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Measuring Time

A History of Precision Clocks

UGears

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1 Measuring Time

Understanding how time is defined and measured is critically important in our technologically based society. In financial systems, for example, knowing the exact time that a buy or sell order is executed is extremely important. Failure to execute an order in the proper sequence could mean the lost of millions of dollars. The speed that you drive your car down the road is measured in miles per hour. Exceeding the posted speed limit can be costly. Cell phones, the internet, and the GPS Global Positioning System, depend on very accurate time measurements. These systems would not be possible with out atomic clocks. Navigation of spacecraft to Mars and throughout the solar system rely on precise time synchronization between the world wide network of ground stations. Electrical power distribution systems depend on the accuracy of atomic clocks to maintain control and stability of the electrical power grid. And the list goes on and on. This chapter looks at how the definition and measurement of time has evolved from early civilizations to the present.

2 Early Western Civilizations

Anthropology research indicates that early humans inhabited the Earth more than 2 million years ago. These early people migrated out of Africa into Europe, Asia and Southeast Asia. Based on stone artifacts, China was inhabited as early as 1.6 million years ago. To the north, Neanderthals populated Europe and parts of Asia from 400,000 to 30,000 years ago. Modern man (homo sapiens) emerged in Africa about half way through the Neanderthal period, around 200,000 years ago. They also migrated out of Africa arriving in China and southeast Asia about 100,000 years ago. Because of its colder climate, population of Europe occurred later beginning around 45,000 years ago. Homo sapiens in Europe competed with and gradually replaced Neanderthals who already lived there. The Neanderthals became extinct 30,000 years ago. Studies indicate that homo sapiens existed in Australia 50,000 to 60,000 years ago and crossed over the land bridge from Asia to the Americas within the past 30,000 years or so. The last ice age period of maximum glaciations occurred from 21,000 to 24,000 years ago.

For most of the last 2 million years humans were primarily gathers and hunters, living in small nomadic tribes wandering in search of food. Their diet included berries, fruits, nuts, roots, leafy vegetables, eggs as well as meat scavenged from the carcasses of dead animals who had died naturally or were killed by predators. Hunting evolved as tools and weapons were developed.

About 10,000 years ago the practice of cultivating grain-bearing grasses and domesticating animals emerged, marking the important shift from hunting and gathering to agriculture based subsistence. Agriculture was particularly productive in river valleys with abundant water and fertile soil. These valleys attracted a growing population of people who established permanent settlements along the rivers. Early civilizations grew out of these settlements.

The first known civilizations in the west developed along the Tigris and Euphrates river system in about 3500 BC in a region known as Mesopotamia. This region, north of the Persian Gulf, is now southeastern Iraq, see Figure 1. Mesopotamian included the Sumer, Akkadian, Babylonia, and Assyrian empires. The indigenous Sumerians and Babylonians dominated Mesopotamia from 3500 BC to the fall of Babylon in 539 BC. The region was conquered by Alexander the Great in 332 BC and became part of the Greek Empire.

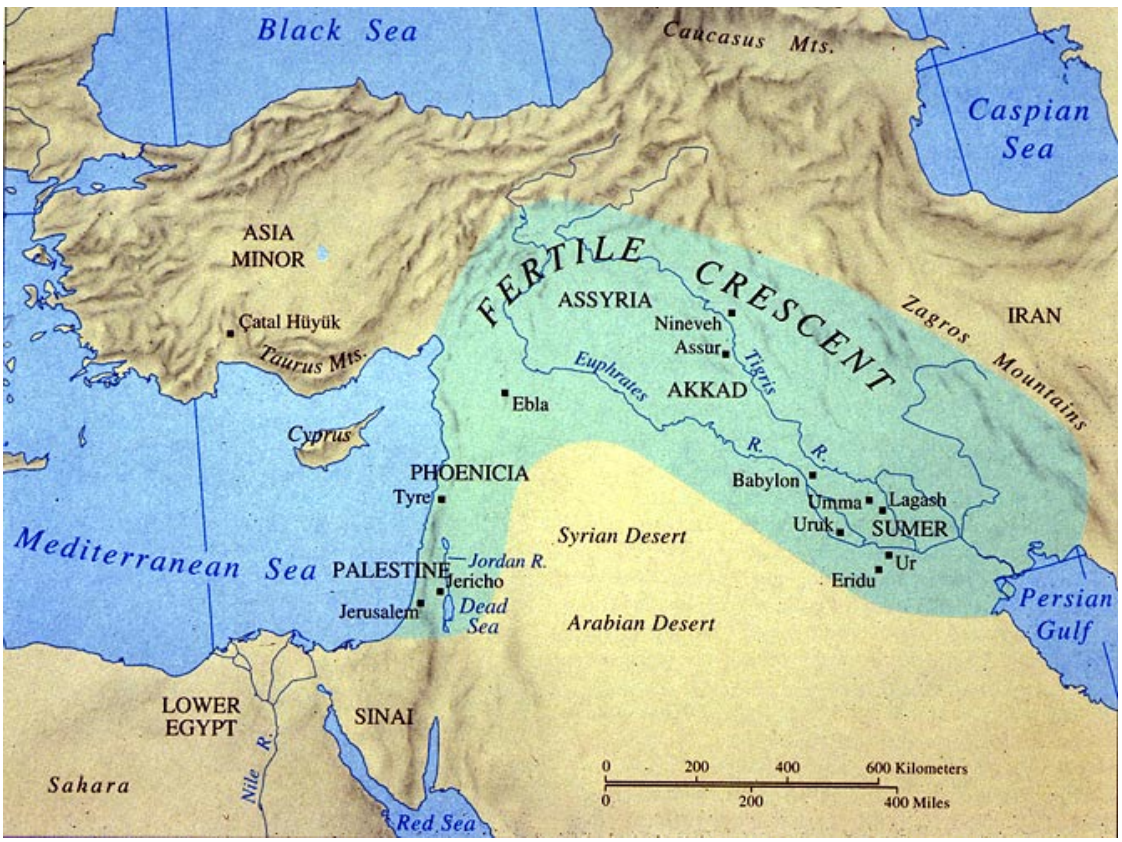


Figure 1 Mesopotamia (source: owlcation.com)

The Mesopotamians developed one of the earliest known forms of writing. Called Cuneiform script, it was written on clay tablets using blunt reeds as stylus. Cuneiform writing began as pictographs and gradually evolved into a system of alphabetic signs.

The Egyptian civilization developed along the Nile River, as shown in Figure 2, with the Egyptian 1st Dynasty dating back to 3100 BC. The 1st Dynasty marks the beginning of Egyptian history following unification of Upper and Lower Egypt.

Most of the Egyptian Pyramids were built from 2670 – 2392 BC during the Old Kingdom (the 3rd through the 5th Dynasty) in Lower Egypt. A second period of pyramid building occurred from 1991 – 1759 BC during the Middle Kingdom (the 12th and 13th Dynasty). The Valley of the Kings in Upper Egypt was the principal burial place of the pharaohs and privileged nobles during the Egyptian New Kingdom. The New Kingdom includes the 18th – 20th Dynasties from the 16th through the 11th century BC.

The 30th Dynasty was the last native ruling dynasty of ancient Egypt. The dynasty was overthrown by the Persians in 343 BC who were themselves conquered by Alexander the Great in 332 BC. Following the untimely death of Alexander in 323 BC, Ptolemy Lagides, one of Alexander's generals, declared himself Pharaoh of Egypt and established the Ptolemaic Kingdom. The Ptolemaic Kingdom became a powerful Greek Hellenistic state which included all of Egypt and extended north to Syria (Figure 3). Alexandria was established as the capital city. Construction of the new city in the Nile River delta began shortly after Alexander's liberation of Egypt from Assyria in 332 BC. In accordance with Alexander's wishes, Alexandria was constructed on a lavish scale to be the world center of commerce, culture, and learning. Alexandria was all of that. It quickly grew to become one of the greatest cities in ancient times. Only Rome exceeded Alexandria in size and wealth. The city survived for over 900 years, falling to the Arabs in 641 AD. The powerful Ptolemaic Dynasty lasted for nearly 300 years, ending with the death of Cleopatra VII and the Roman conquest in 30 BC.

Figure 2 Ancient Egypt (source: questgarden.com)

Figure 3 The Greek Empire (source: pinterest.com)

3 Babylonian Astronomers and Mathematicians

The Babylonians were outstanding astronomers and mathematicians. The history of both modern day astronomy and mathematics trace back to the early Babylonians. The Babylonians were the first to recognize that astronomical phenomena were periodic. Using this knowledge they applied mathematics to predict the occurance of astronomical events.

Babylonian mathematicians utilized a sexaqesimal base 60 numbering system which they inherited from the Sumerians, who had developed it around 2000 B.C. Why they chose 60 as their number base is unknown. The most likely explanation is its divisibility by 1, 2, 3, 4, 5, 6, 10, 12, 15, 20, 30 and 60. The Babylonian numbering system (unlike the Egyptian, Greek, and Roman numbering systems) was a true place-value system similar to our current day base ten system in which a number like 524 = 5x100 + 2x10 + 4x1. The Babylonians were the first to use this advanced type of numbering system. The place-value numbering system allowed the Babylonians to make great advances in the field of mathematics.

From the perspective of the Babylonians, and other early cultures, the Sun revolved around the Earth. It became apparent to the Babylonian astronomers that the Sun also traveled through the background of fixed stars. While they could not directly see the Sun's position against the stars (the Sun was only visible during the day), they inferred its position based on the time specific stars rose and set each night. They also observed that the time a particular star rose changed each night, rising again at the same time approximately 360 days later. (It may be that they observed the time to actually be 365 days but rounded the period back to 360 days for consistence with their sexaqesimal numbering system). In addition, they observed that approximately 12 new moons occurred during the 360 days. The ecliptic is the apparent path which the Sun follows as it travels through the background stars. Each day the Sun appeared to move (1/360) th of the distance around the ecliptic circle.

The Babylonian sexaqesimal numbering system and their astronomical observations were closely related. Old Babylonian inscriptions and tablets indicate that they used a 360 day per year calendar consisting of 12 months with 30 days per month. Notices that 360, 30, and 12 are all multiples or factors of their base 60 numbering system. A 13th month was added every six years to keep the calendar aligned with the seasons. One of the earliest recorded uses of 360 as the total days in a year is found in the Hebrew Bible, Genesis 8–9 in which the Great Flood is described as lasting for 12 months of 30 days each.

It is believed that the Babylonians divided the circle into 360 equal parts (360 degrees) based on the movement of the Sun along the ecliptic. Adhering to the sexaqesimal numbering system, the Greek astronomers later divided a degree into 60 minutes and a minute into 60 seconds.

4 Measuring Time in Ancient Egypt

The concept of time during early civilizations was based on natural events that indicated significant changes in the environment. Seasonal winds and rains, the flooding of rivers, flowering of trees and plants, breeding cycles of animals and the migration of birds were all very important events to them. The phases of the moon, movement of the sun, and changes in the position of stellar constellations were early and natural methods of measuring time, particularly for predicting the arrival and duration of particular seasons of the year.

Based on these events, the Egyptians developed a calendar by at least the middle of the Old Kingdom (ca. 2450 BC), and probably several centuries before that. Like most agricultural societies, it is believed that the ancient Egyptians organized their calendar according to the cycles of the moon and the agricultural seasons. Similar to the Babylonians, the Egyptian calendar consisted of twelve months (twelve lunar cycles) of thirty days each (360 days per year) with an additional 5 days added at the end of each year. Each month was three weeks long with ten days per week. The start of a month was marked by the disappearance of the waning moon. In addition, the year was divided into three seasons of 4 months each. It is believed that the Egyptian New Year occurred on the day that the star Sirius reappeared after its 70 days below the horizon. Sirius being the brightest star in the sky. The reappearance of Sirius also coincided with the beginning of the annual Nile River flooding, flooding that brought life-giving waters down from the highlands of Ethiopia.

Most scholars agree that the Egyptian day began at dawn, just before sunrise, rather than at sunset. By 1100 BC Egyptian astronomers were using a collection of 24 stars evenly spaced across the night sky to measure the passage of time during the night. They subdivided the night into12 equal segments of time by noting when these specific stars rose and set. Similarly, sundials were used to divide the period of daylight into 12 equal segments creating a daily cycle of 24 segments which we associate with hours. However, sunrise and sunset varies seasonally. Consequently the length of the Egyptian hour also varied seasonally.

5 The First Clocks

Knowing the approximate time of day became more important as civilizations evolved and social interactions became more complex. For example, knowing whether it was morning or afternoon had significants. This required some means of determining when noon occurred.

Most historians credit the Egyptians with being the first civilization to use clocks.

The gnomon (Figure 4) was probably the first device used for indicating the time of day. It was developed some time prior to 3500 BC. It consisted simply of a vertical stick stuck into the ground. The length of the shadow cast by the stick gave an indication of time of day.

Figure 4 Gnomon – The earliest sundial (source: electronics.howstuffworks.com)

Between 2500 - 2000 BC the Egyptians began building tall tapering four-sided monuments known as obelisks. Obelisks (Figure 5) symbolized the Sun God Ra and were often 50 to 60 feet high. Obelisks were commonly used in ancient Egyptian architecture, frequently placed in pairs at the entrance of temples. The moving shadows formed by an obelisk created a kind of sundial enabling people to divide the day into two parts by indicating when noon occurred. Later, marks were placed around the base of the obelisk to show smaller divisions in time. The length of the shadow at noon was also used to identify the longest and shortest day of the years. The Washington Monument in Washington D.C is a modern day example of a large obelisk.

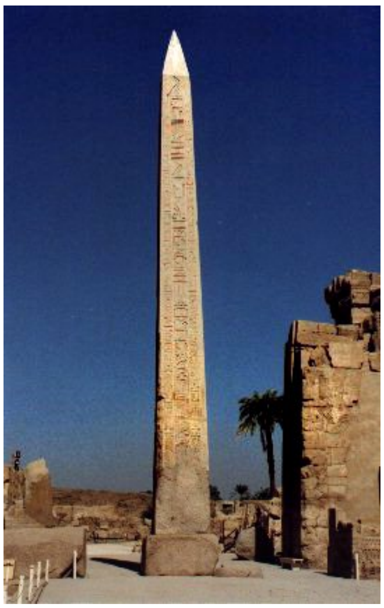


Figure 5 Ancient Egyptian Obelisk (source: pinterest.com)

Beginning during the New Kingdom (ca. 1500 BC) there is evidence that shadow clocks, sundials, and water clocks were used to measure time. However, there is no evidence that the Egyptians subdivided time into segments shorter than an hour. They had no concept of minutes or seconds.

It is believed that the first Egyptian sundial was the T-shaped instrument shown in Figure 6 consisting of a horizontal stick and crossbar. In the morning the end of the stick with the crossbar was placed facing east, and in the afternoon it was placed facing west. The crossbar cast a shadow on the stick. At noon the shadow was very short, while the shadow was long early in the morning or late in the afternoon. The shadow falling on marks scribed on the stick indicated relative time of day.

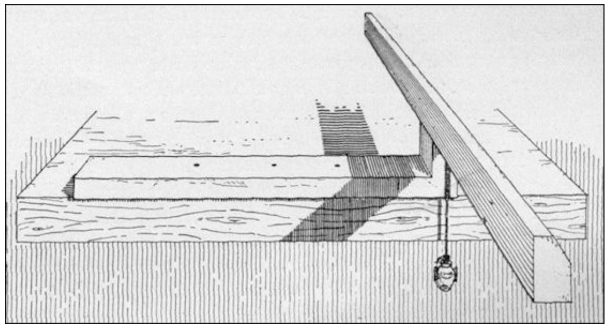


Figure 6 Egyptian T Sundial (source: technologyuk.net)

Egyptians and Babylonians were using clepsydras (water clocks) as early as 1400 BC. In its earliest form, a clepsydra consisted of a container filled with water (Figure 7). A small hole near the bottom of the clepsydra allowed water to slowly flow out of the clepsydra at a relatively constant rate. The clepsydra usually had a slanted interior surface to allow for decreasing water pressure as the water drained from the clepsydra. Horizontal lines scribed on the interior surface indicated how much water had flowed out of the clepsydra, and thus how much time had elapsed since the clepsydra was last filled. In daily use, the clepsydra was calibrated using a sundial. That is, the clepsydra was filled with water at a particular time of day as indicated by the sundial. Clepsydra could, of course, be used both day and night. Clepsydras were probably the most accurate clocks of the ancient world. Modern tests indicate that these ancient clocks were accurate to about fifteen minutes per day.

Figure 7 Egyptian Clepsydra (source: daviddarling.info)

Numerous sundials of various designs were developed in the centuries that followed. Sundials were used to tell the time of day through 1200 AD when they were gradually replaced in Medieval Europe by mechanical clocks.

Figure 8 Greek Sundial (source: Electronics | HowStuffWorks)

Figure 9 Roman Sundial (credit: Mark Goddard)

Shadow clocks and sundials keep apparent solar time, that is, time based on the apparent motion of the Sun. However, the Earth's non-circular orbit combined with the tilt of its axis causes the apparent motion of the Sun to vary with the seasons. Consequently, the time indicated by a sundial also varies with the seasons. For example, the length of an hour measured on a sundial can change by as much as 16 minutes from one season to another. The concept of mean (non-varying) solar time did not occur until around 150 AD when it was defined by Claudius Ptolemy.

The design of water clocks continuously evolved over the 2,600 years during which they were extensively used. The Greeks and Romans built complex water clocks using water wheels, gears, and escapements to measure the flow of water out of or into the device, thus achieving more accurate measurements of time (Figure 10). Water clocks continued in use until finally replaced in medieval Europe by the first mechanical clocks in about 1200 AD.

Water clocks, however, had limitations. Water froze in cold climates and quickly evaporated in warm regions. In addition, few people had access to water clocks. They were primarily found in palaces and other places of wealth.

Small intervals of time were important throughout history, for example how long a member of the Roman Senate was allowed to speak or a Babylonian landowner was allowed to divert water onto his land. These small intervals of time were typical measured with water clocks and later hour glasses (Figure 11).

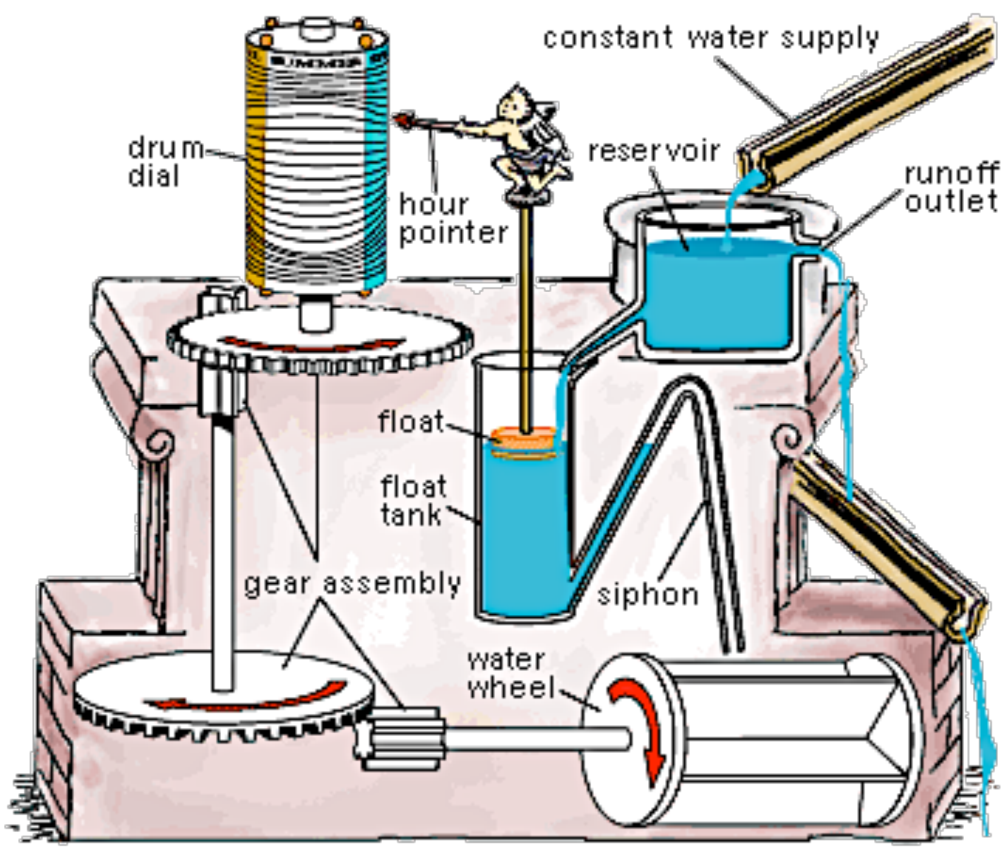


Figure 10 First century AD roman water clock (source: UNRV.com)

Figure 11 Typical Hourglass (source: shutterstock.com)

The hour remained the smallest division of a day until European development of accurate mechanical clocks during the 16th century AD. Prior to the 16th century, minutes and seconds had no meaning to the general public. Minutes and a seconds became relevant only when mechanical clocks with the accuracy to display these units of time were built, that is, clocks with minute and second hands. Until then, minutes and seconds had meaning only to astronomers who used these units in their astronomical observations.

