How Watches Keep Time

It would be hard to imagine existing without time. Our lives would be chaos. How would we know when to get up in time to go to work, to go home, to meet someone, to watch our favorite TV show? How would we know how long to cook an egg or bake a cake? How would the officials know when to stop a football game for halftime? We need some means of measuring the time of day—7 a.m., time to wake up—and the passage of time—35 minutes have elapsed—take the cake out of the oven.

1. The Five Elements of Time Keeping

Ever since man has determined the need for measuring time, he has invented mechanisms for doing so. Time keeping machines—we'll call them generically clocks or watches—require five essential elements:

1. a **time base or time keeping mechanism**,
2. an **accumulator** to count and store the passage of time,
3. a **setting and adjustment mechanism** to synchronize the clock with another clock and make fine adjustments to the time base,
4. a **display** to show the time of day, and
5. a **power source** to run the whole thing.

The Time Base or Time Keeping Mechanism

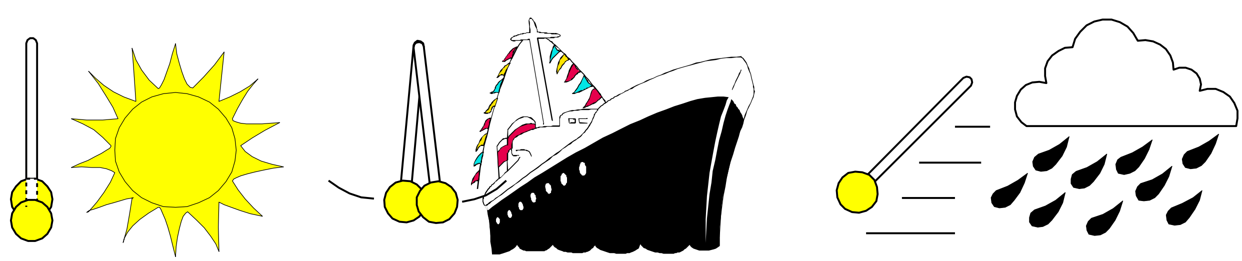
The time base is the *heart* of the clock. It's the mechanism that measures time, usually in small beats or ticks. The rest is support—to supply power, set, store and display the time.

There is an old joke about which type of clock you would rather have: a clock that is never right or one that is right once every 12 hours? You might think that a clock that is never right is useless, but consider a watch that is always 5 minutes fast. It is never right, but it is most useful because you can compensate for inaccuracy by subtracting 5 minutes from its indicated time. A watch that is right once every 12 hours has stopped!

The watch that is always 5 minutes fast is accurate, but is merely set to the wrong time. Consider a watch that gains one minute a day. It is not accurate but is consistent. It is a useful watch because you can compensate by either setting it back one minute every day or remembering how many days since you last set it and subtract one minute for each day.

The worst case is a watch that varies erratically, losing two minutes one day and gaining three minutes the next.

What affects the stability of an otherwise accurate watch? The most common environmental effects are temperature, physical movement and wind currents



Temperature Movement Wind currents

Some time base mechanisms are more susceptible to these environmental influences than others.

Time base mechanisms rely on the accuracy and repeatability of periodically occurring phenomena. Examples are the rotation of the earth on its axis as in the case of the sundial or the period of oscillation of a pendulum or vibrating mass and spring as in the case of most watches.

The Time Accumulator Mechanism

The time accumulator is the *brain* of the clock. It keeps track of the time by counting the beats or ticks of the time base mechanism. This is in the form of a container to store the water or sand of the water clock or hourglass, gears in most watches and clocks, or electronic counters in the case of digital watches.

Setting and Adjustment Mechanism

The setting mechanism is the eyes and ears of the clock because it allows the clock to receive input from the outside world. Setting mechanisms allow us to move the hands of an analog clock or change the digits of a digital watch. Even the sundial has some form of adjustment such as moving the dial or adjusting the angle of the gnomon.

The adjustment mechanism allows the user or a technician to adjust the time base mechanism—to speed it up or slow it down—as necessary to keep the clock or watch accurate.

