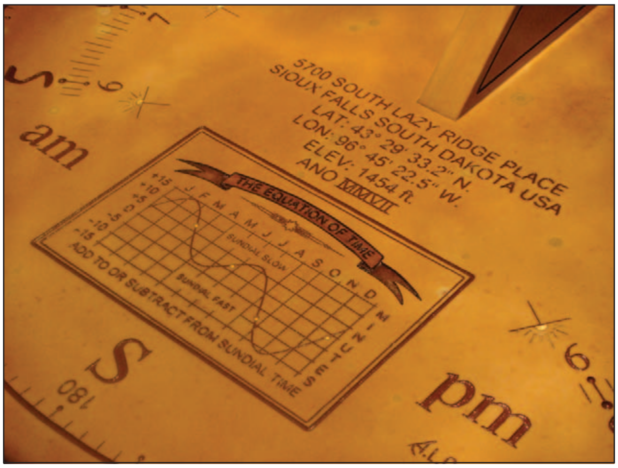

Fig. 2. An equation of time inscribed on a sundial.

Sundials are often inscribed with a graph, called the *equation of time* (Fig. 2), that converts the time displayed by a sundial to *mean solar time*, or the time kept by modern clocks. The concept of mean solar time and the principles for determining the equation of time date back to at least 150 AD and the work of Claudius Ptolemy. Even so, apparent solar time continued to be used for general timekeeping until at least the late eighteenth century [2], [3], [4].

Sundials obviously couldn't work at night, so measuring time in the dark interval between sunset and sunrise was a challenging problem. During the same era when sundials appeared, Egyptian astronomers began observing a set of 36 decan stars that divided the circle of the heavens into equal parts. The passage of night was marked by the appearance of eighteen of these stars, three of which were assigned to each of the two twilight periods when the stars were difficult to view. The period of total darkness was marked by the remaining twelve stars, resulting in twelve divisions of night, again due to the duodecimal system. During the New Kingdom (1550 to 1070 BC), the system was simplified to use a set of 24 stars, twelve of which marked the passage of night [5].

Fig. 3. Egyptian Water Clock, circa 1400 BC (courtesy of the Science Museum, London).

The *clepsydra*, or water clock, could also measure time during the night and was perhaps the most accurate clock of the ancient world. A specimen found at the temple of Amun-Re in Karnak dates back to about 1400 BC. This clock consisted of a vessel with slanted interior surfaces that were inscribed with markings that divided the night into twelve parts during various months (Fig. 3). Water slowly dripped out of a hole at the bottom of the vessel, and the water level would drop from hour line to hour line. Modern tests have shown that these ancient water clocks might have been accurate to about fifteen minutes per day [6].

Once the light and dark hours were each divided into twelve parts, the concept of a 24-hour day was in place. However, the length of these hours still varied seasonally. The idea of fixed length hours did not originate until Greek astronomers needed such a system for their theoretical calculations. Hipparchus, whose main work took place between 147 and 127 BC, proposed dividing the day into 24 equinoctial hours, based on twelve hours of daylight and twelve hours of darkness on the days of the equinoxes. Even so, measuring time with hours of fixed length did not become common until the age of mechanical clocks.

Minutes and Seconds

Hipparchus and other Greek astronomers employed astronomical techniques that were previously developed by the Babylonians. The Babylonians relied on the sexagesimal (base 60) number system that they had inherited from the Sumerians, who had developed it around 2000 BC. We don't know why 60 was chosen, but it was convenient for expressing fractions, since 60 is the smallest number divisible by the first six counting numbers and is also divisible by 10, 12, 15, 20, and 30. Although it is no longer used for general computation, the sexagesimal system is still used to measure angles, geographic coordinates, and time.