6 The Greek Astronomers

The Greeks acquired much of their early understanding of astronomy and mathematic from the Babylonians. This knowledge was gained through trade and through Alexander The Great's conquest of Egypt in 332 BC and Persia in 330 BC. Alexander ordered historical Babylonian astronomical records translated from Cuneiform into Greek with the translations subsequently sent to Greece.

Eratosthenes (276 – 194 BC) was one of the early Greek astronomers who made use of the astronomical knowledge gained from the Babylonians. Eratosthenes lived in Alexandria during the Egyptian Ptolemaic Dynasty when Egypt was a Greek Hellenistic State. With the knowledge gained from the Babylonians, Eratosthenes used the sexagesimal system to divide a circle into 60 parts. He was also able to calculated the circumference of the Earth. He was the first to do so. Eratosthenes understood well the position of the Sun during summer solstice in Egypt. It was known that the Sun reflected off the water at the bottom of a deep well in the Egyptian city of Swenet at exactly noon on the day of the summer solstice. This event could only occur at Swenet, and other locations along the Tropic of Cancer, when the Sun was at its zenith (directly overhead). Knowing this, Eratosthenes used a gnomon to measure the Sun's angle of elevation in Alexandria at noon on the summer solstice. The angle that he measured was 1/50th of a circle in a direction south of the zenith. Assuming that the Earth was spherical, and that Alexandria was due north of Swenet, he concluded that the arc distance from Swenet to Alexandria must be 1/50th of the Earth's circumference. He also knew the distance between Swenet and Alexandria based on generations of Egyptian surveying records. Using this information he calculated that the circumference of the Earth was 28,968 miles, an error of about 16.3% .

Eratosthenes is also considered the Father of Geography. Working with information on exploration and travel available to him at the Alexandria Library, he create the first map of the world as it was known at that time. He also developed a system of grids which he placed over his map to estimate the distance from one location to another. This system of grids was the first attempt to create a geographic coordinate system.

Greek astronomer and mathematician Hipparchus (190 – 120 BC) is considered the greatest astronomical observer of ancient Greece. He lived at least part of his life on the Greek island of Rhodes located in the eastern Aegean Sea. Hipparchus quantitatively and accurately modeled the motion of the Sun and Moon, discovered and measured the Earth's precession (the slow change in the orientation of Earth's axis), and compiled the first comprehensive star catalog of the western world, using in part techniques acquired from the Babylonians. In addition, he developed trigonometry, constructed trigonometric tables, and solved problems of spherical trigonometry. Based on this work, he was able to develop a reliable method for predicting solar eclipses. He also expanded on Eratosthenes' coordinate system. Hipparchus normalized the east to west lines of latitude, making them parallel, and devised a system of 360 lines of longitude that ran north to south from pole to pole encompassing the Earth. He insisted that geographic maps must be based only on astronomical measurements of latitudes and longitudes and triangulation for finding unknown distances.

In addition to his other accomplishments, Hipparchus established an hour as 1/24th of a day, eliminating the season variation in the length of an hour as originally defined by the early Egyptians.

Most of what we know concerning the work of Eratosthenes, Hipparchus and other early Greek astronomers comes from the treatise "Almagest" written by Claudius Ptolemy (a resident of Alexandria, Egypt) around 150 AD. Ptolemy explained and expanded on Hipparchus' work by subdividing each of the 360 degrees of latitude and longitude into smaller segments. Using the sexaqesimal numbering system, each degree was subdivided into 60 parts, each of which was again subdivided into 60 smaller parts. The first division, or first minute, was shorted to simply a "minute." Similarly, the second segmentation, or "second minute," became a second. Whether definition of the minute and second was actually the work of Ptolemy or that of Hipparchus is unclear.

7 The Roman Republic and Empire

The Roman Republic began in 509 BC, approximately 250 years after the founding of the city of Rome. It ended in 27 BC with the fall of the republic and establishment of the Roman Empire. In nearly 500 years of existence, the republic expanded throughout Italy, Spain, France, Greece, parts of northern Africa and much of the eastern Mediterranean.

A series of civil wars, climaxing with the assassination of Julius Caesar, marked the end of the republic and the beginning of the Roman Empire characterized by its autocratic form of government. The following 200 years was a period of unprecedented stability and prosperity. The empire reached its greatest expanse during the reign of Trajan from 98 – 117 AD, its territory including England, all of western Europe, the Baltic states, Turkey, the middle east, Egypt, and north Africa (Figure 12). The empire began to decline in the 4th century AD culminating in the fall of its central government in 476 AD.

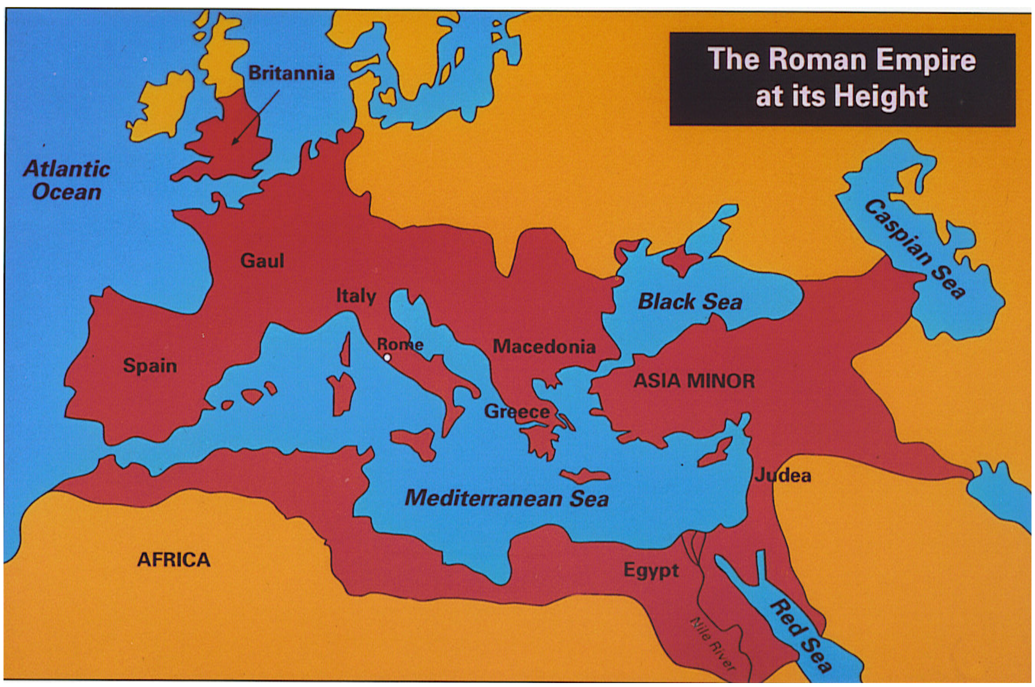


Figure 12 Roman Empire 98 – 117 AD (source: Printerest)

For nearly 1,000 years Rome controlled most of the western civilized world, assimilating the cultures of the lands that it conquered and propagating the resulting Roman culture throughout the region.

The Romans used the 24 hour day originated by the Egyptians and refined by the Greeks. They considered the hour to be the smallest practical unit of time.

8 The Arabic Numbering System

Following the fall of Rome and throughout the Dark Ages of Medieval Europe, the major Islamic cities of Baghdad, Cairo, and Cordoba became the intellectual centers for science, philosophy, mathematics, and education in the western world. During this period the Muslim world was a collection of cultures that drew together and significantly advanced the knowledge gained from the ancient Persian, Egyptian, Greek, and Roman civilizations. Many classic works of antiquity that might otherwise have been lost were translated into Arabic and Persian and later into Turkish, Hebrew, and Latin.

One of the deterrents to advancements in science was the lack of an adequate number system. Many of the ancient cultures used number systems based on ten. The Egyptian hieroglyphs in existence since 3000 BC used a purely decimal system. The classical Greek numbering system used powers of ten as did Roman numerals, both of which included an intermediate base of 5. However, all of these were non-positional numbering systems requiring a large number of numeric symbols. For example, the Egyptian system used different symbols for 1-9, 10–90, 100-900, and 1000-9000 as shown in Figure 13. In contrast, the Babylonians used the sexaesimally base 60 system. While the Babylonian numbering scheme was a positional system, using a base of 60 was complex to work with. Performing calculations with these early numbering systems was tedious at best.

Between the 1st and 4th century AD mathematicians in India developed a numbering system that was both positional and base 10. Known as the Hindu system, it utilized only ten numeric symbols representing the numbers 0 through 9. The actual symbols used to represent the ten numbers are independent of the system itself, and in fact various sets of symbols have been used. Calculations using the Hindu system were much simpler than in any previous number system.

The Hindu system was introduced to the Islamic mid east by Persian mathematician Khawarizmi who wrote the book "On the Calculation with Hindu Numbers" in about 825 AD, and also by Arab mathematician Al-Kindi who wrote four volumes "On the Use of the Indian Numerals" around 830 AD.

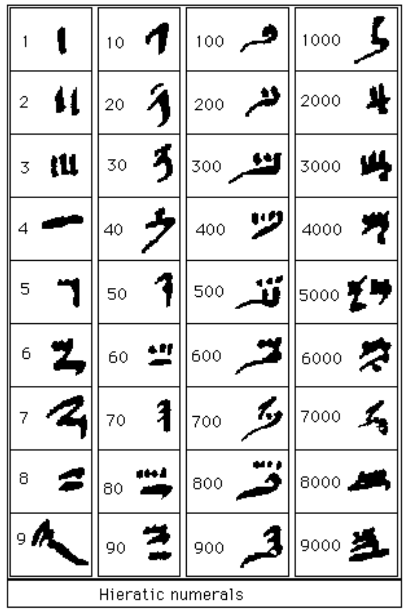


Figure 13 Egyptian Numerals (source: mathshistory.st-andrews.ac.uk)

The Arabic-Hindu number system was brought to Europe by Leonardo Fiobonacci in 1202 AD. The number system is called the Arabic number system because the Europeans obtained it from the Arab mathematicians. It has been used by European mathematicians since the 12th century. In the 15th century the Arabic-Hindu numbering system replaced Roman numerals as the system used by the general public. The Arabic-Hindu number system (Arabic system using the early Europe nomenclature) is today the most commonly used number system in the world.

9 Astronomical Use of Minutes, Seconds, Thirds, and Fourths

Al-Biruni (973-1048 AD) is regarded as one of the greatest scholars of the medieval Islamic era. He had considerable knowledge in the fields of physics, mathematics, astronomy, and the natural sciences, as well as being conversant in multiple languages including Persian, Arabic, Greek, and Hebrew. A large part of his life was spend in what is now Afghanistan.

Al-Biruni's astronomical work included carefully studying the motion of the moon. It is reported that he predicted the occurrence of new moons as a number of days, hours, minutes, seconds, thirds, and fourths following a specific date. Using this sexaesimally numbering approach, a minute is 1/60th of an hour, a second is 1/60th of a minute, a third is 1/60th of a second, and a fourth is 1/60th of a third. Thus a second literally means the "second" 1/60th division of an hour. It is unlikely that he had any instruments capable of measuring time to the precision of his calculations.

In 1267 Roger Bacon (English philosopher, and Franciscan friar) created tables indicating when full moons would occur. Using the same sexaesimally approach as Al-Biruni, entries in his tables specified the number of hours, minutes, seconds, thirds, and fourths, following noon on specified calendar dates, when a full moon would occur. Again, there were no clocks in existence capable of measuring time to that accuracy.

10 First Mechanical Clocks

No one knows for sure who built the first mechanical clocks. Most historians agree that mechanical clocks first appeared in Italy in the early part of the fourteenth century. There is evidence that Italian public tower clocks were in use by 1321.

Most of the early mechanical clocks were built for cathedrals. The Salisbury cathedral clock in England (Figure 14), is believed to have been built in 1386. It is claimed to be the oldest working clock in the word. These first clocks were relatively large heavy pieces of machinery that were installed in church towers where they could be seen or heard throughout the town, hence their name tower clocks. The early clocks did not have a clock face as we know it today. Instead they were designed to strike each hour of the day using bells and bell hammers that were part of the clock mechanism.

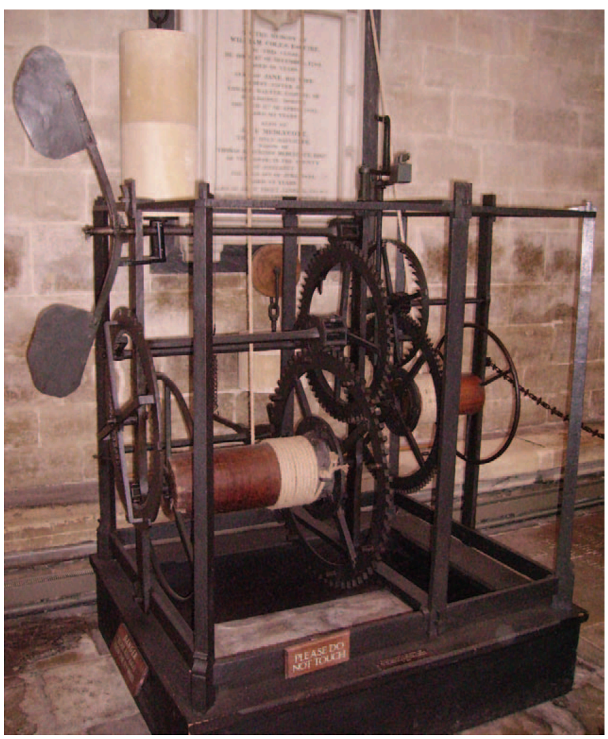


Figure 14 Salisbury cathedral clock in England (source: historiesoftheunexpected.com)

The mechanism of an early mechanical clock is shown in Figure 15. The clock was driven by a heavy weight connected to the clock by a rope wrapped around the geared cylinder at the bottom of the clock. The weight and cylinder can easily be seen in the view on the right. The saw toothed escapement wheel at the top right of the clock, known as a crown wheel (because of its appearance), controlled the clock's speed, that is, how fast the clock dial moved and how slowly the clock weight dropped. Notice that this clock like most of the early mechanical clocks has only an hour hand.

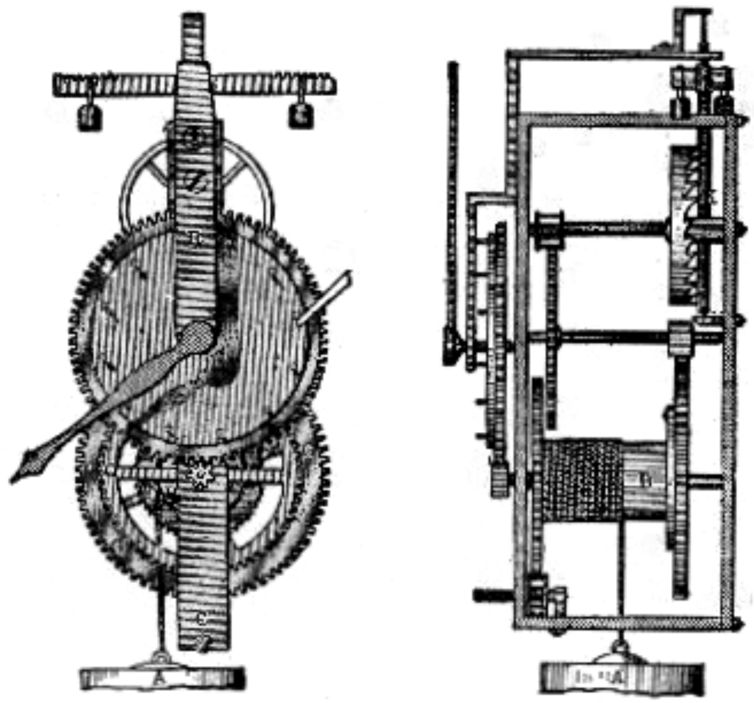
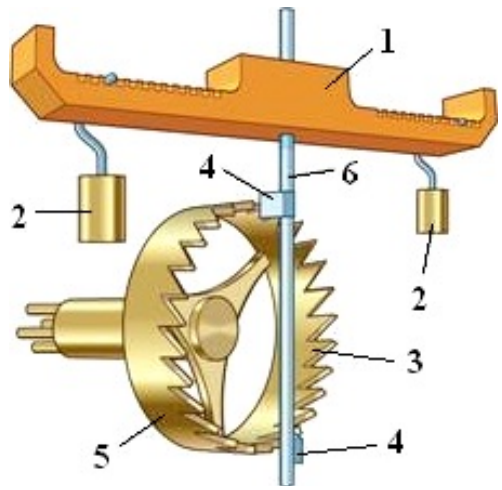


Figure 15 Early mechanical clock (source: abbyclock.com)

The early clocks used a verge and foliot escapement mechanism, shown in Figure 16. The foliot is the horizontal segment of the mechanism with small weights at both ends. The verge is the vertical rod which alternately engages the top and bottom of the crown wheel by means of two metal tabs called pallets. The pallets are not parallel, but oriented at an angle so that only one pallet at a time engages the teeth of the crown wheel. The clock gears, driven by the clock's heavy hanging weight, turn the crown wheel causing a tooth to push against one of the pallets. The verge and foliot rotates in one direction as the tooth pushes past the pallet. As it does so, the second pallet is rotated into the path of the teeth on the opposite side of the wheel. One of the teeth contacts and pushes against the second pallet forcing the verge and foliot to rotate in the opposite direction. Consequently, the verge and foliot swings back and forth driven by the crown wheel. Each swing of the verge and foliot allows one tooth of the crown wheel to pass, advancing the wheel by one tooth position. This oscillating motion of the verge and foliot controls how fast the crown wheel and the other gears in the clock turn. The speed at which the foliot swings back and forth is controlled by the small weights suspended from the foliot. Moving the weights outward toward the ends of the foliot slows the rotation of the foliot, slowing down the speed of the clock. Moving the weights inward speed up the clock.



1 – Foliot; 2- Weight; 3-Crown wheel tooth; 4-Pallet; 5- Crown wheel; 6 - Verge

Figure 16 Verge and foliot escapement mechanism (source: britannica.com)

For nearly 300 years the verge and foliot mechanism was the primary escapement used in mechanical clocks.

The early verge and foliot clocks were not very accurate. They probably lost or gained one to two hours per day, making them even less accurate than the water clocks that preceded them. The best verge and foliot clocks achieved an accuracy of about 15 minutes per day by the mid 1600s.

A few clocks with both an hour and a minute hand began to appear in about 1475. Astronomer Tycho Brahe in 1570 had four clocks each with hour, minute and second hands which he complained were so inaccurate that they never agreed with one an other. Accuracy was very important to Tycho. Tycho's observations of stellar and planetary motion were much more accurate than those of any predecessor or contemporary. Tycho achieved a precision of 1 – 2 arc minutes in his observations which was far beyond that of earlier star charts.

However, other than astronomers, minutes and seconds had little meaning to the general public. In fact, an hour was not commonly understood to be a duration of 60 minutes. It was not practical for the general public to consider minutes and seconds until pendulum clocks with the ability to accurately display minutes and seconds began to appear in the mid to late 1600s.