Display

The display is the *face and hands* of the clock. This is output from the clock to the human user. It is usually in the form of a face with hands, or a digital display, or in the case of the sundial, the position of a shadow on the face.

Power Source

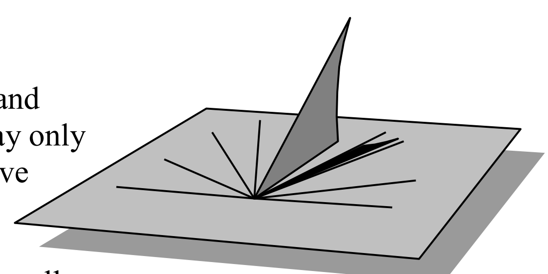
The power source is the *muscle* of the clock. Until someone invents a true perpetual motion machine, a clock requires some source of power, be it chemical energy stored in the tallow of a wax candle, the winding of a spring, the lifting of a weight, or the power from a battery or the AC power line. Even the sundial has a power source, albeit external: the rotation of the earth. Is the rotation of the earth perpetual motion? No, because the earth is slowing down every year and will eventually stop. But not for millions of years. Don't lose any sleep over it.

2. <u>Type of Clocks</u>

We will examine clocks that use the rotation of the earth on its axis as the time base, such as the sundial. The candle as a clock employs the rate of burning of wax as its time measuring mechanism. The water clock and hourglass rely on the time it takes a flowing substance—water or fine sand—to transit through a small orifice.

The most accurate clocks rely on the period of oscillation of a pendulum or vibrating mass and spring or other natural oscillation. We will examine escapement mechanisms used with pendulums and with the balance wheel and hairspring. We will also consider other mechanical oscillators and finally the oscillations of atoms, as in the atomic clock.

3. <u>Sundials</u>



The earliest timekeepers were sundials. Sundials are stable, accurate and consistent but not very precise. That is, one can resolve the time of day only down to about five or ten minutes. Temperature and wind currents have little effect on sundials. But physical movement affects the display of the correct time which is the reason that sundials are mounted to a fixed surface. There have been pocket and wrist sundials that have a small magnetic compass to orient them north. The dial must be oriented with respect to the north pole, and the gnomon—the vertically mounted wedge-shaped piece—must be angled based on longitude of the sundial's location. Sundials do not function at night.

The Time Base or Time Keeping Mechanism

The time base mechanism of the sundial is external: the earth's rotation. This is constant day after day, and although the earth is slowing down each year, the rate of slowdown is minuscule. The earth is like a large friction-free top that has so much momentum—and virtually nothing to slow it down—that it becomes an excellent time base mechanism. Until the adoption of the atomic clock as a time standard, the rotation of the earth was *the* world's time standard.

The Time Accumulator Mechanism

The rotational position of the earth relative to the sun is taken to be the time accumulator mechanism. Since the sun rotates at a fixed rate, it will rotate exactly 15° in one hour. The position of the earth's rotation represents the time of day.

Setting and Adjustment Mechanism

The sundial must be custom built for its location on the earth. It is set once when it is built and should never require setting again. However in some sundials the reading has to be corrected for the season of the year. Every location along a line of latitude that has a sundial will display high-noon at a different time, unlike our time zones today where all locations within a time zone have exactly the same time. For example when town A shows high-noon, town B, situated—1° to the west—will show high-noon 4 minutes later.

There is no speed adjustment for a sundial since the speed of the earth's rotation is, for all practical purposes, constant.

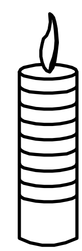
Display

The sundial's display is the sun's shadow that the gnomon casts on the dial. It doesn't work during overcast or at night. The earth's rotation is still keeping the correct time, it just that we can't see it until the sun appears again.

Power Source

The power source of the sundial is the large momentum of the earth's rotation. The sun is the source of power for the display, but not for the timekeeping mechanism.

4. <u>Candle</u>



The candle is the least accurate clock. A candle clock has hour circles inscribed on the barrel and the passage of time is determined by the number of circles that are remaining. The candle is usually shielded by a surrounding glass cylinder.