The Greek astronomer Eratosthenes (circa 276 to 194 BC) used a sexagesimal system to divide a circle into 60 parts. He devised an early geographic system of latitude, with his latitude lines running through well-known places on Earth. A century later, Hipparchus improved on this system by rationalizing the lines of latitude, making them parallel and obedient to the Earth's geometry instead of its familiar places. Hipparchus also devised a system of longitude that ran north to south, from pole to pole. His latitude and longitude systems each encompassed 360 degrees, employing the methods of the Babylonians, who had divided the arc of a circle into 360 parts. Claudius Ptolemy made further refinements to this coordinate system. In his *Almagest* (circa 150 AD), he subdivided each of the 360 degrees of latitude and longitude into 60 parts, which were again subdivided into 60 smaller parts. The first division, *partes minutœ primœ* or "first minute", became known as the "minute". The second division, *partes minutœ secundœ* or "second minute", became known as the "second". Thus, both the circular face of a clock and the sphere of a globe owe their divisions to a Babylonian number system that is now about 4000 years old [7] [8].

It would be long after the *Almagest*, however, before minutes and seconds were used for everyday timekeeping. Measuring minutes wasn't practical until near the end of the sixteenth century, when mechanical clocks with minute hands began to appear [6]. Earlier clocks divided the hour into halves, thirds, quarters, or sometimes even 12 parts, but the hour was not divided by 60, nor was it understood to be the duration of 60 minutes. This changed as clock technology improved, but many of today's clocks still do not display seconds.

Clocks in the Middle Ages

Numerous other clocks were invented that kept time using a continuous process, such as a flow rate or melting rate. Water clocks were probably the world's most accurate timekeeping devices until the end of the Middle Ages in the fifteenth century. Many elaborate water clocks were developed that improved upon the accuracy of the simple vessels first used in Egypt. Calibrated to agree with the flow rate of water, some water clocks utilized multiple vessels, siphons, and various types of hydraulic mechanisms, and others even marked the passage of time by moving dials or ringing bells. Of course, all water clocks had limitations. Water could freeze in cold climates and quickly evaporate in warm climates, and sloshing water did not line up well with hour marks. In addition, few people had access to a water clock. For the most part, they were only found in palaces and other places of wealth [2] [6].

The sandglass was another type of "flow" clock. Their origin is unknown, and it seems that very few existed before the fourteenth century. A sandglass consists of two vertical glass bulbs connected by a small opening that allows a trickle of sand to flow from the top bulb to the bottom bulb (Fig. 4). They were usually less accurate than water clocks, because the flow rate of sand is less predictable than water. The friction of the sand could also widen the opening, potentially making a sandglass less accurate the more it was used. However, sandglasses were more affordable, more portable, and less affected by temperature than water clocks. The sea's motion made water clocks unusable on ships, so mariners measured ship speed, distance travelled, and periods of duty with sandglasses until the eighteenth century. Of course, they were never well suited for continuous timekeeping; a sandglass that could run through the night would be too large and heavy for a person to turn over. Their main use was to measure short time intervals–a good example being the three-minute egg timers that are still found in today's kitchens [2], [6], [9].

Candle clocks measured time based on melting rate, rather than flow rate. The candle was calibrated so that its approximate melting rate was known, and either the candle itself or a nearby chart was marked with a scale indicating the passage of time. The candle's height indicated the current time. By sticking a nail in the candle at a desired time interval, a candle clock could be used as an interval timer in much the same fashion as a sandglass. When the part of the candle surrounding the nail melted, the nail would fall and clatter onto a plate below.

Fig. 4. A sandglass used for timing a one hour interval.

Many historians credit the invention of the candle clock to King Alfred the Great of England in the latter part of the ninth century, although they were almost certainly used before then. King Alfred's clocks consisted of six twelve-inch candles, each divided into one-inch sections. It would take four hours for one candle to burn. Thus, one inch of candle was equal to about twenty minutes, and six candles represented one day. The candles allowed the king to divide his day into three eight-hour segments, one for study and prayer, one for official business, and one for rest [6]. Because they were used for centuries as clocks, both sandglasses and candles remain enduring symbols of the passage of time. The iconic sandglass is often associated with timekeeping, and a candle that melts down to nothing or is snuffed out prematurely is often a metaphor for the end of life.