11 Pendulum Clocks

Galileo began studying pendulums around 1602, apparently intrigued by the swinging motion of chandeliers. He discovered that pendulums exhibit a property known as isochronism. Isochronism means that the period of a swinging pendulum is approximately independent of the amplitude or length of its swing. This is a critical property which makes a pendulum useful in regulating the speed of a clock. Galileo also found that the period of a pendulum is proportional to the square root of its length and independent of the mass of the pendulum bob (the weight at the end of the pendulum rod). Galileo initially used the free swinging pendulum in simple timing applications. For example, a particular event may be completed in 50 swings of a pendulum. The idea of using a pendulum to build a clock occurred to Galileo around 1637. Galileo began working on a pendulum clock but died before completing the project.

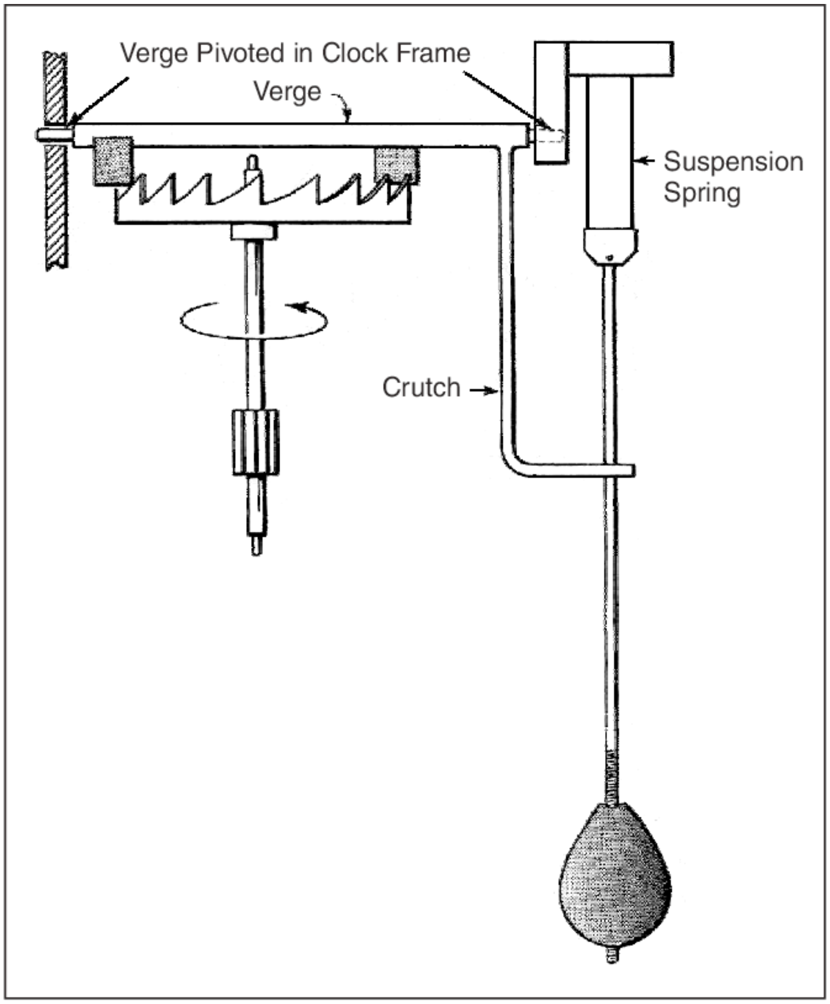
11.1 Pendulum Clocks with Verge and Foliot Escapements

Dutch scientist Christiaan Huygens, best known for his wave theory of light, designed the first pendulum clock based in part on the work done by Galileo. The clock was built for Huygens by clockmaker Salomon Coster who completed the clock in 1657.

Huygens pendulum clock used a verge escapement, but the foliot was replaced with a pendulum. The improvement in accuracy was so profound that many existing verge and foliot clocks were rebuilt to use a pendulum in place of the foliot.

The pendulums used in the verge and pendulum escapements swung through an angle of about 90^{o} . To avoid very wide cases, most verge and pendulum clocks used short pendulums.

In Figure 17 the pendulum is supported by a suspension spring allowing the pendulum to swing back and forth. The pendulum rod alternately contacts one leg of the crutch (shown on the right side of the figure) and then the other leg as the pendulum swings back and forth causing the crutch and attached verge to rotate back and forth. As they do so, the pallets (the two rectangular tabs attached to the verge) alternately push against the crown wheel teeth causing the wheel to turn. The crown wheel is connected to the clock hands through a series of gears. The clock hands move as the crown turns.



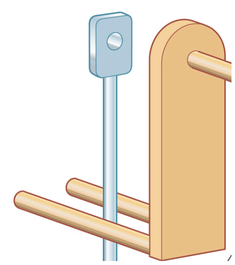


Figure 17 Verge and pendulum escapement (source: Sematic scholar)

11.2 Pendulum Clocks with Anchor Escapements

Introduction of the anchor escapement in about 1670 reduced the required pendulum swing from roughly 90° to around 4° – 6°. It is believed that the anchor escapement was invented by British scientist Robert Hooke around 1657. Hooke is best know for his discovery of the law of elasticity, known as Hooke's law. The anchor escapement allowed clock makers to use longer slower pendulums that increased clock accuracy while reducing friction and wear. Most large anchor escapement clocks used pendulums that were about 39 inches in length with a period of approximately two second.

The anchor escapement, shown in Figure 18, consists of two parts:

- The escape wheel, which is a vertical wheel with pointed teeth, and
- The anchor, shaped vaguely like a ship's anchor, which rotates back and forth on a pivot just above the escape wheel.

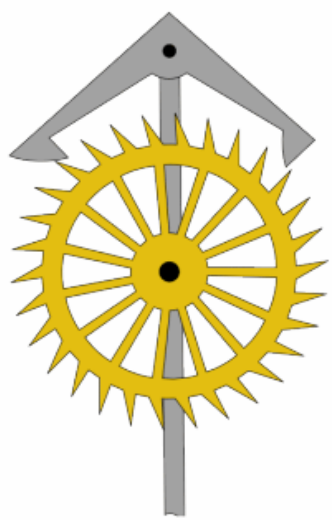


Figure 18 Anchor escapement (source: wikipedia.com)

The complete escapement mechanism is shown in Figure 19.

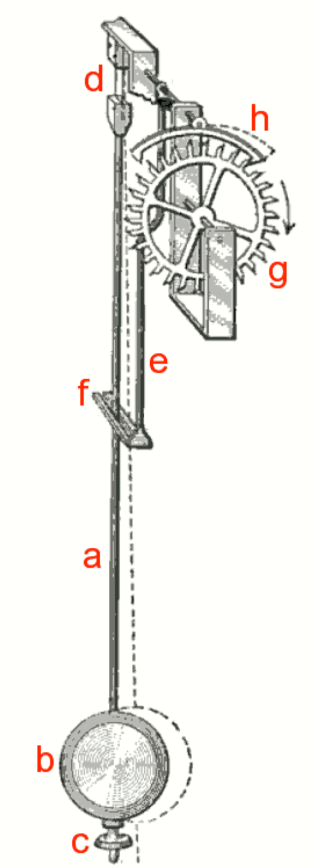


Figure 19 Pendulum and anchor escapement clock (source: wikipedia.com)

The various parts of the clock shown in Figure 19 are:

(a) pendulum rod
(b) pendulum bob
(c) rate adjustment nut
(d) suspension spring
(e) crutch
(f) fork
(g) escape wheel
(h) anchor

The pendulum engages the anchor escapement by means of the forked shaped crutch shown in Figure 20.

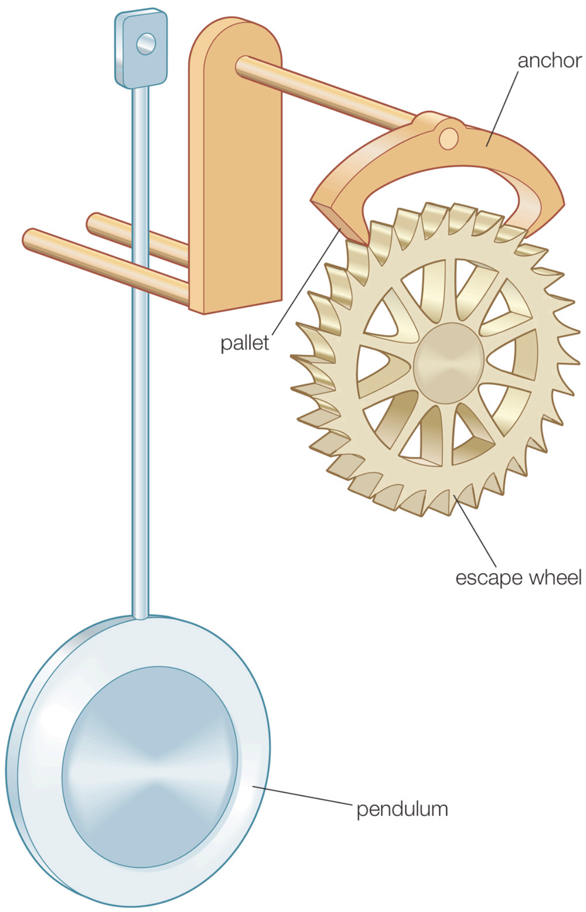


Figure 20 Pendulum, crutch, and anchor arrangement (source: Encyclopedia Britannica)

The square tab with a hole in it at the top of the pendulum rod attaches the pendulum to the clock body, usually through a suspension spring. The anchor rocks back and forth as the pendulum rod contacts one leg of the crutch fork and then the other.

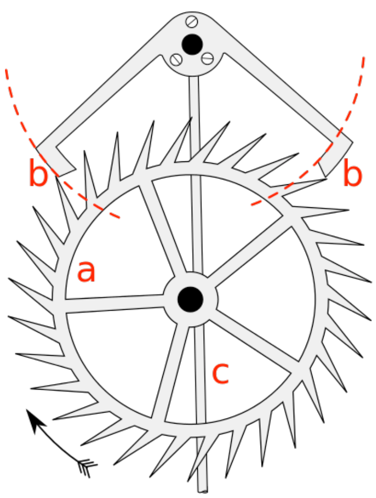
The two tips of the anchor, the pallets, engage the teeth of the escape wheel as shown in Figure 20. As the anchor rocks back and forth each pallet alternately catches and releases a tooth on the escape wheel. The pallet moving away from the escape wheel releases a tooth allowing the wheel to turn. As it does so the second pallet moves toward the wheel catching a tooth on the opposite side of the wheel. In the process, the wheel advances one tooth position. When the pendulum moves in the opposite direction, the second pallet moves away from the wheel, releasing its tooth, just as the first pallet catches the next tooth on its side of the wheel beginning a new cycle. Operating through a gear chain, the escape wheel causes the hands on the clock face to move.

One of the problems with the pendulum – anchor escapement is called recoil. The momentum of the pendulum results in the pallet moving toward the escape wheel to continue moving inward after contacting a wheel tooth. This causes the escape wheel to move slightly backwards (recoil). This problem causes excessive wear to the gear teeth and creates clock inaccuracies. It can also cause the points of the escape wheel teeth to dig into the pallet surface. The teeth of the escape wheel are slanted backward, opposite to the direction of rotation, while the surface of the pallets are slightly convex in an attempt to compensate for this problem.

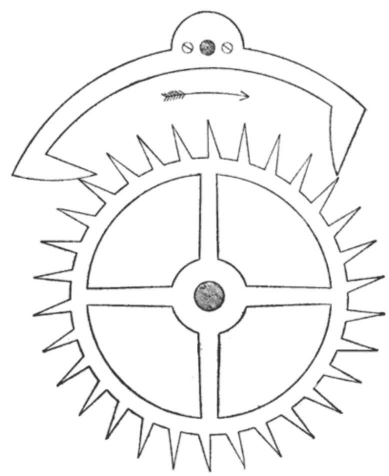
11.3 Pendulum Clocks with Deadbeat Escapements

The deadbeat escapement, invented around 1675 by astronomer Richard Towneley, eliminated the recoil problem. The deadbeat escapement requires more precise manufacturing techniques and is more susceptible to wear than the anchor escapement. Consequently it was initially used only in precision clocks. Its use spread throughout the 19th century becoming the standard escapement for most quality pendulum clocks. Today nearly all pendulum clocks use this escapement.

The deadbeat and the anchor escapements are shown side by side in Figure 21.



Deadbeat Escapement



Anchor Escapement

Figure 21 Deadbeat and the anchor escapements (source: Wikipedia)

The components of the deadbeat escapement shown in Figure 21 are: (a) escape wheel, (b) pallets showing concentric locking faces, (c) crutch.

Deadbeat pallets have two faces. The first face is a “locking” or “dead” face with a curved surface concentric with the axis on which the anchor rotates. The dead faces are shown as dashed arches in Figure 21. The second face, on the end of each pallet, is a sloping impulse face. Notice in Figure 21 that the end of the anchor escapement pallet (the part of the pallet closest to the wheel) is pointed. The end of the deadbeat pallet is instead a slanted flat surface (the impulse face).

When the escape wheel is released, a tooth of the wheel lands on the dead face of the pallet moving inward toward the wheel. The tooth remains resting against the dead face for most of the pendulum's outward swing and return. For this period the escape wheel is "locked" and unable to turn. The force exerted by the tooth on the dead face is directed through the anchor's pivot axis allowing the pendulum to swing freely. Near the bottom of the pendulum's swing the tooth slides off the dead face and onto the slanted "impulse" face allowing the escape wheel to turn.

The deadbeat, like the anchor escapement, is a frictional rest escapement in which sliding of the escape tooth on the dead face adds friction to the pendulum's swing. However, the deadbeat escapement has less friction than the anchor escapement because there is no recoil force.

As illustrated in Figure 21, the teeth of the anchor escape wheel slant backward relative to the wheel's direction of rotation. In contrast, the deadbeat escape wheel teeth are radial or slant forward to ensure that the tooth makes contact with the "dead" face of the pallet, preventing recoil.

11.4 Pendulum Period

The period of a pendulum is:

$$T = 2\pi\sqrt{\frac{L}{g}}$$

where T is the period in seconds, L is the length of the pendulum in meters, and g is the acceleration of gravity, measured in meters per second squared, at the location of the pendulum. For example, the period of an anchor escapement clock with a 39 inch (0.99 meter) pendulum is 1.99 seconds when the acceleration of gravity is 9.80665 m/sec^2.

The length of a pendulum is the distance from the pendulum's pivot point to the center of the pendulum's bob, as shown in Figure 22. The period of the pendulum is controlled by moving the bob up and down the pendulum rod. Moving the bob up toward the pivot point shortens the length L, shorting the pendulum's period, and causing the clock to run faster. Moving the pendulum down lengthens the pendulum's period resulting in the clock running slower.

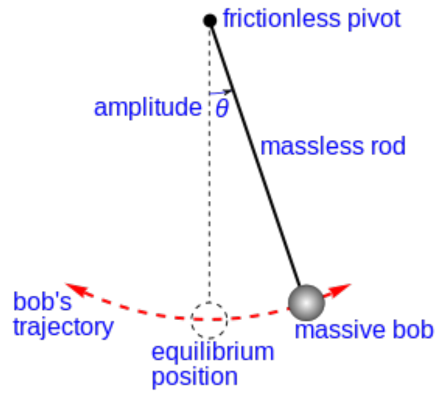


Figure 22 Motion of a Pendulum (source: Wikipedia)

The period of a pendulum increases slightly with the amplitude of its swing, which also results in a decrease in the clock's accuracy. That is, increasing the swing amplitude increases the number of seconds per day that the clock gains or loses. For this reason pendulums used on anchor and deadbeat escapement clocks use swing amplitudes of only 2 to 4^{o}. This is in contrast to verge and pendulum escapements that have swing amplitudes of about 90^{o}.

11.5 Temperature Compensation

The length of the pendulum rod changes slightly with temperature. An increase in temperature causes the rod to expand in length slowing the clock down. Similarly, a decrease in temperature causes the rod to contract speeding the clock up. Wood expands and contracts less with changes in temperature than metals. For this reason quality pendulum clocks often use wooden rods instead of metal rods.

In 1721 George Graham invented a high precision clock using a mercury pendulum (Figure 23). The bob of this pendulum consisted of two glass cylinders containing liquid mercury. An increase in temperature caused the pendulum's metal rod to expand, slowing the clock down. The increase in temperature also caused the mercury to expand upward in the two cylinders in the direction of the pivot point. This had the affect of shorting the pendulum and speeding the clock up. The expansion of the rod and the mercury off-set one an other allowing the clock to keep more accurate time.

Figure 23 Mercury Pendulum (source: Wikipedia)

The gridiron pendulum was the most widely used temperature compensating pendulum of its time. The pendulum was invented by John Harrison in 1726. It consisted of parallel sets of metal rods mounted in a frame as shown in Figure 24. One set of rods used a high-thermal-expansion metal such as zinc or brass. The other set consisted of a low-thermal-expansion metal such as steel. The pendulum was designed so that a change in length due to the high-thermal-expansion metal was off-set by the low-thermal-expansion metal resulting in little or no change in pendulum length with temperature change. This temperature compensation mechanism is illustrated in Figure 24. View B shows the pendulum at normal temperature. View C shows the pendulum after an increase in temperature. Notice in C that the zinc rods (yellow rods in the figure) have expanded in length, shorting the over all length of the pendulum because of the inverted position of the zinc rods. As the zinc rods expand they lift the pendulum rod upward accounting for the shorting in the pendulum length. The increase in temperature also caused the iron rods (blue rods in the figure) to expand in length, increasing the over all length of the pendulum. In View C you have to look closely to notice that the pendulum blue rods are slightly longer than in View B The expansion of the two sets of rods in opposite directions cancelled out causing the over all length of the pendulum to remain unchanged.

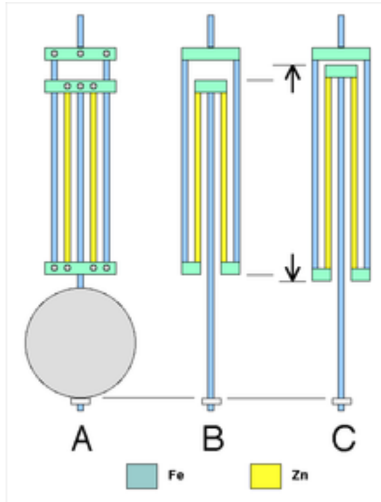


Diagram of a gridiron pendulum
A: exterior schematic
B: normal temperature
C: higher temperature

Figure 24 Gridiron Pendulum (source: Wikipedia)

11.6 Atmospheric drag

Air pressure, humidity, and temperature create a drag on a swinging pendulum which adversely affects clock accuracy. The drag also consumes clock power requiring the clock weights to be rewound more frequently. To reduce drag, pendulum rods and bobs are streamlined and often polished. High accuracy pendulum clocks were built for the National Bureau of Standards, and other standard organizations and laboratories, by enclosing the clock in an air tight chamber which was then evacuated to a very low air pressure. The low air pressure reduced pendulum drag significantly increasing clock accuracy.

11.7 Affects of Gravity

Earth's gravity changes with latitude and elevation. Consequently, a pendulum clock must be recalibrated if it is moved to a new location or elevation. For example, a pendulum clock moved from sea level to 4,000 feet will lose 16 seconds per day if it is not recalibrated. Even moving a clock from the ground floor to the top of a tall building can have an affect on clock accuracy. Since the period of a pendulum is

$$T = 2\pi\sqrt{\frac{L}{g}}$$

the length L of the pendulum must either be elongated or shortened to compensate for the change in gravity g. This is accomplished by moving the pendulum bob up or down the pendulum rod as needed.

11.8 Clock Leveling

A pendulum clock must be absolutely level to work properly and keep accurate time. If not perfectly level, the pendulum swings more to one side than the other. This upsets the symmetrical operation of the clock escapement. A clock which is not level exhibits a none uniform ticking sound. Instead of the normal tick...tock...tick...tock, an out of beat tick-tock...tick-tock...tick-tock sound is heard.

11.9 High Precision Pendulum Clocks

The pendulum clock was the world's most precise timekeeping device from its invention in 1656 by Christiaan Huygens until the 1930s when it was replaced by the quartz clock.

The National Bureau of Standards used pendulum clocks from 1904 through the early 1930 as the standard time reference for the United States.