The Time Base or Time Keeping Mechanism

The candle is not a very accurate clock but served as a useful timekeeper for the passage of the night hours when sundials would be useless. The time base is the rate at which the candle burns. The candle is sensitive to all environmental conditions including temperature, physical movement and wind currents. We have all observed that candles on hot days burn faster and the wax drips excessively. Any wind currents could cause the flame to grow or contract and change the rate at which the candle shrinks. The composition of the tallow in the candle has an effect of the accuracy. One batch of tallow might have a different mix of ingredients and would burn at a different rate than another batch.

The Time Accumulator Mechanism

The accumulator is the candle itself. The amount of candle remaining is the measurement of the passage of time. Less candle remaining, less time remaining.

Setting and Adjustment Mechanism

The candle has to be lighted at a known time, perhaps in the late afternoon while the sundial was still capable of displaying the time.

Adjusting the speed of a burning candle is limited to keeping the temperature constant and keeping the flame away from any air currents.

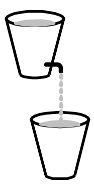
Display

The display is the same as the time accumulator: the amount of candle remaining. Circles inscribed on the cylindrical surface of the candle could be used to count the hours.

Power Source

The chemical energy of the wax tallow in the candle is its power source. The candle is the only clock that consumes itself during its rather short useful life. The ultimate disposable clock!

5. Water Clock



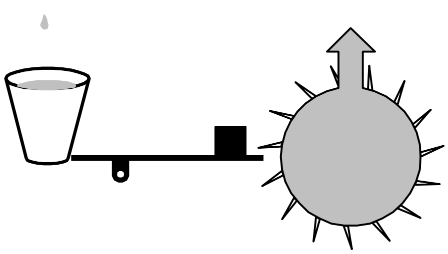
The water clock relies on the rate of water dripping through a small orifice in the upper source container. The amount of water accumulated in the lower collection container will measure time, or the amount of water absent from the source container can also be used to ascertain the passing of time. In some cases the water fills a small container that would tip over when its contents reached a certain level and the tipping action would move a gear one notch.

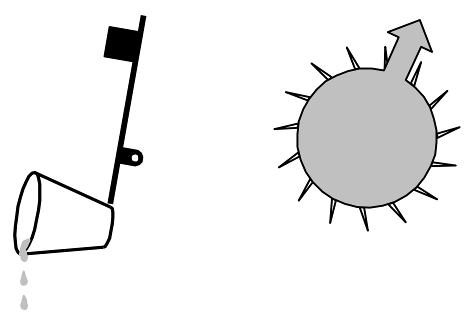
The Time Base or Time Keeping Mechanism

The water clock is susceptible to freezing and impurities in the water. If the orifice is blocked in any way it would impede the flow of water and change the speed of the clock.

The Time Accumulator Mechanism

The accumulator in the water clock is the amount of water accumulated in a collection container. Every drop of water that drips from the upper container must be accounted for. In the more elaborate implementations with tipping mechanisms and gear counters, the gears are also part of the accumulator mechanism. For example at one drip per second, if the mechanism tipped after 60 drips, the hand would advance once a minute.





Setting and Adjustment Mechanism

Setting the water clock involves emptying the collection container and if so equipped, moving the hands manually to the correct time.

The speed adjustment for a water clock necessitates an adjustment of the drip nozzle, changing the orifice diameter.

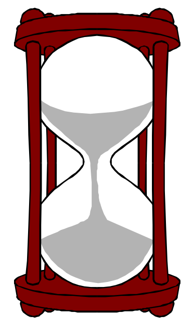
Display

The water clock display is either the amount of water in the collection container or the position of the hands on the more elaborate clocks.

Power Source

The power of the water clock comes from someone lifting the water into the source container.

6. Hourglass



The hourglass is similar in principle to the water clock. Hourglasses track the passage of time by passing an amount of sand from a source bulb through a small metering orifice into a collection bulb. The time it takes to empty the source bulb into the collection bulb is calibrated during the construction of the hourglass by selecting the amount of sand that is sealed into the hourglass. Usually one hour of sand is used but other sized glasses are common, such as in a three minute egg timer. After the hourglass is built and the sand is sealed into the bulbs, it should not be affected by humidity or temperature, but would be susceptible to movement and vibration.