In spite of the ingenuity displayed by the inventors of these early clocks, the historian Marc Bloch was correct to point out that time measurement was all but unknown to most citizens during the Middle Ages. The people of that era

> *….lived in a world in which the passage of time escaped their grasp all the more because they were so ill-equipped to measure it. Water-clocks, which were costly and cumbersome, were very rare. Hourglasses were little used. The inadequacy of sundials, especially under skies quickly clouded over, was notorious* [10].

This changed with the advent of the mechanical clock.

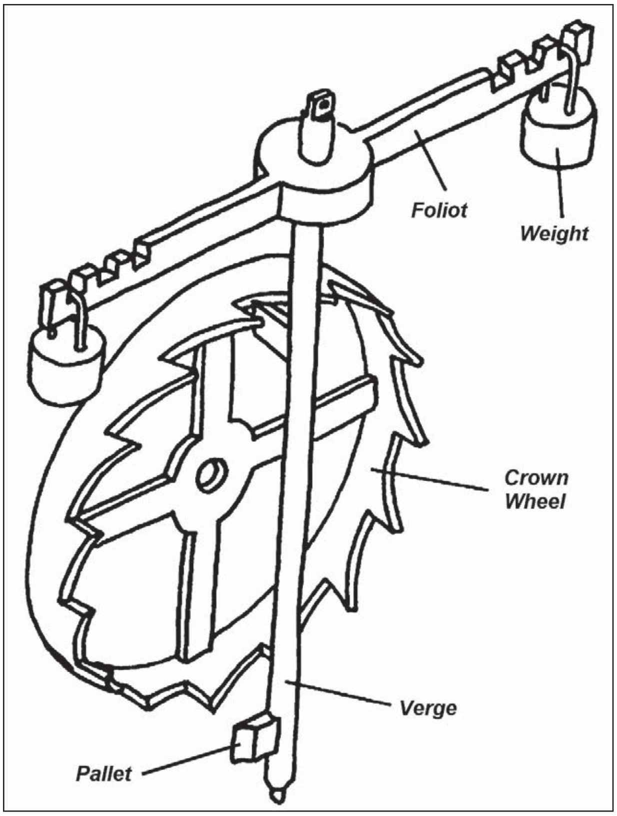

Fig. 5. Block diagram of verge escapement with foliot.

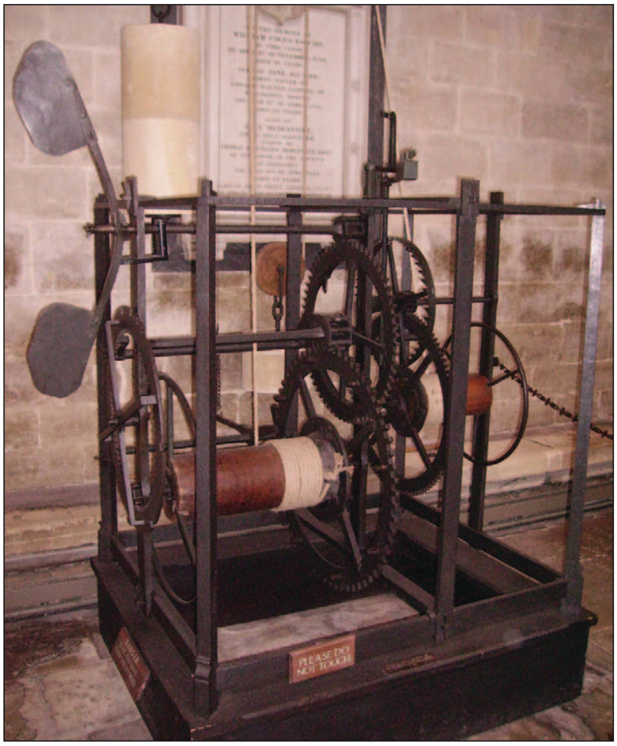

Fig. 6. Salisbury Cathedral Clock, 1386.

Mechanical Clocks

Mechanical clocks were made possible by the invention of the *escapement*, a device that converts rotational motion into a back and forth, or oscillating motion. The continuous motion of the escapement produces the "tick-tock" sound of a mechanical clock. As we have seen, early man-made clocks kept time by measuring continuous processes, such as the flow of water or sand. The escapement allowed clocks to keep time by measuring repetitive motions, such as the swing of a pendulum. The devices that produced this repetitive motion, called *oscillators*, became the heart of all modern clocks.