The first standard was the Riefler pendulum clock shown in Figure 25. This clock was purchased from Clemens Riefler of Munich in 1904. The clock used an Invar pendulum which significantly reduced the pendulum's sensitivity to temperature changes. Invar (meaning invariable) is a nickel-iron allow which has an unusually low coefficient of thermal expansion. The Invar pendulum was invented in 1896 by Swiss scientist Charles Edouard Guillaume who received the Nobel Prize in Physics in 1920 for this discovery.

In addition, the Riefler clock was enclosed in an evacuated encasement to reduce pendulum atmospheric drag. The clock's weight was raised by an electromagnet every 30 seconds. This was done to ensure that a constant torque was applied to the clock mechanism.

The clock achieved an accuracy of about 10 milliseconds per day (plus or minus 1 second every 100 days). The clock was calibrated using time signals broadcast by the U.S. Naval Observatory.

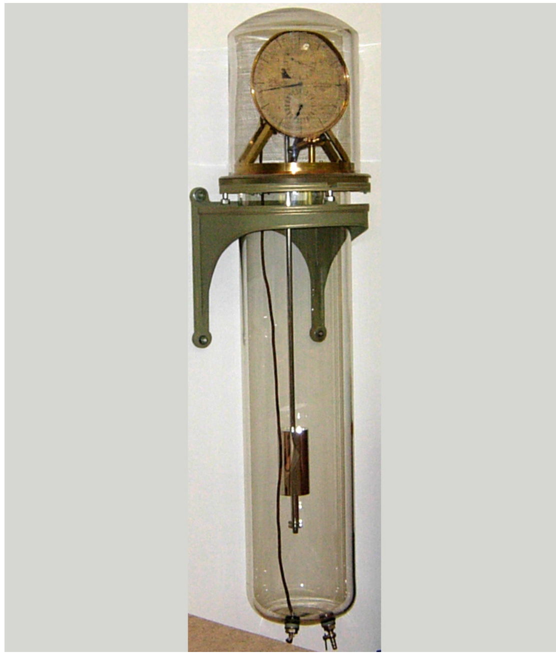


Figure 25 Riefler Clock (source Wikipedia)

The Riefler clock was replaced in 1929 by the Shortt clock (Figure 26). This clock was invented by British railway engineer William Hamilton Shortt in 1921. The Shortt clock was extensively used by astronomical observatories in the 1920s and 1930s.

The Shortt clock was a complex electromechanical device that used a two pendulum master slave mechanism. The slave pendulum drove the clock works and was electrically synchronized to the mater pendulum. The master pendulum swung freely in an evacuated encasement unaffected by the friction encountered by the slave pendulum in driving the clock mechanism.

Every 30 seconds a gravity lever escapement made contact with the master pendulum giving the master pendulum the energy needed to keep swinging. The motion of the gravity lever also sent an electrical pulse to a mechanism that kept the slave pendulum synchronized to the master pendulum.

A number of Shortt clocks were on record as gaining or losing no more than one second per year.

In Figure 26, the master pendulum is shown in its evacuated encasement on the left while the slave pendulum and the associated clock works are on the right.

Figure 26 Shortt Clock (source: Wikipedia)

12 Quartz Clocks

Quartz clocks are the most popular type of clock ever produced. Billions of quartz oscillators are manufactured annually for use inside all types of clocks, watches, mobile phones, computers, radios, etc.

A quartz clock uses an electronic crystal oscillator to produce a very precise high frequency signal. The high frequency signal is divided down to a lower frequency needed to drive the clock's synchronous motor which in turn moves the clock's hour, minute, and second hands. In Figure 27 a 120 KHz crystal oscillator is divided down to 60 Hz to drive the motor. An amplifier is provided between the oscillator and the first frequency divider to prevent the divider from loading down the oscillator adversely affecting its frequency. A power amplifier is used to drive the synchronous motor. Crystal oscillators allow quartz clocks to achieve at least an order of magnitude more accuracy than the best high precision pendulum clocks.

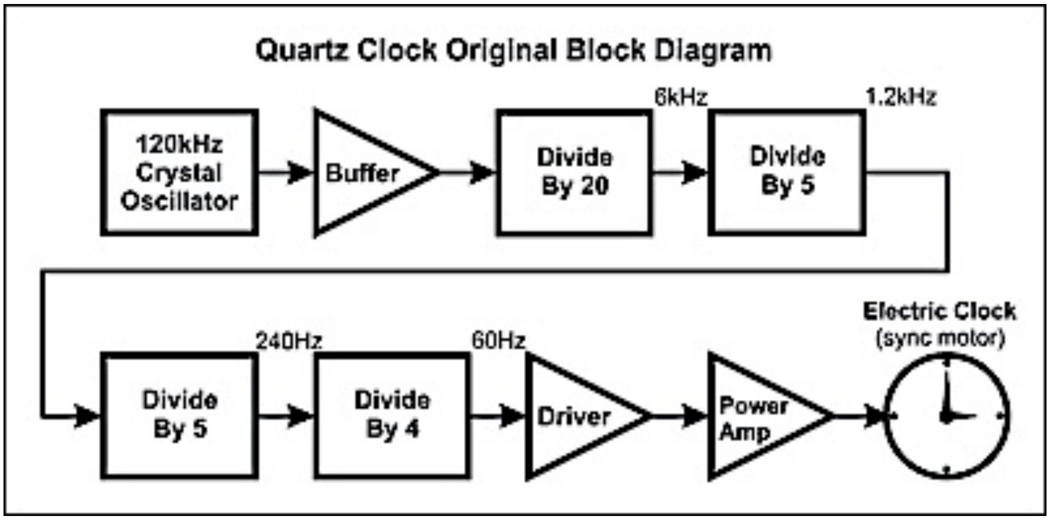


Figure 27 Typical quartz clock block diagram (source: tronola.com)

The first quartz clock was built by Warren Marrison and J.W. Horton of Bell Telephone Laboratories in 1927 using a vacuum tube crystal oscillator. Quartz clocks evolved over the next 3 decades. However, their use was limited to research and standards laboratories due to their expensive bulky vacuum tube oscillators and electronic frequency dividers (Figure 28). The National Bureau of Standards, now the National Institute of Standards and Technology (NIST), used quartz clocks as the United States time standard from the 1930s until replaced by atomic clocks in 1967. Figure 29 shows four 100 KHz temperature controlled quartz crystal oscillators installed at the National Bureau of Standards in late 1929. The original four clocks had an accuracy of 10 parts per million (ppm), that is $\pm$ 864 milliseconds per day. This accuracy was increased to 0.01 ppm ($\pm$ 864 microseconds per day) by 1952.

Figure 28 Vacuum tube replica of an early quartz clock (source: tronola.com)

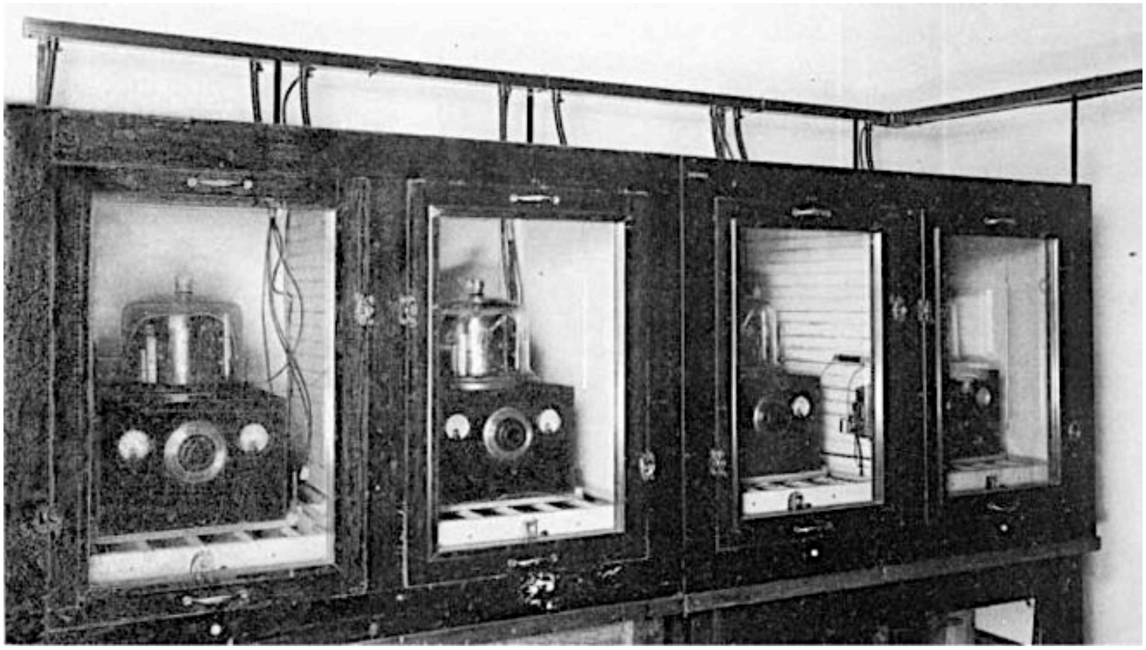


Figure 29 Four temperature controlled quartz crystal oscillators at NBS in 1929 (source: Wikipedia)

In Figure 29, each black rectangular device is a vacuum tube crystal oscillator and frequency divider. The cylindrical units on top of the oscillators are temperature controlled crystals.

The advent of solid state digital electronics in the 1970s allowed compact and inexpensive quartz clocks to be mass produced. Since the 1980s quartz crystal oscillators have replaced mechanical balance wheel movements as the world's most widely used clock technology. Nearly all consumer clocks today utilize quartz crystal oscillators.

Most consumer clocks and watches use a quartz crystal in the shape of a small tuning fork (Figure 30). The crystal is laser trimmed to vibrate at a frequency of exactly 32,768 Hz, which is an integer power of two, specifically 2^{15} Hz. This frequency is high enough that most people can not hear it. An inexpensive 15 bit solid state counter is used to divide the frequency down to 1 second (1 Hz) pulses needed to drive the clock’s hour, minute, and second display.

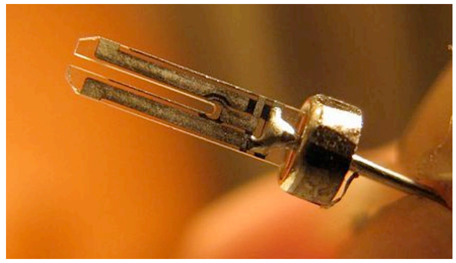


Figure 30 Quartz crystal resonator with the case removed (source: Wikipedia)

The accuracy of quartz crystal oscillators is typically about 6 parts per million (0.0006%) at $31\ ^{o}C\ (87.8\ ^{o}F)$. At this rate a typical quartz clock or watch gains or loses about 16 seconds in 30 days ($\pm$ 518 milliseconds per day).

Temperature change is a major cause of frequency variation in crystal oscillators. Oven-controlled crystal oscillators are used in applications requiring stable high precision clocks. In these applications the crystal is mounted in a very small electric oven that is held at a constant temperature. High precision laboratory and high end radio equipment often use oven-controlled crystal oscillators.

12.1 Vacuum Tubes

The two element (diode) vacuum tube was invented by J.A. Fleming in 1904. A typical diode tube consists of a negatively charged cathode and a positive plate as shown in Figure 31. In operation, the cathode is heated to a high temperature causing electrons to escape from the cathode material. The positive charge on the plate draws the electrons from the cathode to the plate creating an electrical current as illustrated in Figure 32. Typically a second electrical current flowing through a thin wire called the filament, positioned inside the cathode cylinder, heats the cathode to its high temperature. In other cases the filament and cathode are combined into a single element. Both situations are shown in Figure 31.

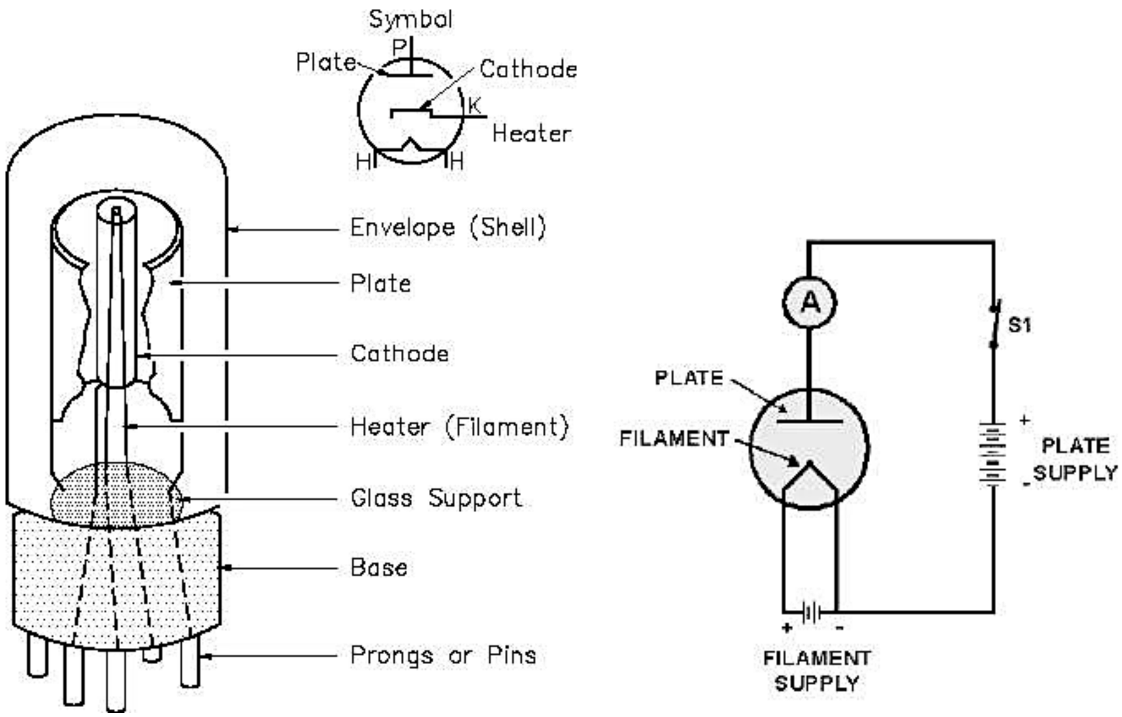


Figure 31 Diode vacuum tube (source: https://nuclearpowertraining.tpub.com)

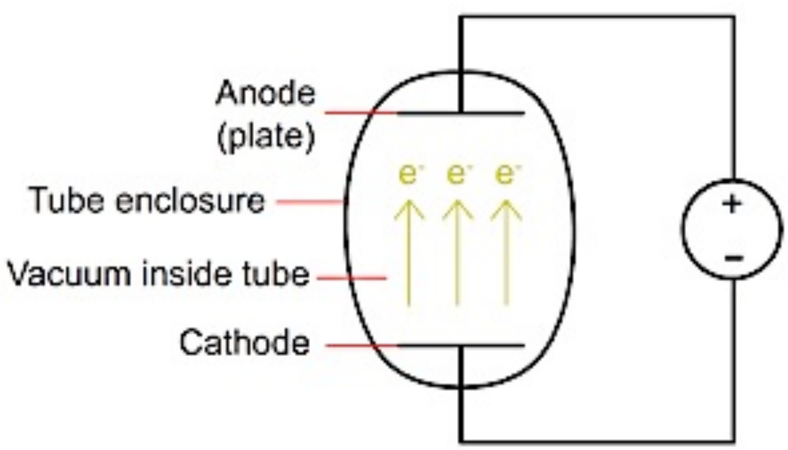


Figure 32 Vacuum diode operation (source: engineering.com)

Use of vacuum diode tubes consist primarily of converting (rectifying) sinusoidal signals into pulsed direct current (d-c) as illustrated in Figure 33. They are also used as signal detectors in radio receivers and other devices. When the first vacuum diode was invented it was hoped that it would provide better performance than crystals already in use in early radio receivers for detecting and demodulating weak signals. However, that initially did not turn out to be the case. Eventually, vacuum diode tubes did achieve their anticipated performance as vacuum tube manufacturing techniques improved.

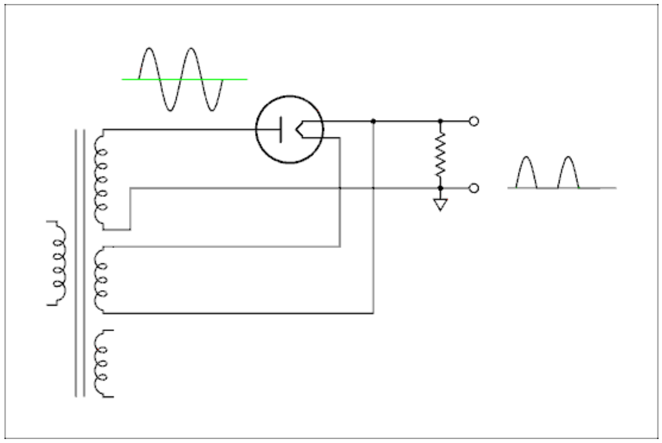


Figure 33 Vacuum tube rectifier (source: anglefire.com)

In 1907 Lee de Forest invented the three element (triode) vacuum tube by placing a widely spaced coil of wire, called a grid, between the vacuum tube cathode and plate as shown in Figure 34. A small change in the grid voltage, relative to that of the cathode, creates a large change in the electrical current flowing from the cathode to the plate, making possible the concept of signal amplification illustrated in Figure 35. In this figure a small input signal $v_{in}(t)$ applied to the grid produces a large output signal $v_{out}(t)$ at the plate.

Invention of the triode vacuum tube marked the beginning of the electronic age. Triode tubes found immediate widespread use as amplifiers in both the telephone and radio industries. However, operation of the early amplifiers often resulted in some of the output signal becoming coupled back into the amplifier input. If the coupling was significant enough the amplifier oscillated. While oscillation is extremely annoying in an amplifier, it lead to the invention of the vacuum tube oscillator in 1912 by Edwin Armstrong. One of the first uses of the vacuum tube oscillator was in the regenerative receiver also invented by Armstrong.

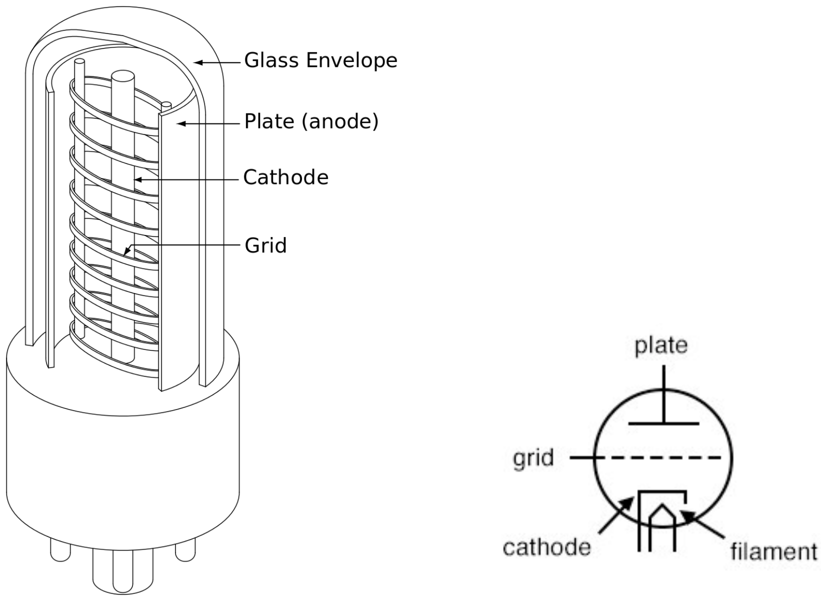


Figure 34 Triode vacuum tube (source: Wikimedia Commons)

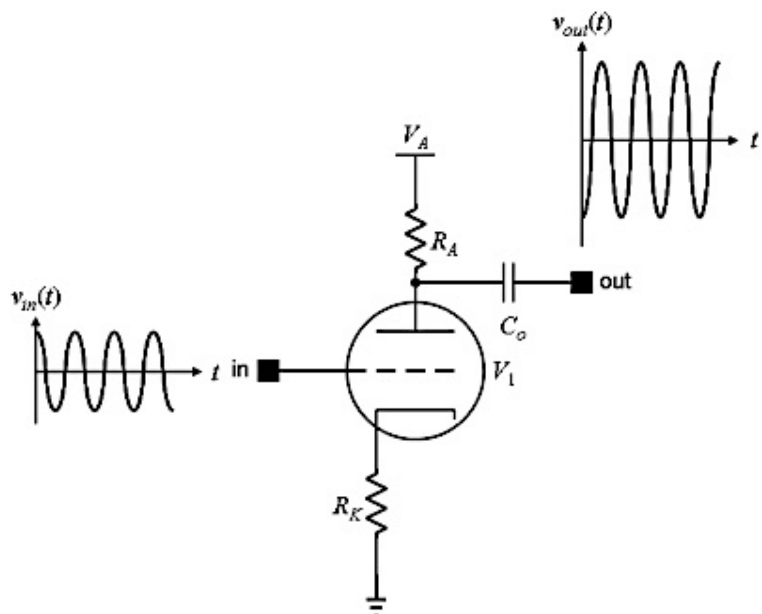


Figure 35 Triode vacuum tube amplifier (source: https://web.eecs.umich.edu)

A vacuum tube oscillator consists of an amplifier with intentional coupling between its output and input implemented by a capacitor – inductor circuit tuned to the desired resonant frequency of the oscillator (Figure 36).