The Time Base or Time Keeping Mechanism

The time base of the hourglass relies on the rate of dry sand falling through a small orifice. Our experience with sugar or sand would caution us to take the accuracy of the hourglass with a grain of salt! The sand must be of very uniform size. The sand can get stuck and stop flowing altogether. Someone must turn the hourglass over as soon as the top bulb is empty. This would not be a good method of keeping track of time throughout the night. Any delay in this maneuver will contribute to inaccuracy of the time of night. A larger glass containing many hours of sand could track larger time periods, perhaps overnight. Marks on the side of the collection container would indicate the passage of each hour.

The Time Accumulator Mechanism

The amount of sand in the containers is the accumulator. If someone turns over the hourglass, that person must keep a tally of turnovers. This tally is part of the accumulator mechanism.

Setting and Adjustment Mechanism

Turning over the hourglass is the setting method.

The hourglass is calibrated during manufacture by fine-tuning the amount of sand sealed into it. Once the hourglass is sealed, there is nothing that can be done to change its speed.

Display

The amount of sand in the containers is the display mechanism. The trouble with the hourglass is that you have to be there and observe precisely when the cycle completes. If you see a expired hourglass, you don’t know when it expired. A minute ago? An hour? Three hours? Who would know?

Power Source

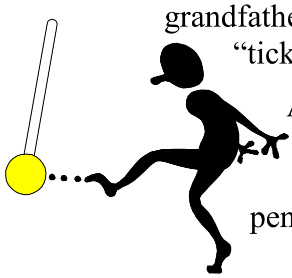
Turning over the hourglass—effectively lifting the sand from the lower to the upper container—is the power source.

7. Pendulum

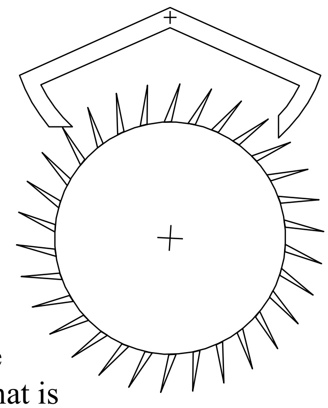
The pendulum clock's time base relies on the period of oscillation of a swinging weight attached to the bottom of a rigid rod. The rod is suspended from a very low-friction pivot such that the pendulum swings in a vertical plane.

The Time Base or Time Keeping Mechanism

A pendulum—when given an initial push—will swing at a fixed rate or period. The period is determined by two factors: L, the length of the rod; and g, the acceleration of gravity. The period is calculated by the formula T = 2 pi √(L/g), where g is about 9.8 meters per second per second, but varies at different locations on the earth. A pendulum of length 0.25 meters or about 10 inches has a period of approximately 1 second. A large grandfather clock that tick-tocks every second has a period of 2 seconds, or one second between "tick" and "tock." The length of the rod is about one meter or 40 inches.



A pendulum will eventually slow down and stop swinging unless it is given a little push now and then. In a pendulum clock a tiny kick is induced at the bottom of every swing, where the speed of the pendulum is fastest. This increases the momentum of the pendulum without disturbing the timing of the period. The small kick is generated by a mechanism called an *escapement*.



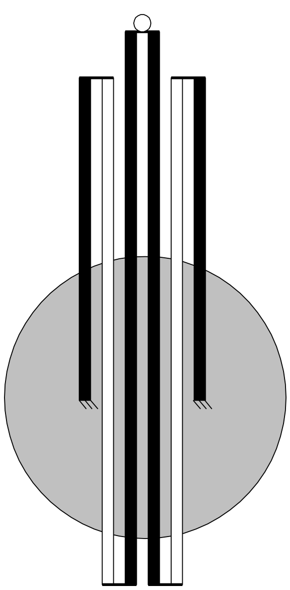
An escapement consists of a specially designed wheel that resembles a gear and a pair of *pallets* attached to a rocker arm coupled to the pendulum rod near the pivot point. Every time the pendulum reaches the bottom of the swing, the escapement wheel advances one tooth and at the same time gives the pendulum its little kick. In the diagram to the right the wheel is rotating clockwise.