There is no consensus about who built the first mechanical clocks or where they first appeared. However, most historians agree that they existed in Italy in the early part of the fourteenth century and quickly spread throughout Europe. Dante made allusions to mechanical clocks in his *Divine Comedy*, completed between 1315 and 1321, and there is evidence of public tower clocks existing in Italy around that same period [6]. These clocks were controlled by a verge escapement, the first known type of mechanical clock escapement. The *verge* is a vertical rod, similar to an axle. Two metal plates, called pallets, are connected to the verge. A crown wheel, with saw-tooth shaped teeth, was typically rotated by energy from a slowly falling weight on a rope. As the crown wheel rotates, its teeth catch the first pallet and turn the verge in one direction until the second pallet is in the path of the teeth. The crown wheel's teeth then catch the second pallet and reverse the direction of the verge, and the cycle continuously repeats. In most early mechanical clocks, the verge would swing a horizontal bar back and forth. The bar, called the *foliot*, had weights hanging from each end, and the clock's rate could be adjusted by moving the weights either closer to or further away from the verge (Fig. 5). The oldest surviving example of a verge and foliot clock is the Salisbury Cathedral clock in England, which is believed to have been built in 1386 (Fig. 6). Most medieval mechanical clocks were controlled by verge and foliot mechanisms, but some early Italians clocks, such as Giovanni De Dondi's Astrarium clock, built in 1365, used a crown shaped balance wheel instead of a foliot [2], [6], [11].

The early verge and foliot clocks were far from accurate, even less accurate than the water clocks that preceded them. Some probably gained or lost more than one hour per day. Later versions were more accurate but probably still gained or lost at least fifteen minutes per day. This large error was not due to the verge escapement, but instead due to the foliot oscillator. The invention of the pendulum oscillator immediately increased mechanical clock accuracy to about one minute per day, reaching less than ten seconds per day by end of the seventeenth century.

Although he never built a pendulum clock, the Italian Galileo Galilee was the first scientist to study pendulums. While a medical student in 1583, Galileo had used the human pulse rate to check the regularity of a pendulum. He later applied the reverse concept, measuring pulse rate with the help of a pendulum [6], [12]. He discovered that pendulums were *isochronous*, meaning that the period of their swings was approximately constant and independent of the width of the arc or the angle of the swing. (It was later found that this was most true with very small angles.) Around 1637, he recognized that the natural periodicity of a pendulum could be applied to timekeeping. He made plans to build a clock but by then had lost his eyesight and was unable to complete his work before his death in 1642.

Probably influenced by Galileo, the Dutch scientist Christiaan Huygens is usually credited with inventing the pendulum clock. A renowned scientist who is especially remembered for his wave theory of light, Huygens was not a clockmaker. He contracted the construction of the first pendulum clock to Saloman Coster, who completed it in 1657. The clock still used a verge escapement, but the foliot was replaced with a pendulum. The improvement in accuracy was so significant that many existing verge and foliot clocks were rebuilt with pendulums. Fig. 7 is a diagram of Huygen's second pendulum clock, built in 1673, where the verge escapement was turned ninety degrees so that the crown wheel faces up. This clock had a claimed accuracy of 10 seconds per day ($\sim 1 \times 10^{-4}$). Pendulum clocks soon appeared throughout Europe, with prominent clock dials that emphasized the new levels of accuracy [13]. Some even had second hands. A few pre-pendulum clocks also had second hands, but they were known to be inaccurate. Their purpose was simply to indicate that the clock was running.

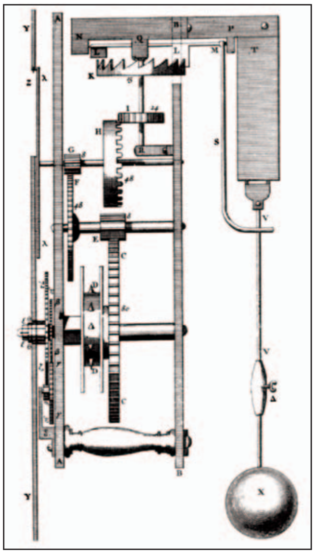

Fig. 7 Huygen's pendulum clock mechanism, 1673.