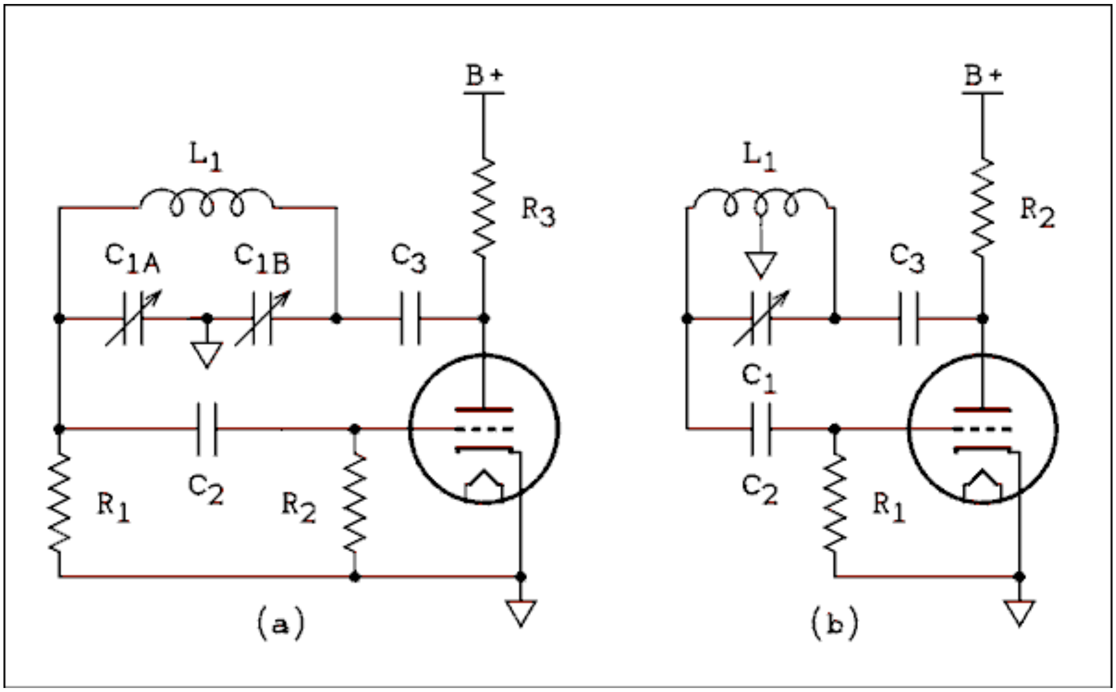


Figure 36 Vacuum tube oscillators (source: http://www.next.gr/oscillators/colpitts)

In Figure 36 the feedback circuit from the plate to the grid is formed by L_1 and C_1. In Figure 36a the capacitors C_{1A} and C_{1B} are center tapped to ground. In b the inductor L_1 is center tapped to ground. In both cases the capacitor(s) C_1 are variable allowing the oscillator to be tuned over a range of frequencies.

Vacuum tube oscillators were extensively used as frequency sources for radio transmitters and in the mixer circuits of radio receivers (a mixer circuit converts a desired incoming signal to a lower frequency that can be more easily amplified and filtered). However, one of the problems with vacuum tube oscillators is thermal instability causing the oscillator frequency to drift. The capacitors and inductors used in the feedback loop to control the oscillator's frequency change in value as the oscillator heats up or cools down causing the frequency of the oscillator to change. Through proper design frequency drift could be controlled to tolerable levels in early radio equipment.

In theory, vacuum tube oscillators could have been used as the frequency source for "electronic clocks". In such clocks the high frequency output of the oscillator would have been electronically divided down to hours, minutes, and seconds. However, due to their inherent frequency instability, the accuracy of such clocks would have been far less than high quality pendulum clocks.

12.2 Quartz Crystals

In 1921 Walter G. Cady discovered that the frequency stability problem in vacuum tube oscillators could be solved by using a quartz crystal to control the oscillator's frequency instead of an inductor-capacitor (LC) circuit.

Quartz (Figure 37) is a hard crystalline mineral composed of silicon dioxide SiO_2. The silicon dioxide atoms are linked in a SiO_4 tetrahedra with each oxygen atom shared between two tetrahedra giving the overall chemical formula of SiO_2 (Figure 38).

Figure 37 Quartz Crystal (source: johnbetts-fineminerals.com)

While quartz is found in many parts of the world (it is the second most abundant mineral in Earth's crust) most of the quartz originally used in crystal oscillators was mined in Brazil.

Quartz has considerable mechanical and chemical stability with a hardness nearly equal to that of ruby and sapphire. Because of its chemical stability, its composition is not easily modified in normal environments. The rigidity of quartz is such that it will fracture if deformed beyond its elastic limits.

Quartz crystal exhibits a Piezo-electric effect. That is, a small electrical voltage develops across the crystal when it is slightly deformed through tension or compression, as illustrated in Figure 39.

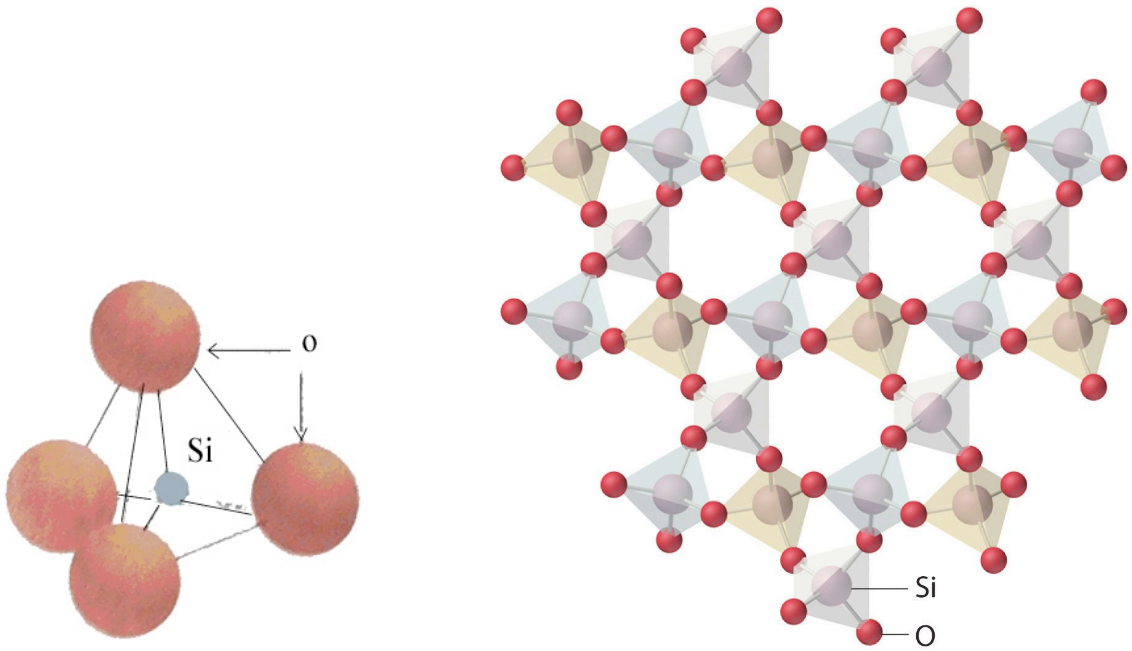


Figure 38 Quartz Structure (source: www.sunnyray.org and Pinterest)

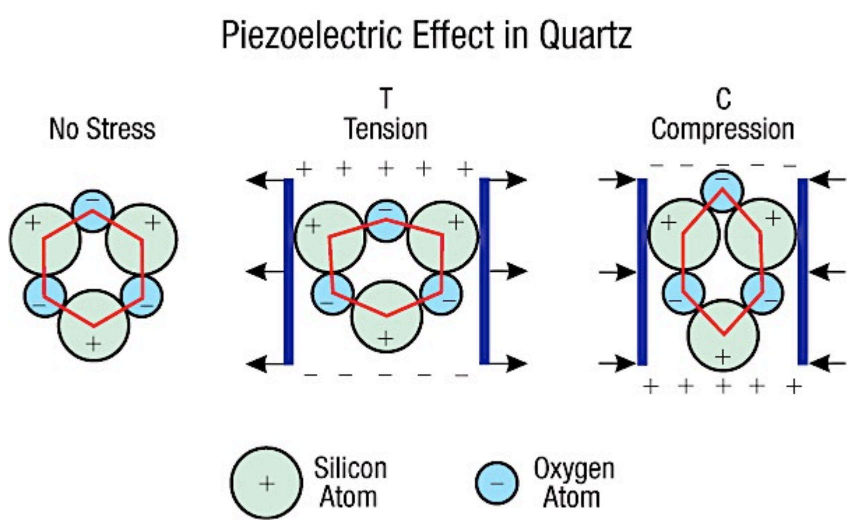


Figure 39 piezoelectric effect in a quartz crystal
(source: https://www.autodesk.com/products/eagle/blog/piezoelectricity/

This property was at one time used in the tone arm of record players (Figure 40). A small thin rectangular slab of crystal attached to a pick-up needle was mounted in the tone arm head. The crystal functioned as a transducer converting the mechanical movement of the tone arm into electrical signals as the tone arm needle followed the groves in the record.

The record player amplified the signals from the tone arm reproducing the music mechanically stored on the record platter.

Figure 40 Record player tone arm (source: dreamstime.com)

The opposite Piezo-electric effect also occurs. Applying an electrical voltage across a piezoelectric crystal will cause the crystal to expand or contract slightly, converting electrical energy into mechanical energy. An a-c voltage placed across a small rectangular slab of quartz crystal will cause it to vibrate at a frequency inversely proportional to its physical thickness. It is this property that is exploited to produce crystals for crystal oscillator circuits.

A typical medium frequency slab of crystal (better know as a blank) is about 10 mm x 5 mm x 1 mm. A blank is ground and polished to produced its desired frequency of oscillation. Once the blank has been properly prepared it is mounted between two metal plates forming its connects to an oscillator circuit, as illustrated in Figure 41 and Figure 42.

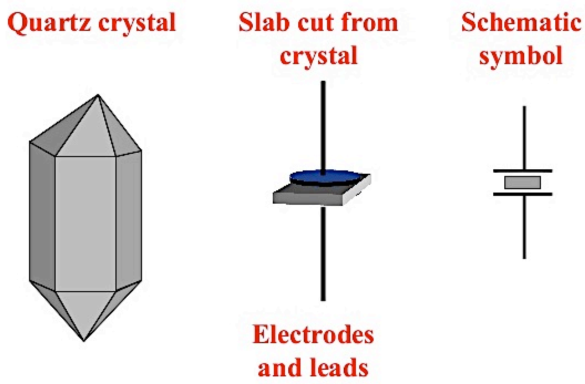


Figure 41 Piezo-electric crystal cut from quartz (source: Analog IC Tips)

Figure 42 An assembled quartz crystal (source: ResearchGate)

In Figure 42 the surface marked as #1 is the cut and polished quartz crystal wafer (slab) while #2 is the electrical connection to the crystal.

Electrically, the equivalent circuit of a quartz crystal consists of a large inductance L in series with a small capacitance C and a low resistance R as illustrated in Figure 43. In parallel with this series circuit is a second capacitor C_m which represents the capacitance of the two metal plates forming the electrical connection to the quartz crystal wafer. One of the plates is shown in Figure 42 marked as item #2.

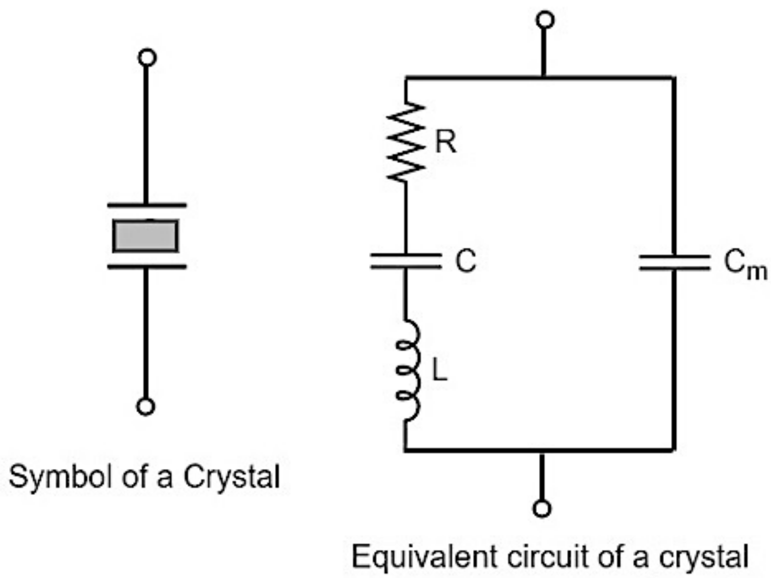


Figure 43 Crystal equivalent circuit   (source: tutorialspoint.com)

Consequently, a crystal has two resonant frequencies, a series resonance frequency fs produced by its series L, C, R circuit and a slightly higher parallel resonance frequency fp formed by L, C, and R in parallel with C_m. These two frequencies are shown in Figure 44. The total impedance of a crystal vs frequency is illustrated in Figure 45.

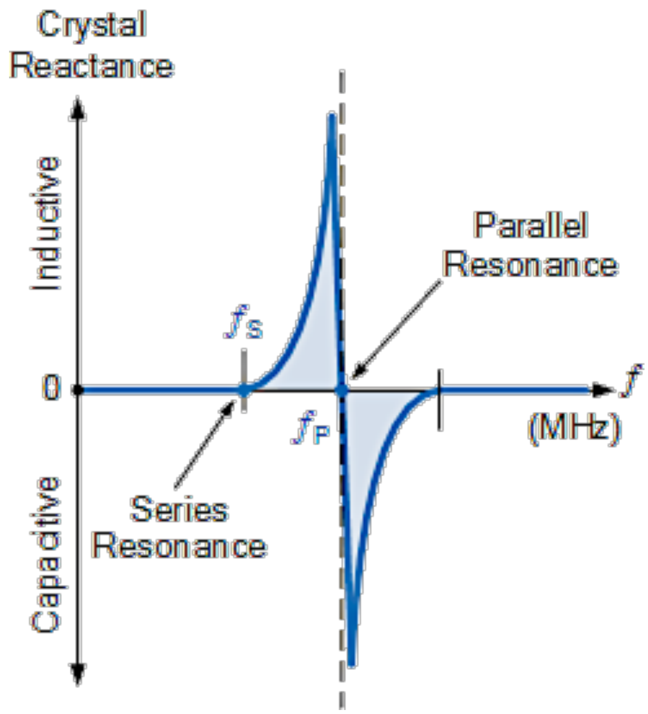


Figure 44 Crystal reactance vs frequency
(source: https://www.electronics-tutorials.ws/oscillator/crystal.html)

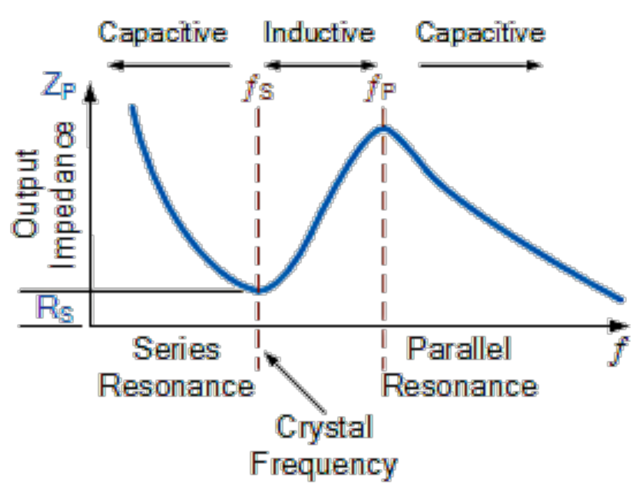


Figure 45 Impedance of crystal vs frequency
(source: https://www.electronics-tutorials.ws/oscillator/crystal.html)

The impedance of the crystal's series circuit is

$$Z_s = \sqrt{R^2 + (X_L + X_C)^2}$$

where

$$X_L = 2\pi f L$$

and

$$X_c = \frac{-1}{2\pi f C}$$

At its series resonant frequency

$$|X_L| = |X_C|$$

However, the signs of X_L and X_C are opposite so at series resonance

$$Z_s = \sqrt{R^2 + (X_L + X_C)^2} = \sqrt{R^2 + (0)^2} = R$$

Thus the series resonant impedance of a crystal is very low equal only to the value of R which is small. This low impedance is illustrated in Figure 45 for the frequency f_s. The crystal's series resonant frequency is

$$f_s = \frac{1}{2\pi\sqrt{LC}}$$

where L and C are their respective magnitudes.

The parallel impedance of a crystal is

$$Z_p = \frac{Z_s\, X_{Cp}}{Z_s + X_{Cp}}$$

where

$$X_{Cp} = \frac{-1}{2\pi f C_p}$$

Parallel resonance occurs when the reactance of the crystal's series LCR leg equals the reactance of the parallel capacitor C_m . The series impedance of a crystal is inductive at the parallel resonant frequency as illustrated in Figure 45. So at parallel resonant

$$|Z_s| = |X_{Cp}|$$

However, Z_s and X_{Cp} are opposite in sign, which means that at parallel resonance

$$Z_p = \frac{Z_s\, X_{Cp}}{Z_s + X_{Cp}} \approx \frac{Z_s\, X_{Cp}}{0}$$

producing a very high crystal impedance at parallel resonance.

The parallel resonant frequency of a crystal is

$$f_p = \frac{1}{2\pi\sqrt{L\left[\frac{C\, C_p}{C + C_p}\right]}}$$

12.3 Quartz Crystal Oscillators

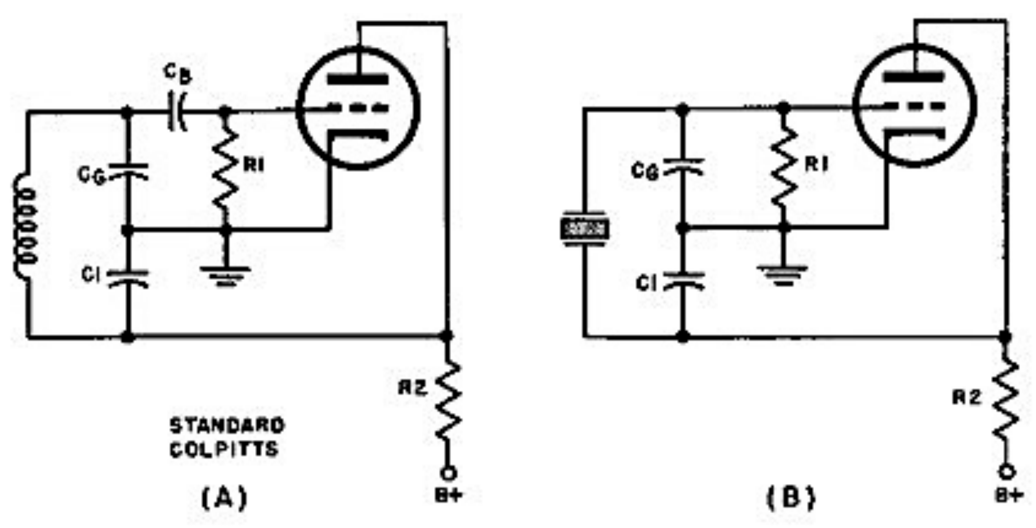


Figure 46 Colpitts oscillator circuits
(source: https://www.electronics-tutorials.ws/oscillator/crystal.html)

Figure 46A shows a typical LC tuned vacuum tube Colpitts oscillator. The frequency of oscillator is determined by the inductor in parallel with the two capacitors C_G and C_I. This tuned circuit forms the feedback circuit between the vacuum tube plate and the grid which is necessary for oscillation. The blocking capacitor C_B is required to prevent the plate's high d-c voltage from reaching the grid. Without this capacitor the high plate d-c voltage would pass through the inductor directly to the grid. R1 provides the grid bias voltage while R2 is the plate load resistance.