The escapement wheel is coupled to a gear chain that is powered by a mainspring or a weight. The gear chain also turns the hands of the clock. If the rocker arm is removed, the escapement wheel—and the clock's hands—would spin rapidly until the power source was exhausted. The escapement lets a small, metered parcel of energy that is stored in the mainspring or weight to *escape*.

Of the most common environmental effects—temperature, physical movement and wind currents—movement precludes the use of the pendulum in any application other than a stationary one. For this reason a pendulum clock cannot be used aboard a rolling ship. Since celestial navigation requires accurate timekeeping, the invention of the balance wheel and balance spring (hairspring) clock—described later—was a prerequisite for accurate maritime navigation.

To guard against errant wind currents disturbing the pendulum, the clock is usually housed in a wooden cabinet, often with a glass door or window to allow the swinging pendulum to be observed.

Since the period of the pendulum is related to the length of the rod, the accuracy of the pendulum clock is determined by the stability of the rod length. The rod is constructed of wood or metal. Wood absorbs moisture and thereby changes length which will effect the period of the pendulum. Metals expand when they become warmer and a longer rod increases the period of the pendulum.



To solve the temperature sensitivity problem of the pendulum clock, the temperature compensated pendulum was invented. Different types of metal expand at different rates. For example steel expands at .0011 percent per Celsius degree whereas brass expands at .0019 percent per Celsius degree. If the pendulum rod is folded back on itself such that expansion of the steel portion causes the overall pendulum rod to lengthen and expansion of the brass portion causes the pendulum to shorten by the same amount, then the pendulum will be immune from temperature changes.

For example assume the steel portion is a total of 19 inches long and the brass portion is 11 inches long. The temperature rises 10°C. The 19 inches of steel will expand (19")(10°)(0.0011%) and the weight will drop 0.00209 inches. The 11 inches of brass will expand (11")(10°)(0.0019%) and the weight will rise 0.00209 inches. The drop of the weight equals the rise of the weight and cancel each other and the length of the pendulum does not change.

The Time Accumulator Mechanism

The escapement wheel is driven by a gear train. The gear train is the time accumulator mechanism, storing each tick and tock as a position of the gears.

Setting and Adjustment Mechanism

The hands of most pendulum clocks are turned by hand. That is, the glass in front of the face is usually mounted on a door which is opened and one reaches in and physically turns to the minute hand to the proper time. The hour hand will follow due to the 12:1 gear reduction. The pendulum’s period can be easily changed by moving the weight up or down the rod.

Display

The display consists of hands as in any conventional clock. Sometimes more elaborate displays are offered on grandfather clocks such as the phases of the moon. This merely requires more gears to reduce the rotations of the hour hand every 12 hours to one rotation of the moon phase disk every 29½ days.

Power Source

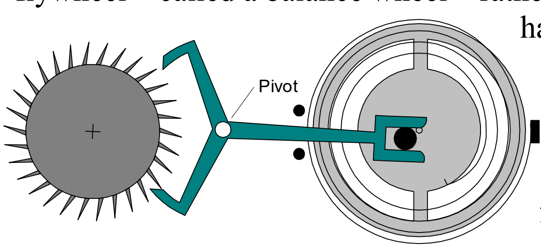
The power source for the pendulum clock is usually one or more weights. Every week or so, someone has to pull the weight back to the top of the clock. Other weights are used to power the hour chimes that are common on grandfather clocks. On smaller pendulum clocks, a mainspring is the power source, as is the case for escapement clocks and watches.

8. Balance Wheel and Hairspring

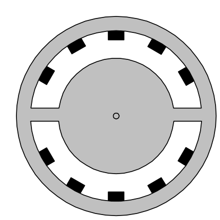
The invention of the balance wheel and hairspring in 1675 was crucial for accurate celestial navigation. The pendulum could not be used in a rolling, pitching ship. In 1761 an accurate marine chronometer with a balance wheel and hairspring was designed and kept time on board a rolling ship to about one-fifth of a second per day.