After the foliot was replaced by the pendulum, clockmakers soon focused on the verge escapement as the main source of inaccuracy. A new mechanism, called the anchor escapement, made it easier to build an accurate pendulum clock. Probably invented around 1666 by Robert Hooke, the anchor escapement first appeared in a clock built by William Clement of London in 1671 [11]. It reduced the wide pendulum swings of the verge escapement to about three to five degrees. This made the pendulum more isochronous and allowed the use of longer, slower moving pendulums that required less energy to sustain oscillation [2]. The tall, narrow shape of a grandfather clock that we recognize today is due to the use of the anchor escapement. However, verge escapements continued to be used in clocks and watches until the early nineteenth century and were even used in the clocks of John Harrison.

John Harrison and the Problem of Determining Longitude at Sea

The most often told timekeeping story is probably that of John Harrison. Self-educated and a carpenter by trade, Harrison was naturally drawn to clock making. He repaired clocks from an early age and built his first clock, a long-case clock with a wooden mechanism, in 1713. With assistance from his brother, he went on to build a series of clocks in the 1720s that kept time to within fractions of a second per day (parts in 10^6), inventing a new low-friction mechanism known as the grasshopper escapement. Harrison's land clocks were the most accurate in the world, and their performance was not equaled until the late nineteenth century.

The greatest scientific problem of Harrison's time was finding a ship's longitude at sea. It was a huge economic problem, because trade with other countries depended upon sailing. It was also a problem of life and death. There were no landmarks in the ocean, and thousands of sailors had died due to ships being lost or colliding with shorelines. Latitude, or position in the north-south direction, could be accurately estimated by using a quadrant to measure the altitude of the North Star in the northern hemisphere or the Sun in the southern hemisphere. Determining longitude, or position in the east-west direction, was more complicated. Because the Earth continually turns on its axis, there was nothing visible from one longitude that was not seen in the same day from every other longitude. During the course of a day, mariners would see the same Sun, the same Moon, and the same stars. However, they would see them at different times, so the key to determining longitude was an accurate clock. If a ship somehow had an accurate clock that was synchronized at a reference longitude, for example at zero degrees longitude (what later became known as the Prime Meridian), sailors could navigate by comparing their local time to the shipboard clock. Local time could be obtained from the sky, for example by waiting until the Sun was directly overhead to determine noon. For every four minutes of difference between local time and the ship's clock, sailors would then know they were one degree east or west of their reference longitude.

To solve the longitude problem, the British Board of Longitude began offering prizes in 1714. The top prize was for £20,000 (about five million dollars today), to be awarded for a method of continuously determining longitude to within thirty nautical miles. At the equator, one degree of longitude

Fig. 8. John Harrison's marine chronometer (H4), 1759.

equals about 69 miles, so this meant that longitude must be kept within about half a degree. The terms of the prize stated that this accuracy would have to be held during an entire outward voyage from England to the West Indies, a trip that would probably last at least sixty days. Half a degree translated into two minutes of time, so the clock could gain or lose no more than two seconds per day. Harrison had already built clocks that could easily do this on land, but they would be unable to function on ships tossed about by the sea.

In one of the greatest examples of perseverance in human history, Harrison pursued the longitude problem for more than forty years. He built a series of five clocks, now known as H1 through H5. Nearly thirty years were invested into the first three clocks, and H3 alone took nineteen years to complete. Unable to meet the prize requirements, Harrison finally abandoned the idea of building a large sea clock and focused on building H4, completed in 1759. Much smaller than its three predecessors, H4 looks like an oversized pocket watch (Fig. 8) with a dial that was about 13 cm in diameter. It used a heavily modified verge escapement with pallets made of diamond. The oscillator was a spring and balance wheel that was compensated for temperature changes. Harrison wrote that there was nothing "more beautiful or curious in texture than this my watch or Timekeeper for the Longitude…. I heartily thank Almighty God that I lived so long, as in some measure to complete it" [2], [3], [11], [13–16].