Figure 46B is a crystal controlled vacuum tube Colpitts oscillator. The circuit in Figure 46B is similar to that in Figure 46A with the exception that the inductor in Figure 46A has been replaced with a crystal. In addition, the blocking capacitor C_B in Figure 46A is not required in Figure 46B since the dielectric properties of the crystal and crystal holder perform the voltage blocking function.

The General Radio Model 275 (Figure 47) was the first commercially available crystal oscillator. Produced in 1924 it measured 10 in × 11 in × 8 in and weighed 19 lbs. The oscillator contained one quartz crystal ground to a frequency specified by the purchaser and sold for $145.

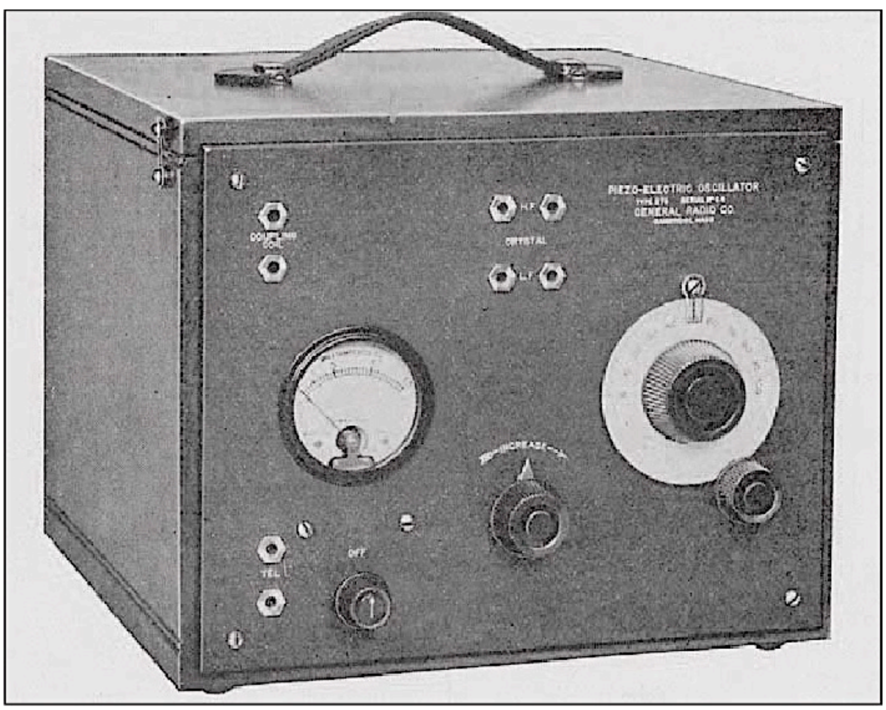


Figure 47 First commercial crystal oscillator
(source: https://tf.nist.gov/general/pdf/2533.pdf)

Crystal oscillators were extremely important to the radio broadcast industry. In 1923 there were 570 AM radio stations crowding the 1,000 KHz wide AM broadcast band. Stations were spaced 10 KHz apart. For example, if one station were assigned a frequency of 990 KHz, the next station operated on 1,000 KHz and the next on 1,010 KHz, etc. If the frequency of a radio station varied just 1% (10 KHz) it would end up operating on top of the adjacent station.

In 1927 Congress created the Federal Communications Commission (FCC) to regulate radio communications in the United States. The FCC subsequently required all radio broadcasters to stay within 500 Hz of their assigned frequency. This was tightened to 50 Hz in 1932, a stability of 50 ppm at a frequency of 1,000 KHz. This requirement was not a problem. In 1928 General Radio began selling the Model C-21-H crystal oscillator with a stability of 1 ppm.

Semiconductor crystal oscillators began replacing vacuum tube oscillators in the 1960s. Figure 48 shows a semiconductor common collector (emitter-follower) Colpitts crystal oscillator circuit. The resistors R_1 and R_2 determine the d-c bias level for the transistor's base while emitter resistor R_E sets the oscillator's output voltage level. Resistor R_2 is made as large as possible to prevent loading the parallel connected crystal.

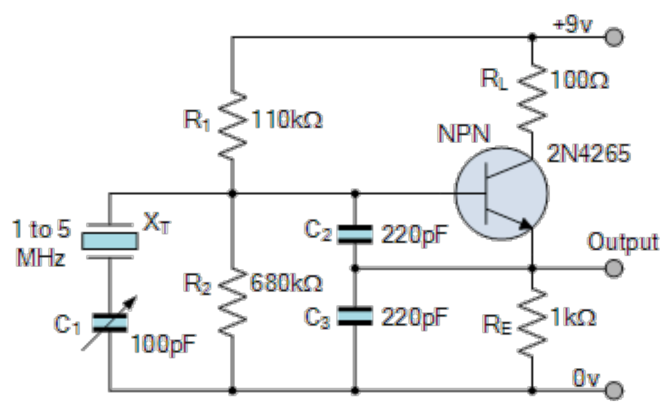


Figure 48 Semiconductor crystal oscillator
(source: www.electronics-tutorials.ws/oscillator/crystal.html)

Today most microprocessors and micro-controllers have two oscillator pins labeled OSC1 and OSC2. An external quartz crystal circuit, RC oscillator network, or ceramic resonator is connected to these pins to produce the internal clock for the microprocessor. In Figure 49 a crystal is connected to the pins. Within the microprocessor a circuit roughly similar to that of Figure 48 completes the microprocessor oscillator circuit.

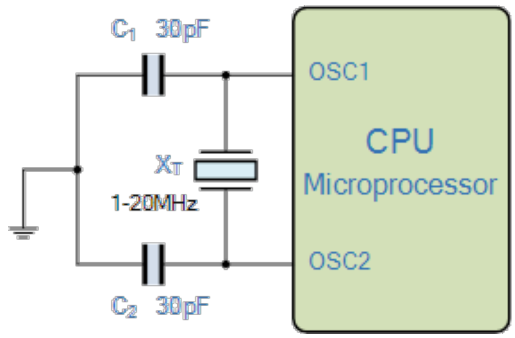


Figure 49 Microprocessor clock circuit
(source: www.electronics-tutorials.ws/oscillator/crystal.html)

The frequency stability of LC Colpitts, and other similar vacuum tube and semiconductor oscillators, is extremely poor due to the temperature sensitivity of the inductor and capacitors used in their turned circuits. Changes in temperature cause the physical properties of the inductor and capacitors to change, changing their values and thus the frequency of oscillation. For many applications, such as radio transmitter variable frequency oscillators (VFOs), frequency stability is not particularly critical. However, for many other applications, for example radio broadcast station frequency control, the poor stability of LC oscillators is unacceptable. As discussed above, these applications require a crystal controlled oscillator. While the frequency of a crystal oscillator is fixed, its stability is on the order of 1 to 10 parts per million (ppm) over a temperature range of 0^o C to 70^o C.

Temperature-compensated and oven-controlled crystal oscillators are used for more precise frequency control.

A temperature-compensated crystal oscillator (TCXO) utilizes an external circuit that measures ambient temperature. Based on this measurement, the frequency of the oscillator is slightly adjusted by the circuit to compensate for the temperature change. The adjustment is often accomplished using components such a varicap diodes. Temperature-compensated crystal oscillators typically provide a stability of 1 to 0.5 ppm.

Oven-controlled crystal oscillators (OCXO) provide even greater stability. In this case the crystal is enclosed in a tiny thermally insulated container with a thermostatically controlled heater as illustrated in Figure 50. The heater maintains the crystal at a constant temperature above that which it would normally experience within the electronic equipment enclosure. This results in a far greater degree of temperature stability. Typically the internal temperature of the oven is 75 to 85^oC.

Figure 50 Oven-controlled crystal oscillator (source: www.electronics-notes.com/articles/electronic components/quartz-crystal-xtal/ocxo-oven-controlled-crystal-xtal-oscillator.php)

The table below compares the temperature stability of basic crystal oscillators, TCXO and OCXO oscillators

Temperature Range	Basic Crystal Oscillator	TCXO	OCXO
0^o C to 70^o C	$\pm 10\ ppm$	$\pm 0.5\ ppm$	$\pm 0.003\ ppm$
-20^o C to 70^o C	$\pm 25\ ppm$	$\pm 0.5\ ppm$	$\pm 0.02\ ppm$
-40^o C to 85^o C	$\pm 30\ ppm$	$\pm 1\ ppm$	$\pm 0.003\ ppm$

12.4 Quartz Crystal Clocks

The invention of the quartz clock is generally credited to William Marrison. In October 1927 Marrison and his colleague Joseph W. Horton at Bell Telephone Laboratories presented a paper describing a 50 KHz quartz crystal clock. This was the first published account of a quartz clock.

The advantages of a quartz crystal clock were immediately obvious. Its most important property being its inherent stability which was far greater than the best pendulum clocks of the time. Unlike pendulum clocks, the quartz crystal clock was independent of gravity allowing it to operate at any latitude and elevation without any compensating adjustments. In addition, it was practically immune to shock allowing it to be used under conditions entirely unsuitable for pendulum clocks, for example in earthquake zones, on railroads, and aboard aircraft.

Over a period of several years, Marrison refined his quartz clock to use a 100 KHz vacuum tube oscillator. The oscillator output frequency was divided twice, each time by a factor of 10, using a vacuum tube frequency divider. The 1KHz output signal from the frequency divider controlled a small 1,000 cycle synchronous motor, thus locking the motor's frequency to the frequency of the crystal oscillator.

The first commercial quartz clock was developed by General Radio. Horton left Bell Labs in 1928 and join General Radio. He becoming their chief engineer designing a series of Syncro-Clocks that avoided infringing on Marrison's patents by utilizing a different frequency divider circuit

The problem with all quartz crystal clocks is that the oscillator frequency is far to high to directly drive the synchronous motor controlling the clock's second, minute, and hour hands. Various schemes were devised to reduce the oscillator's high frequency output to that required by the motor. Over time the multivibrator frequency divider, similar to the one shown in Figure 51, became the most widely used method for dividing down the clock's crystal oscillator frequency.

In Figure 51, the clock's crystal oscillator signal was fed to the multivibrator input shown on the left side of the diagram. Negative halves of the sinusoidal signal from the crystal oscillator were shunted to ground by the vacuum diode tube #1. Positive halves of the signal passed through diode 2 into capacitor C. The trigger tube was biased well below cutoff. Plate current in the trigger tube began to flow when a sufficient number of positive input pulses accumulated in capacitor C to raise the grid voltage just above cutoff. The flow of plate current triggered the multivibrator (the two cross coupled vacuum tubes on the right side of the diagram) causing it to produce one output pulse. Thus n input pulses from the crystal oscillator were required to produce one multivibrator output pulse. In equation form

$$f_o = \frac{f_i}{n}$$

where

f_o = the frequency divider's output frequency

f_i = its input frequency (the frequency of the clock's crystal oscillator)

n = the division number, the number of input pulses needed to accumulate in capacitor C to trigger the multivibrator causing it to produce one output pulse.

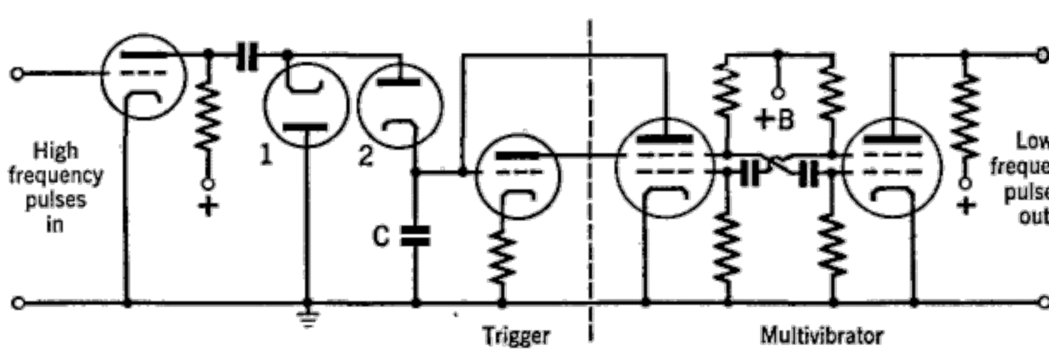


Figure 51 Multivibrator frequency divider circuit
(source: http://www.vias.org/basicradio/basic_radio_31_11.html)

The multivibrator frequency divider was replaced with low cost digital integrated circuit counters in the 1960s. A counter circuit for a typical 12 hour clock is shown in Figure 52. In this figure an additional 15 bit counter circuit, not shown in the diagram, divides down the clock's 1,966,080 Hz crystal oscillator frequency to 60 Hz.

Crystals for clocks can be cut and trimmed very precisely to produce specific frequencies. However, no two crystals can be cut exactly alike or produce exactly the same frequency. Thus the accuracy of a quartz clock will always be limited as well as its ability to precisely agree with other quartz clocks.

In addition, crystals are affected by temperature, aging, humidity, and contamination all of which adversely affects their frequency of oscillation. The most affective way to control variations in temperature is to enclose a crystal in a temperature controlled oven as discussed previously. Aging is more difficult. The characteristics of a quartz wafer slowly change over time affecting the crystal's frequency of oscillation. The rate at which a crystal wafer ages typically depends on the way the crystal is packaged and mounted. The aging rate will be more predictable if the crystal wafer is kept free from humidity and contamination. Interestingly, the rate at which a crystal wafer ages decreases over time. However, some change in frequency due to aging is inevitable.

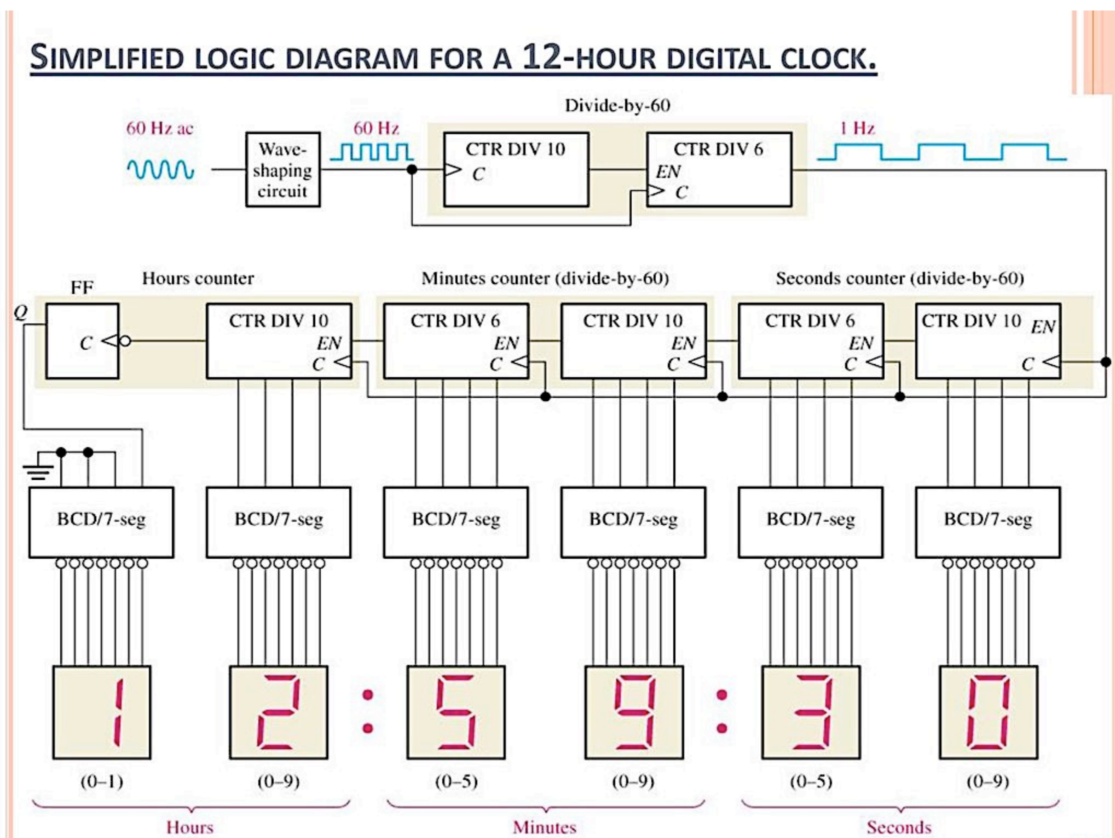


Figure 52 The counter circuit for a typical 12 hour clock (source: SlidePlayer)

13 Atomic Clocks

Atomic clocks have fundamentally altered the way in which time is measured. Prior to atomic clocks, the second was defined by dividing down astronomical events. For example, in 1799 the French Government officially defined the second to be 1/86,400 th of a day as originally defined by astronomers at least 700 years earlier.

$$1\ second = \frac{1\ Day}{86{,}400} = \frac{1\ Day}{(24\ hr/day)(60\ min/hr)(60\ sec/min)}$$

By 1960 the second was defined to be

$$1\ second = \frac{Earth's\ Orbital\ Period\ in\ the\ year\ 1900}{31{,}556{,}925.9747}$$

This all changed in 1967, when the second was redefined using oscillations within the Cesium-133 atom instead of Earth's orbital period. Specifically, the second is defined as the time it takes a Cesium-133 atom, in a precisely defined state, to oscillate exactly 9,192,631,770 times. That is,

1 second = 9,192,631,770 periods of the Cesium – 133 atomic clock

The accuracy of atomic clocks are required for the Global Positioning System (GPS) system, for navigating spacecraft throughout the solar system, synchronizing the internet, maintaining stability of the power grid, synchronizing automated financial trading, and many other applications. Some 400 atomic clocks around the world contribute to calculation of International Atomic Time (TAI) which in turn is used to determine Coordinated Universal Time (UTC) and local times around the world.

13.1 Difference Between Atomic and Previous Clocks

Atomic clocks are different than all previous types of clocks. In a quartz clock, for example, a slab of quartz crystal is cut and ground (machined) to a particular thickness which determines its frequency of oscillation. The tolerance to which a crystal can be cut and ground is limited by the machinery used in the manufacturing processing. Variations within the tolerance limits means that each crystal will in fact be unique, oscillating at a slightly different frequency from each of the other crystals produced by the same machinery. Consequently, the clocks built using these crystals will all keep slightly different time.

In contrast, all atoms of a particular type, for example Cesium-133 ($^{133}Cs_{55}$), are identical. Oscillations occurring in one cesium atom, within a particular quantum state, are absolutely identical to oscillations occurring in all other cesium atoms in the same state. This was understood early on leading to the idea of using atoms as the time base for extremely accurate clocks. The problem was how to build such a clock.

13.2 Development of the First Atomic Clocks

Experiments with atomic clocks were finally made possible by rapid advances in quantum mechanics and microwave electronics that took place in the 1930s and 1940s. Most of the concepts that led to atomic clocks were developed by Isidor Isaac Rabi and his colleagues at Columbia University.

The first working atomic clock was developed by Harold Lyons and his associates at the National Bureau of Standards (NBS) in 1948. Note: NBS was renamed the National Institute of Standards and Technology (NIST) in 1988. The clock developed by Lyons used the 23.8 GHz inversion transition of the ammonia molecule as its resonance source. The clock consisted of a quartz oscillator electronically synchronized to the frequency of the ammonia absorption line. Frequency dividers divided down the output of the quartz oscillator to 50 Hz. Two ammonia clocks were built. While they failed to achieve the accuracy of the best quartz clocks at the time, they did prove that atomic clocks were feasible.