The Time Base or Time Keeping Mechanism

The balance wheel and balance spring (hairspring) clock incorporates a coiled spring rather than gravity and a flywheel—called a balance wheel—rather than a pendulum. The balance wheel winds the hairspring until the hairspring is tight enough to stop the rotation of the balance wheel at which time the balance wheel reverses direction, unwinds, and then winds the hairspring in the opposite direction. At the middle of the balance wheel's cycle when it has reached its maximum speed it toggles the rocker arm coupled to an escapement wheel. The period for small wristwatches is about 2½ cycles per second. Some chronometers run at 5 cycles per second.



The balance wheel can also be temperature compensated by attaching small weights made of a metal with different coefficient of expansion to the periphery of the balance wheel. As the balance wheel expands the small weights expand towards the center of the wheel to keep the moment of inertia constant.



The Time Accumulator Mechanism

As in the pendulum clock, the escapement wheel is driven by a gear train. The gear train is the time accumulator mechanism, storing each tick and tock as a position of the gears. Gears can be added to display the day of the week, the date and the month.

Setting and Adjustment Mechanism

Balance wheel clocks could be built much smaller than clocks with large pendulums, and the setting mechanism is usually a knob or stem that when engaged turns the hands of the clock. This is similar to the dual purpose winding and setting stem on mechanical wristwatches. On inexpensive alarm clocks there are usually two or more knobs. One winds the mainspring, another winds the alarm mainspring, one sets the hands and the other sets the alarm.

The adjustment mechanism for the balance wheel is to move the anchor point where the hairspring is attached to the frame of the watch. This effectively tightens or loosens the spring and changes the period of oscillation.

Display

The display consists of hands as in any conventional clock.

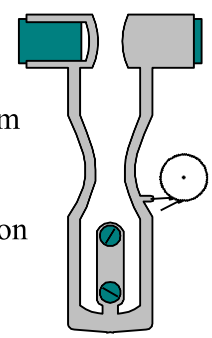
Power Source

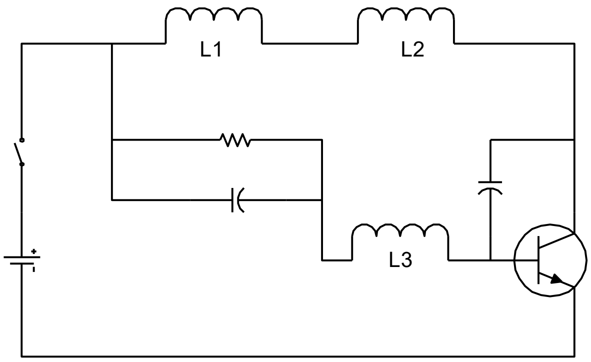
The mainspring is the power source for the balance wheel and hairspring clock or watch. The mainspring is geared to the escapement wheel and drives the escapement to give the balance wheel the little kick at every tick and tock.

9. Tuning Fork

The Time Base or Time Keeping Mechanism

The tuning fork watch relies on the natural frequency of oscillation of a small, U-shaped part. The Accutron™—introduced by Bulova in 1960—uses a tuning fork excited by two electromagnet-powered coils driven by a one transistor oscillator circuit. The vibrations of one arm of the tuning fork are coupled to a fine-toothed cog wheel by a tiny ruby coupling link. The cog wheel has 320 teeth and the entire wheel is only a tenth of an inch in diameter. Each cycle of the tuning fork advances the cog wheel one notch. A second ruby link attached to the mechanism frame prevents the cog wheel from advancing by more than one tooth or from backing up. Unlike a pendulum or balance wheel, no escapement is necessary because the tuning fork is powered by the electromagnet and not the cog wheel. The tuning fork frequency of oscillation is 360 Hz. Accutrons keep time more accurately than balance wheel watches and are less sensitive to the effects of gravity. In the diagram on the right one of the arms of the tuning fork is shown cutaway so that the placement of the coil is visible.