The accuracy of H4 was so advanced for its era that it remains the most renowned of all man-made clocks. Its first sea trial was a round trip from England to Jamaica that began in November 1761 and lasted for 147 days. John Harrison had grown too old for sea travel, so his son William accompanied H4 on the voyage. Adjusted for rate, H4 lost only 1 minute and 54.5 seconds during the voyage, keeping longitude within half a degree for twice the duration and distance specified. However, there was a dispute about the rate correction (2.66 s/day) that had not been declared before the voyage, and Harrison was denied the prize.

After much negotiating, a second sea trial finally began in March 1764. William again sailed with H4, this time on a trip to Barbados. The rate correction was declared prior to the voyage, and to avoid disputes, four different mathematicians were selected to independently calculate the results. During the 46 day voyage, the average estimated error was 39.1 seconds, amounting to less than 10 nautical miles of longitude, or more than three times better than the prize requirements. Unfortunately, the Board of Longitude stubbornly refused to officially award the prize to Harrison or to anyone else. However, Harrison did eventually receive most of the money late in life. He was paid £10,000 when he allowed H4 to be copied in 1765 and another £8,750 in 1773 when he was 80 years old. The most famous clockmaker of all, John Harrison passed away in 1776 [15], [16].

The Shortt Free-Running Pendulum

The height of mechanical timekeeping was reached when the British railway engineer William Hamilton Shortt patented a new type of pendulum clock in 1921. The Shortt clock became a mainstay of astronomical observatories in the 1920s and 1930s and suggested for the first time that the Earth was not a perfect clock – it was possible to detect seasonal variations in its rotational rate.

The Shortt clock was a complex electromechanical device with two pendulums – one a slave and the other a master. In a traditional pendulum clock, the single pendulum is subjected to several tasks that disturb its regularity. Power has to be continuously applied to the pendulum to keep it swinging and its swings had to be counted in order to keep and display time. In the Shortt clock, most of this work was done by the slave pendulum. For the most part, the master pendulum was left alone to swing freely in a vacuum chamber. The master pendulum was disturbed only once every 30 seconds, when it briefly contacted a gravity lever escapement that gave it the energy it needed to keep swinging. The motion of the gravity lever then sent an electrical pulse to a mechanism that kept the slave pendulum synchronized [3]. The free running master pendulum made the Shortt clock more accurate than all previous clocks. Many were on record as gaining or losing no more than one second per year, with perhaps a few seconds per year being

March 1928 THE HOROLOGICAL JOURNAL

THE
PERFECT CLOCK

ASTRONOMERS have now stated that the RATE of the "SYNCHRONOME" FREE PENDULUM at

GREENWICH OBSERVATORY

but for the very small growth of the Invar Rod which was known and forecasted, has been INVARIABLE. Over a period of nearly TWELVE MONTHS while it was under the closest observation.

NO CHANGE OF RATE COULD BE DETECTED.

THE
SYNCHRONOME FREE PENDULUM

was designed by Mr. W. H. SHORTT, M.Inst.C.E., in combination with the Synchronome System, the invention of Mr. F. HOPE-JONES, M.I.E.E., F.R.A.S.

PROFESSOR W. de SITTER of Leyden, discussing in "NATURE" of Jan. 21st, 1928, this entirely new conception of the possibilities of clocks, asks—

"Can these wonderful clocks be of use as a control upon the uniformity of astronomical time like the motion of the moon, the sun, and the planets? Can the handiwork of man compete with the heavenly bodies?"

All who are interested in this astonishing achievement, and who wish to know more of the SYNCHRONOME SYSTEM, particularly its applications to commercial purposes in the supply of UNIFORM AND ACCURATE TIME for Industrial Establishments and Institutions, should apply to:

THE SYNCHRONOME Co., Ltd.,
32 & 34, CLERKENWELL ROAD,
LONDON, E.C.1.
Tel.: No. CLERKENWELL 1517.

MENTION THE "HOROLOGICAL JOURNAL."