In 1950 Lyons and his NBS team selected cesium as the resonance source for the atomic clock that they were then working on. Cesium has several desirable characteristics that make it a good choice. Cesium is similar to mercury in that it is a soft silvery-white ductile metal. It melts, becoming a liquid, at about 28.4^{o} C. Cesium atoms are fairly heavy (133 atomic mass units) causing them to move at a relatively slow speed of around 130 m/s at room temperature. The resonant frequency of cesium is ~ 9.2 GHz. This is a higher frequency than rubidium (~ 6.8 GHz) and hydrogen (~1.4 GHz) which have been used in some later atomic clocks.

The first NBS cesium clock (NBS-1) was announced in 1952, however it was not accurate enough to serve as a time standard. Budgetary concerns and interest in other areas caused the NBS to temporarily interrupt its atomic clock program in 1953. The NBS-1 clock was disassembled and moved from Washington D.C. to the new Boulder, Colorado laboratory in 1954. By 1955 Lyons had left the NBS.

In England, Louis Essen convinced the director of England's National Physical Laboratory (NPL) to pursue the building of a cesium atomic clock. Work began in 1953 and proceeded rapidly. Essen and his team completed the first successful cesium atomic clock in June 1955 (Figure 53). The accuracy of the clock was 0.001 parts per million (ppm) or approximately 0.1 ms per day.

The first successful NBS cesium atomic clock, designated NBS-2, was completed and put into operation at the NBS Boulder, CO laboratory in 1958. This clock approached an accuracy of 0.0001 ppm, approximately equal to $10\mu sec/day$. A series of NBS cesium atomic clocks followed, as illustrated in Figure 54, culminating in 1993 with NBS-7 (renamed to NIST-7) with an accuracy of 5 parts in 10 to the 15th power, 20 times more accurate than NBS-6.

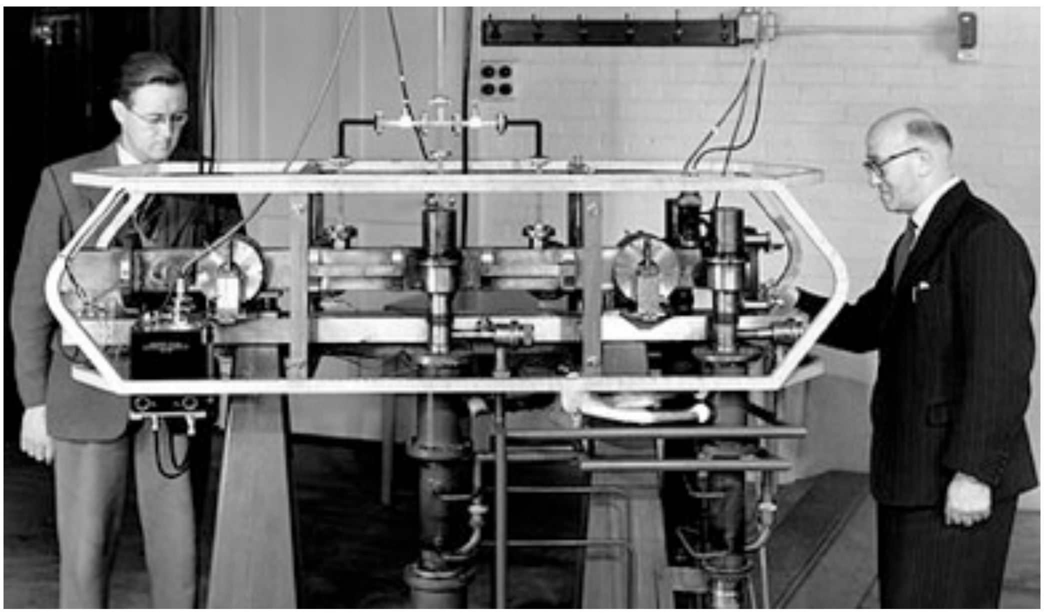


Figure 53 Louis Essen (right) and Jack Parry (left) with the original NPL Cesium clock. (source: Lombardi)

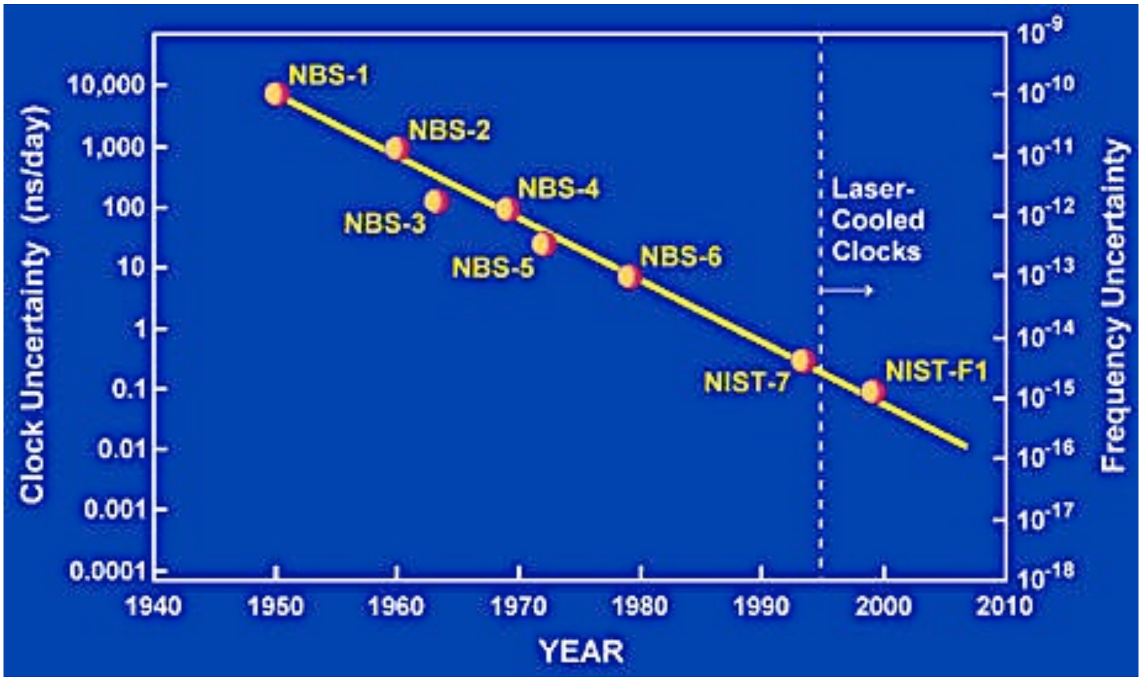


Figure 54 History of Atomic Clocks at NIST (source: NIST)

In 1999 NIST introduced its NIST-F1 cesium fountain atomic clock. Fountain technology allowed the clock to achieve an accuracy of 1.7 parts in 10 to the 15th power, that is, about one second in 20 million years. At that time, NIST-F1 was the most accurate clock ever built (a distinction shared with a similar standard in Paris).

13.3 Atomic Clock Concept of Operation

The basic principle of atomic clocks is relatively simple. All atoms of a specific element are identical, absorbing energy at exactly the same frequency when excited to a higher energy level and radiating that same energy at the same frequency when falling back to their normal ground state. The problem is being able to measure the undisturbed resonance frequency of an atom as its electrons jump between discrete energy levels.

An externally generated electromagnetic field at a specific frequency can boost an atom from one energy level (E_1) to a higher one (E_2). Once at the higher level, the atom spontaneously drops back to the lower energy level by emitting energy. This process occurs continuously as a beam of cesium atoms passes through an electromagnetic field, causing the atoms to oscillate between the two energy levels E_1 and E_2. The resonance frequency (f_0) of the oscillation is the difference between the two energy levels, E_1 and E_2, divided by Planck's constant, h

$$f_0 = \frac{E_2 - E_1}{h}$$

Atoms absorb and emit energy over a small frequency range surrounding f_0, not just at f_0 alone. This frequency spread 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

$$Q = \frac{f_0}{\Delta f_a}$$

The resonant Q of oscillations within an atom is large due to the atom's high resonant frequency f_0 and it relatively small resonance width Δf_a . This Q is enormous compared to that achieved by frequency determining elements (pendulums, quartz crystals, etc.) in all previous types of clocks. For this reason atomic clocks are the world's most accurate clocks.

Operation of a cesium beam atomic clock is illustrated in Figure 55. Cesium atoms are heated to a gas inside an oven, shown at the left side of Figure 55. A small hole in the oven allows a narrow beam of high speed atoms to leave the oven and travel through a vacuum tube toward a pair of magnets. The magnets divert atoms at a particular magnetic energy level into a microwave cavity. The remaining atoms are deflected way from the cavity. Atoms that enter the cavity are subjected to microwave energy produced by a quartz crystal oscillator and frequency synthesizer. Some of the cesium atoms in the cavity will change to a different magnetic energy state if the microwave energy is tuned to the proper frequency.

The beam of atoms passes through a second pair of magnetics after leaving the cavity. Those atoms whose magnetic state were altered in the cavity are diverted by this second set of magnetics to a detector at the right end of the evacuated tube. Atoms whose magnetic states were not altered travel past the detector and are not counted.

The detector output is sent to a feedback servo that continuously tunes the quartz oscillator up and down in frequency. The oscillator output in turn drives a frequency synthesizer that produces the microwave energy injected into to the cavity. Tuning continues until a sharp spike in the detector output is encountered (a maximum number of atoms striking the detector). The microwave frequency producing the spike is equal to the cesium atom resonant frequency. This frequency turns out to be 9,192,631,770 Hz, a little over 9.192 GHz.

The length of the cesium beam tube is typically less than 0.5 meters. Cesium atoms travel inside the tube at velocities greater than 100 meters per second limiting observation time to a few milliseconds. The resonance width of a cesium clock is typically a few hundred hertz, producing a timing accuracy of 1 nsec and a frequency accuracy of 1 x 10^{-14}. The resonant Q of a cesium clock is a few parts in 10^8.

A picture of the NIST-7 cesium beam clock is shown in Figure 56. Notice the vacuum tube mounted on top of the electronic equipment cabinets.

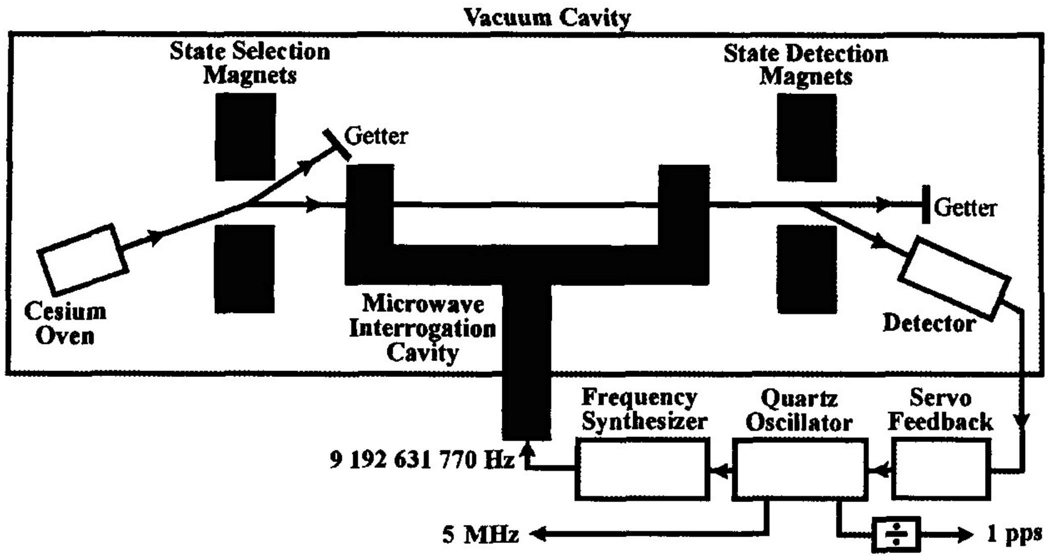


Figure 55 Cesium beam atomic clock (source: Lombardi "Time and Frequency")

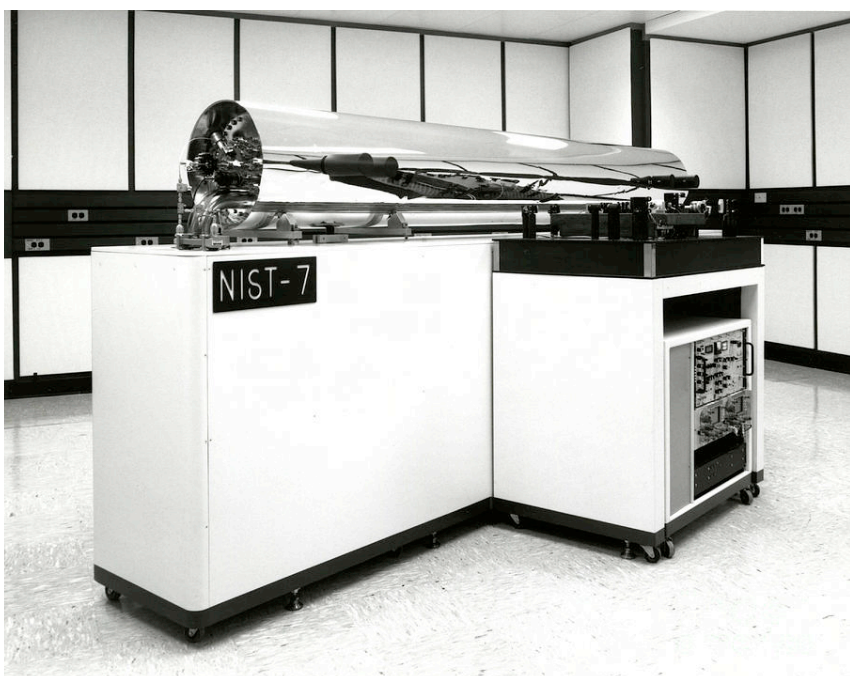


Figure 56 NIST-7 Cesium beam atomic clock (source: NIST)

13.4 Cesium Fountain Atomic Clock

The description which follows of the NIST-F1 caesium fountain atomic clock has been adapted from the article titled "NIST-F1 Cesium Fountain Clock" published by NIST on December 29, 1999 (https://www.nist.gov/news-events/news/1999/12/nist-f1-cesium-fountain-clock).

The NIST-F1 atomic clock is referred to as a fountain clock because it uses a fountain like movement of atoms to increase its accuracy.

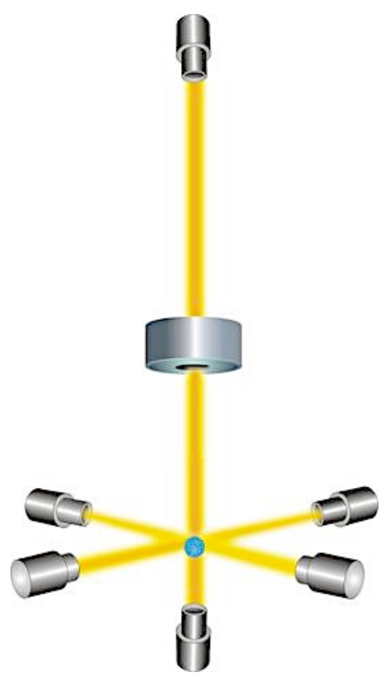


Figure 57: Cesium atoms enter the clock's vacuum chamber (source: NIST).

A gas of cesium atoms enters the clock's vacuum chamber. Six infrared laser beams are then turned on. The laser beams are directed at right angles to each other converging at the center of the chamber. The lasers gently push the cesium atoms together into a ball. In the process the lasers slow down the movement of the atoms and cools them to near absolute zero.

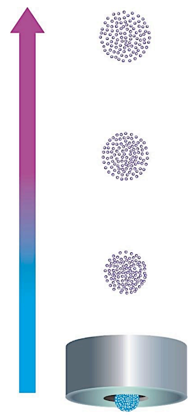


Figure 58: Ball of cesium atoms tossed upward through microwave cavity (source: NIST)

Two vertical lasers are used to gently toss the ball upward (the "fountain" action), and then all of the lasers are turned off. This little push is just enough to loft the ball about a meter high through a microwave-filled cavity.

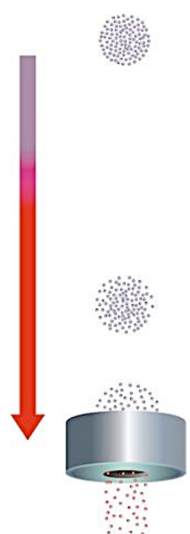


Figure 59: Ball of Cesium atoms fall back through microwave cavity (source: NIST)

Under the influence of gravity, the ball of cesium atoms then falls back down through the cavity.

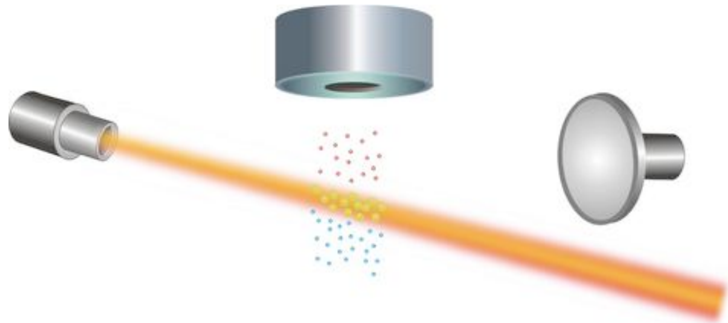


Figure 60: Cesium atoms interact with the microwave energy (source: NIST)

The atomic state of the cesium atoms may or may not be altered as they interact with the microwave energy in the cavity. The degree to which they are altered depends on the microwave frequency.

The entire round trip for the ball of atoms takes about a second. At the finish point, another laser is directed at the cesium atoms. Cesium atoms that were altered in the microwave cavity emit light (known as fluorescence) when hit with the laser beam. The photons of emitted light are measured by a detector (on the right in Figure 60).

This procedure is repeated many times while the microwave energy in the cavity is tuned to different frequencies. Eventually, a microwave frequency is achieved that alters the state of most of the cesium atoms maximizing the fluorescence. This frequency is the natural resonance frequency for the cesium atom (9,192,631,770 Hz).

The combination of laser cooling and the fountain design allows NIST-F1 to observe cesium atoms for a longer period of time. Cesium beam clocks (NBS-1 through NIST-7) measure the resonant frequency of cesium atoms at room temperature. At this temperature the atoms are moving over a hundred meters per second, limiting observation to only a few milliseconds. The laser cooling used in NIST-F1 drops the temperature of the cesium atoms to a few millionths of a degree above absolute zero, reducing their thermal velocity to a few centimeters per second. The observation time is increased further by launching the atoms vertically and then allowing gravity to pull them back down. In the process they pass through the microwave cavity twice, once on the way up and again on the way down. The result is an observation time of about one second instead of a few milliseconds. The longer observation time makes it easier to tune the microwave frequency to the exact resonant frequency of the cesium atom. That is, the resonant frequency of the cesium atom becomes know to a precision far greater than 9,192,631,770 Hz .

The Q of the NIST-F1 cesium fountain clock is about 10^{10}, or about 100 times higher than a cesium beam clock. Although the resonance frequency is the same (9,192,631,770 Hz), the resonance width of the fountain clock is less than 1 Hz, much narrower than the resonance width of a few hundred hertz for a cesium beam clock. The narrower resonance width is due to the longer observation time.

The accuracy of the NIST-F1 clock is about 3×10^{-16}, which means that it will neither gain or lose a second in more than 100 million years. This is approximately ten times more accurate than the previous NIST-7 cesium beam atomic clock.

A picture of the NIST-F1 cesium fountain clock is shown in Figure 61.