Fig. 9. A 1928 advertisement for a dual-pendulum Shortt clock.

typical [17]. Fig. 9 shows a 1928 advertisement for the Shortt clock, where it was billed as "The Perfect Clock."

The remaining articles in this series will illustrate that the Shortt clock was far from perfect; the accuracy of pendulum clocks was surpassed within a few years after the advertisement was published. However, pendulum clocks remain especially useful for illustrating the close relationship between frequency and time.

For example, I noted earlier that oscillators are at the heart of all modern clocks. Oscillators run at a frequency f that is the reciprocal of the period of oscillation, T; therefore $f = 1/T$. Conversely, the period is the reciprocal of the frequency: $T = 1/f$. This relationship is particularly easy to see with a pendulum clock. If a pendulum swings back and forth once per second, the period (T) is 1 s and the frequency (f) is 1 Hz. I initially said that a clock is a device that measures and counts time intervals, and, again, this is easy to see with a pendulum clock. It can keep time by simply counting the swings of its pendulum to accumulate seconds. If the frequency of the pendulum isn't exactly 1 Hz, the clock will either gain or lose time, because a clock can only be as good as its oscillator.

These basic principles of time measurement apply to all modern clocks. In the Second part of this series, we'll begin looking at clocks where the "pendulum" swings much faster and explore the evolution of quartz clocks.

References

[1] J. H. Breasted, *Ancient Times: A History of the Early World*, Chicago: Ginn and Company, 1916.

[2] J. E. Barnett, *Time's Pendulum: The Quest to Capture Time – From Sundials to Atomic Clocks*, New York: Plenum Press, 1998.

[3] D. Howse, *Greenwich Time and the Longitude*, London: Philip Wilson Publishers, Ltd., 1997.

[4] P. K. Seidelmann, *Explanatory Supplement to the Astronomical Almanac*, Mill Valley, California: University Science Books, 1992.

[5] O. Neugebauer, *The Exact Sciences in Antiquity*, Dover Publications, 1969.

[6] G. Dohrn-Van Rossum, *History of the Hour: Clocks and Modern Temporal Orders*, University of Chicago Press, 1996.

[7] Ptomely, *Ptomely's Almagest*, translated by G. J. Toomer, Princeton University Press, 1998.

[8] F. Cajori, *A History of Mathematics*, MacMillan and Co., 1893.

[9] C. E. Stephens, *On Time: How America Has Learned to Live by the Clock*, Smithsonian Institution, Bullfinch Press, 2002.

[10] M. Bloch, *Feudal Society*, translated by L. A. Manyon, University of Chicago Press, 1961.

[11] D. S. Landes, *Revolution in Time: Clocks and the Making of the Modern World*, Cambridge: Harvard University Press, 2000.

[12] F. G. Major, *The Quantum Beat: The Physical Principles of Atomic Clocks*, New York: Springer-Verlag, 1998.

[13] D. Christianson, *Timepieces: Masterpieces of Chronometry*, Toronto: Firefly Books, 2002.

[14] D. Sobel, *Longitude: The True Story of a Lone Genius Who Solved the Greatest Scientific Problem of His Time*, New York: Walker Publishing, 1995.

[15] H. Quill, *John Harrison: The Man who found Longitude*, New York: Humanities Press, 1966.

[16] W. J. H. Andrewes, ed., "The quest for longitude," *Proc. Longitude Symposium*, Harvard University, Nov. 1993.

[17] T. Jones, *Splitting the Second: The Story of Atomic Time*, Bristol and Philadelphia: Institute of Physics Publishing, Bristol and Philadelphia, 2000.

Michael A. Lombardi (michael.lombardi@nist.gov)(Member, IEEE) has worked in the Time and Frequency Division of the National Institute of Standards and Technology (NIST) since 1981. His research interests include remote calibrations, international clock comparisons, disciplined oscillators, and radio and network time signals. He has published more than 90 papers related to time and frequency measurements. Mr. Lombardi is the chairman of the Interamerican Metrology System (SIM) time and frequency working group, and an associate editor of *NCSLI Measure: The Journal of Measurement Science*.