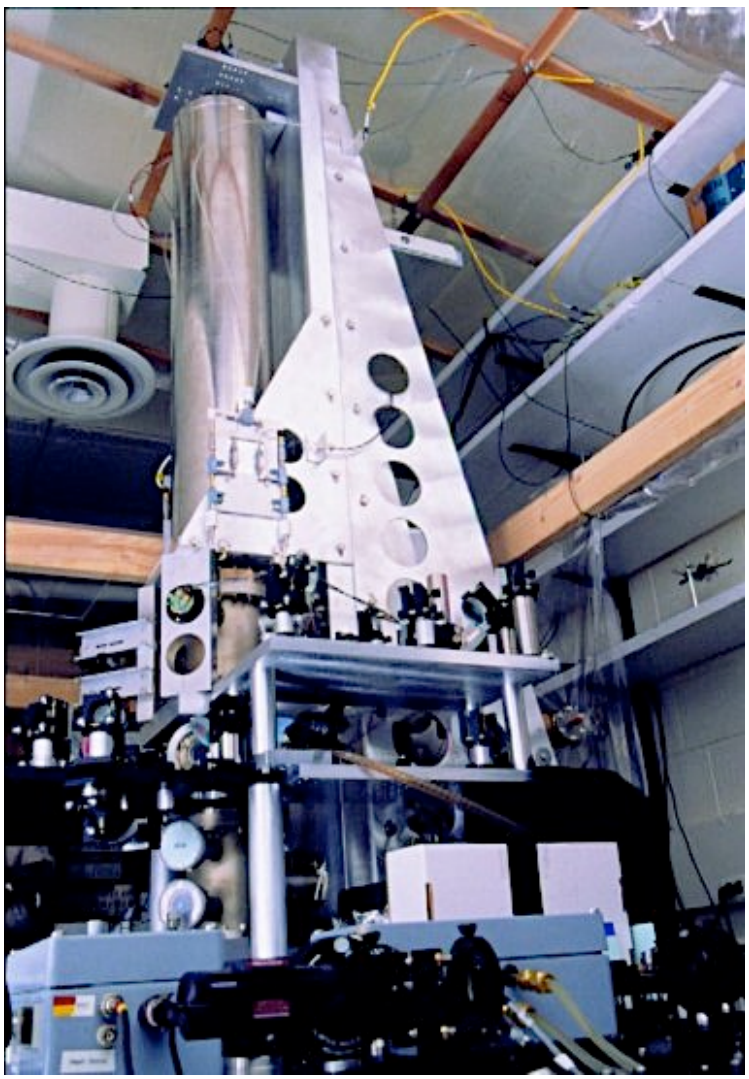


Figure 61 NIST-F1 Cesium Fountain Clock (source: NIST)

Operation of the NIST-F2 cesium fountain clock was inaugurated on April 3, 2014. NIST-F2 will neither gain or lose one second in about 300 million years making it approximately three times more accurate than NIST-F1. NIST-F1 served as the United States time standard from 1999 until 2014 when NIST-F2 came on-line.

13.5 Other Types of Atomic Clocks

Other types of atomic clocks include hydrogen, rubidium, chip size atomic clocks, and optical clocks

13.5.1 Hydrogen Atomic Clock

A hydrogen atomic clock works by pumping hydrogen gas through a magnetic gate as illustrated in the bottom right of Figure 62. Only those atoms in a certain energy state are able to pass through the gate into a storage bulb. Once inside the bulb, some of the hydrogen atoms drop to a lower energy level releasing photons at microwave frequencies. These photons bombard other hydrogen atoms causing them to also drop to lower energy levels releasing still more microwave photons. A microwave field at 1,420,405,752 Hz builds up in the bulb as long as additional hydrogen atoms continue to be pumped through the magnetic gate into the bulb. A resonant cavity around the bulb helps to keep the process going by redirecting photons that escape from the bulb back into the system. Some of the microwave energy from inside the shielded cavity is fed to a phase locked loop that keeps a quartz crystal oscillator locked to the hydrogen atom resonant frequency. Typically, the oscillator runs at 5 MHz.

The 1,420,405,752 Hz resonance frequency of hydrogen is much lower than the 9,192,631,770 Hz cesium atom frequency. But, the resonance width of a hydrogen atomic clock is only a few hertz compared to a few hundred hertz for a cesium beam clock. As a result, the Q of a hydrogen clock is around 10^9, about an order of magnitude better than a cesium beam clock. Consequently, the short term stability of a hydrogen clock over a couple of days is better than a cesium clock. Over longer periods of time, a few days to several weeks, the hydrogen clock performance gradually falls below that of a cesium clock.

A desk size hydrogen atomic clock is shown in Figure 63.

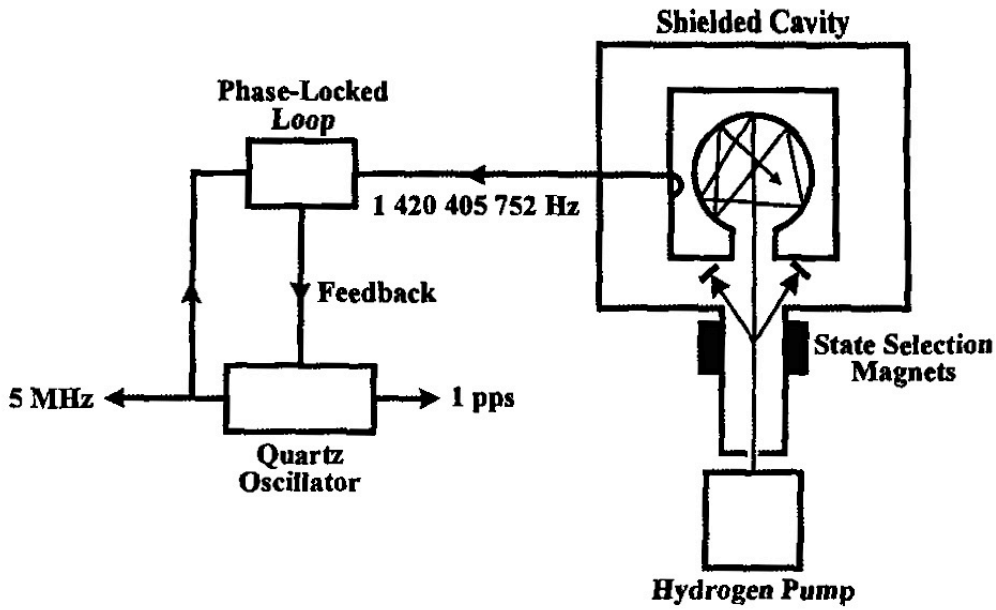


Figure 62 Hydrogen atomic clock diagram (source: Lombardi “Time and Frequency”)

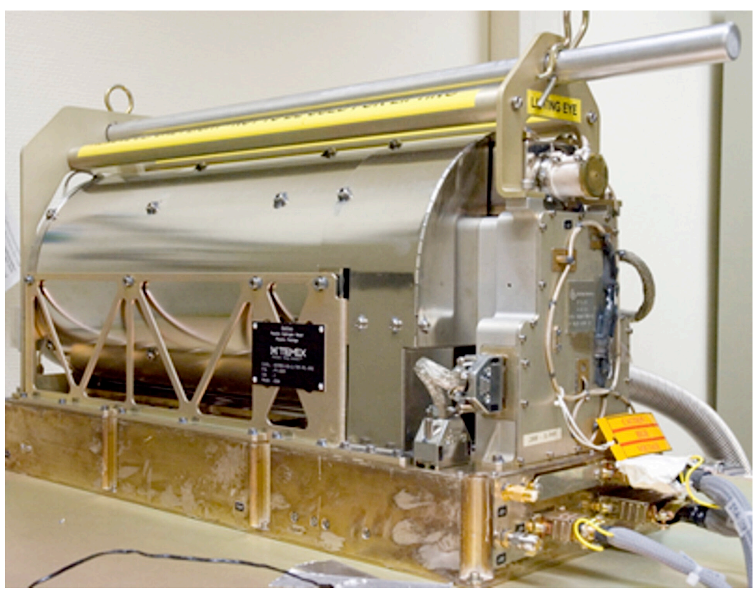


Figure 63 Hydrogen Atomic Clock (source: esa.int)

13.5.2 Rubidium Atomic Clock

Rubidium atomic clocks are generally smaller and lower in cost than other atomic clocks.

Operation of a rubidium clock is illustrated in Figure 64. Rubidium $^{87}Rb_{37}$ vapor inside a cell mounted in a shielded cavity is exposed to microwave energy produced by a quartz oscillator and frequency synthesizer. The microwave energy alters the energy level of some of the rubidium atoms. An optical beam formed by a rubidium lamp is shown into the cell and absorbed by those atoms whose energy levels have been altered. A photo cell detector measures how much of the light beam is adsorbed. The detector output is sent to a feedback servo that continuously tunes the quartz oscillator up and down in frequency. The oscillator output in turn drives a frequency synthesizer that produces the microwave energy injected into to the vapor cell. Tuning continues until the maximum amount of light is absorbed (a sharp dip occurs in the detector output). The frequency at which this occurs is the 6,834,682,608 Hz resonant frequency of the rubidium atom.

The Q of a rubidium clock is around 10^7, an order of magnitude less than that of a cesium beam clock. Shifts in the measured resonant frequency of rubidium clocks is caused primarily by collisions of rubidium atoms with other gas molecules. These shifts limit the long term stability of rubidium clocks. The accuracy of rubidium clocks is around 10^{-12}, two orders of magnitude less than a cesium beam clock. However, this accuracy is adequate for many applications.

Rubidium atomic clocks continue to get small and less expensive, often providing the best price/performance trade off for many applications. Their long term stability is much better than quartz oscillators and they are smaller, more reliable, and less expensive than cesium clocks. Rubidium atomic clocks have become the workhorse for GPS and similar satellite navigation systems. A GPS satellite typically carries 3 to 4 onboard rubidium clocks. They are also extensively used in numerous military applications including secure communications, electronic warfare, command and control plus telemetry and navigation. A typical rubidium atomic clock is shown in Figure 65.

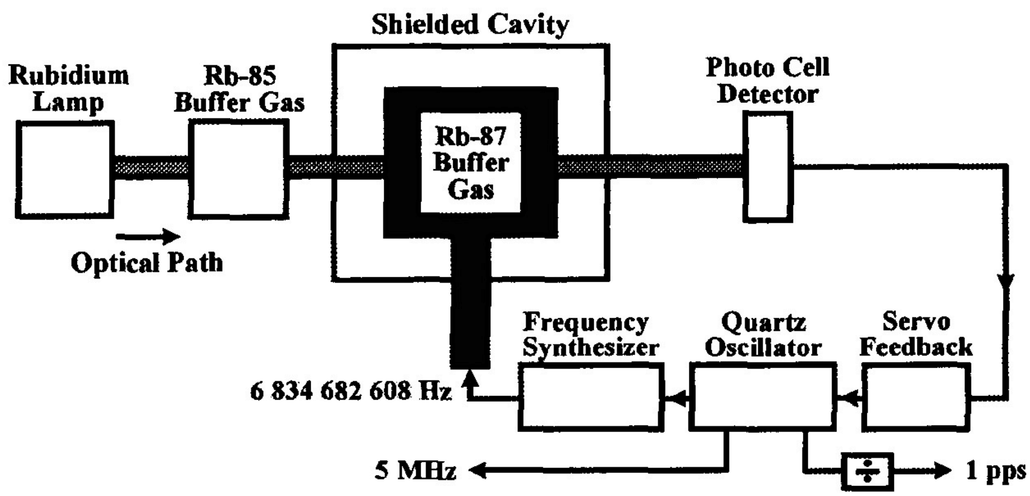


Figure 64 Rubidium atomic clock diagram (source: Lombardi "Time and Frequency")

Figure 65 Rubidium Atomic Clock (source: esa.int)

13.5.3 Chip Size Atomic Clocks

A chip scale atomic clock (CSAC) is a compact, low power atomic clock fabricated using micro-electro-mechanical-system (MEMS) technology. Both cesium and rubidium clocks are available.

For a CSAC cesium clock, liquid cesium in a capsule 2 cubic millimeters in size is heated to vaporize the cesium. The capsule is fabricated using silicon micromachining technology. A semiconductor laser shines a beam of infrared light, modulated by a microwave signal, through the capsule and onto a photo-detector. The microwave signal is produced by a quartz crystal oscillator that drives a microwave frequency synthesizer. Cesium atom absorption of the infrared light is minimized when the frequency of the microwave signal is equal to the cesium atom resonant frequency. When this occurs the photo-detector output peaks (more infrared light striking the photo-detector). The photo-detector is fed to a tiny on-chip servo mechanism that continuously tunes the quartz oscillator frequency synthesizer. Tuning continues until a peak in the photo-detector output occurs, indicating that the microwave signal and the cesium atoms are at the same resonant frequency (6,834,682,608 Hz).

CSAC cesium clocks typically measure 4 x 3.5 x 1 cm (1.5 x 1.4 x 0.4 inches) in size, weigh 35 grams and consumes only 115 mW of power. The accuracy of this type of clock is generally 100 microseconds per day. An important part in development of a CSCA clock is designing the device so it can be manufactured using standard semiconductor fabrication techniques. This is necessary to keep its cost low enough that it can become a mass market device.

CSAC rubidium clocks are also being manufactured. These clocks typically measure 5.08 x 5.08 cm, operates over a temperature of -40 to +75 ^{o}C, and consumes 6.3 watts of power. Their frequency accuracy is 5 x 10^{-11}.

An example of a CSAC clock is shown in Figure 66.

Figure 66 CSAC atomic clock (source: Teledyne)

13.5.4 Optical Clocks

Optical atomic clocks are even more accurate than cesium clocks. Optical clocks use light in the visible spectrum to measure atomic oscillations. The frequency of visible light is about 50,000 times higher than that of microwave radiation, providing more precise measurements of atomic oscillations. Optical atomic clocks are accurate to around 1 second in 15 billion years.

13.6 Timekeeping Accuracy

A summary of clock performance for the major types of precision clocks used throughout history is provided in the table below.

Standard	Resonator	Date of Origin	Timing Accuracy (24 Hr)	Frequency Accuracy (24 Hr)
Sundial	Apparent motion of sun	1500 B.C.	NA	NA
Verge Escapement	Verge & foliet mechanism	14th century	15 min	1×10^{-2}
Pendulum	Pendulum	1656	10 sec	7×10^{-4}
Shortt Pendulum	2 pendulums (master & slave)	1921	10 msec	1×10^{-7}
Quartz Crystal	Quartz crystal	1927	10 μsec	1×10^{-10}
Rubidium Gas Cell	Rb (6,834,682,608 Hz)	1958	100 nsec	1×10^{-12}
Cesium Beam	Cs (9,192,631,770 Hz)	1952	1 nsec	1×10^{-14}
Hydrogen Maser	Hydrogen Maser (1,420,405,752 Hz)	1960	1 nsec	1×10^{-14}
Cesium Fountain	Cs (9,192,631,770 Hz)	1991	100 psec	1×10^{-15}

High accuracy timekeeping is critical to our technologically based society. Systems that depend on highly accuracy clocks include:

- Telecommunications systems, including the internet, require synchronizations to better than 100 billionths of a second.

- The GPS Global Positioning System requires time measurements in which billionths of a second are significant. The GPS system would not be possible without the accuracy of atomic clocks

- Electrical power companies use atomic clock synchronized systems to accurately determine the location of faults when they occur (for example, lightning damage) and to control the stability of their distribution systems.

- Radio astronomers view very distant objects in the universe using long baseline interferometers. An interferometer combines together radio signals from widely spaced receivers thousands of miles apart to form a single image of a distant object. This technology depends on extremely accurate atomic clocks to synchronize the various receivers.

- Navigation of spacecraft throughout the solar system, including critical spacecraft that continuously monitor the Sun, depend on a world wide network of command and control stations synchronized by atomic clocks. Exploration of the solar system, including Mars, would not be possible without atomic clocks.

- CSCA atomic clocks are used in a vast assortment of commercial and military applications including underwater sensors for gas and oil exploration, timing for seismic measurements, operation of drone aircraft, anti-jam and anti-spoofing GPS receivers, and in medical research.

- In financial markets high speed electronic trading requires very accurate time/date stamping to ensure that transactions are processed in the order received. The Security and Exchange Commission now requires brokers to synchronize their time stamps with the NIST atomic clocks.

References

Lombardi, Michael A.' "First in a Series on the Evolution of Time Measurement: Celestial, Flow, and Mechanical Clocks"; IEEE Instrumentation & Measurement Magazine; https://tf.nist.gov/general/pdf/2533.pdf

Lombardi, Michael A.' "The Evolution of Time Measurement, Part 2: Quartz Clocks"; IEEE Instrumentation & Measurement Magazine; https://tf.nist.gov/general/pdf/2534.pdf

Lombardi, Michael A.' "The Evolution of Time Measurement, Part 3: Atomic Clocks"; IEEE Instrumentation & Measurement Magazine; https://tf.nist.gov/general/pdf/2535.pdf

Lombardi, Michael A.' "The Evolution of Time Measurement, Part 5: Radio Controlled Clocks"; IEEE Instrumentation & Measurement Magazine; https://tf.nist.gov/general/pdf/2536.pdf

Lombardi, Michael A.; "Time and Frequency"; Encyclopedia of Physical Science and Technology (Third Edition), 2003

Kamrin, Janice; "Telling Time in Ancient Egypt" Department of Egyptian Art, The Metropolitan Museum of Art, February 2017, https://www.metmuseum.org/toah/hd/tell/hd_tell.htm

Gerginov, Vladislav; "NIST-F1 Cesium Fountain Atomic Clock"; NIST Physical Measurement Laboratory / Time and Frequency Division; https://www.nist.gov/pml/time-and-frequency-division/time-realization/primary-standard-nist-f1

Joseph F. Keithley, "The Story of Electrical and Magnetic Measurements", IEEE Press, New York, 1999

Nikolai Weibull, "A Historical Survey of Number Systems" http://www.math.chalmers.se/Math/Grundutb/GU/MAN250/S04/Number_Systems.pdf

Michael A. Lombardi, "Why is a minute divided into 60 seconds, an hour into 60 minutes, yet there are only 24 hours in a day?", Scientific American, March 5, 2007, http://www.scientificamerican.com/article/experts-time-division-days-hours-minutes/

Wikipedia, "Degree (angle)", http://en.wikipedia.org/wiki/Degree_%28angle%29

Edgar W. Woolard, "The Historical Development of Celestial Co-ordinate Systems" Astronomical Society of the Pacific, http://adsabs.harvard.edu/full/1942PASP...54...77W

Wikipedia, "History of Astronomy, http://en.wikipedia.org/wiki/History_of_astronomy

D. B. Sullivan, "Time And Frequency Measurement At NIST: The First 100 Years", Time and Frequency Division, Physics Laboratory, National Institute of standards and Technology (NIST), Boulder, Co., 2001, http://tf.nist.gov/general/pdf/1485.pdf

Wikipedia, "History of Timekeeping Devices", Wikipedia, http://en.wikipedia.org/wiki/History_of_timekeeping_devices

Dr Miodrag Stoimenov, "Evolution of Clock Escapement Mechanisms", Faculty of Mechanical Engineering, Belgrade, FME Transactions (2012) 40, 17-23. http://www.mas.bg.ac.rs/istrazivanje/biblioteka/publikacije/Transactions_FME/Volume40/1/03_MStoimenov.pdf

Wikipedia, "Pendulum Clock" https://en.wikipedia.org/wiki/Pendulum_clock

Wikipedia, "Anchor Escapement, https://en.wikipedia.org/wiki/Anchor_escapement

Lafferty, Stephen H.; "The Time Machine"; http://tronola.com/Quartz_Clock_ Repro2

Marrison, Warren A.; "The Evolution of the Quartz Crystal Clock", The Bell System Technical Journal, Vol. XXVII, pp. 510-588, 1948.

Fleischer, Cesca; "How Piezoelectricity Works" https://www.autodesk.com/products/eagle/blog/piezoelectricity/

Wikipedia; "Quartz Clock"; https://en.wikipedia.org/wiki/Quartz_clock

Electronics Tutorials, "Quartz Crystal Oscillators", https://www.electronics-tutorials.ws/oscillator/crystal.html

"Guide to Crystal Oscillators -- Popular Crystal Oscillator Circuits"; https://www.industrial-electronics.com/crystal_osc_4.html

Conhaim, R.L.; Understanding Frequency-Control Crystals; Electronics World, May 1964

Angelo, E.J. Jr.; "Electronics Circuits"; McGraw-Hill Book Company, 1958

Cirovic, Michael M, Harter, James H.; "Electronic Devices, Circuits, and Systems third Edition"; Prentice-Hall inc.,1987

Bowick, Chris; "RF Circuit Design"; Howard W. Sams & Co, 1982

U.S. Naval Observatory, "Cesium Atomic Clocks", http://tycho.usno.navy.mil/cesium.html