There are two coils—L1 and L2—each one of which drives one head of the tuning fork. One of the two electromagnetic coils has an additional coil—L3— co-wound on the same axis. This is the sense winding and is used to drive the input to the transistor to turn it on and off. The transistor is nothing but a switch. When the transistor is turned on it powers the electromagnets which attract and move the tuning fork heads. The sense wire detects this movement by detecting a change in the magnetic field and turns off the transistor, causing the tuning fork heads return to their normal position. This cycle continues indefinitely and causes the tuning fork to hum at its natural resonant frequency. The typical schematic diagram of an Accutron is shown here. The two drive coils resistance is approximately 7,000 ohms each and the sense coil is 2,000 ohms. The switch is on the winding stem.

The Time Accumulator Mechanism

The small cog wheel drives a set of gears which turn the second, minute and hours hands.

Setting and Adjustment Mechanism

Early Accutrons did not stop the second hand from turning when setting the minute and hour hands. This precluded setting this very accurate timepiece to an external time signal. An Accutron could be as much as 30 seconds off. Later, a hack mechanism was added to lift the ruby link off the cog wheel and stop the second hand so the watch could be set to a time signal. Early Accutrons had a semicircular ring on the setting wheel on the back of the case with a flip-up handle to grab it. Later, conventional “winding” stems were used, placed at the 3 o’clock or the 4 o’clock position.

At the head of tuning fork there are weights that can be moved to effectively change the length of the fork and change the period of oscillation.

Display

The display is convention second, minute and hour hands. Later, date was added.

Power Source

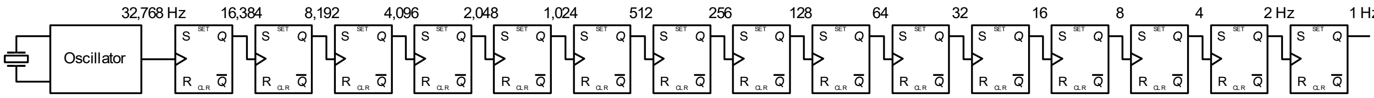
The Accutron originally used a small mercury battery. Recently mercury batteries have been discontinued because of their toxicity, so silver oxide batteries are used today. The battery powers only the tuning fork oscillator. The movement of the tuning fork drives the entire watch mechanism.

10. Quartz Electronic

The Time Base or Time Keeping Mechanism

Quartz watches use a small quartz crystal as the time base. The crystal is shaped like a fork and could be thought of as a tuning fork. Quartz is chosen for its *piezoelectric* property. If a voltage is applied to a quartz crystal it will change shape slightly: expand, contract, or bend. Conversely if a quartz crystal is deformed it will generate a small voltage. This piezoelectric property allows us to build small, accurate, low cost watches.

A small quartz crystal shaped like a tuning fork is sealed into a metal tube about a third of an inch long. The diagram shows an x-ray view of the quartz crystal next to a penny for size comparison. Two wires attached to both sides of the crystal protrude from the sealed end of the tube. These wires are connected to a tiny integrated circuit upon which resides all of the electronics required to implement an electronic watch. The crystal is connected to an oscillator circuit that causes the crystal to continually oscillate at its natural frequency of 32,768 Hz. This frequency is 2 to the power of 15. By dividing the frequency in half repeatedly 15 times, the final frequency will be 1 Hz. or 1 pulse every second. This 1 Hz. signal can drive a stepping motor that moves the second hand of an analog watch or drive the seconds digit counters of a digital watch. Shown below is a chain of 15 “flip-flops.”

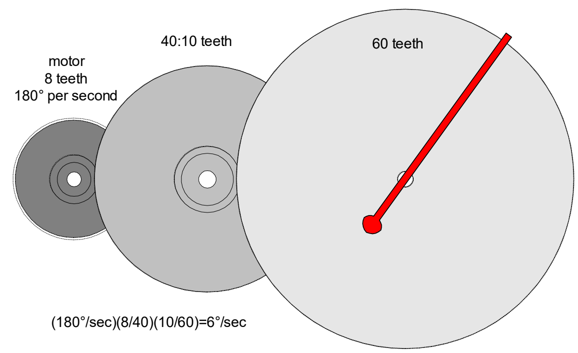


A flip-flop is an electronic circuit whose output signal will toggle between one of only two possible states every time the input signal makes one complete cycle. This divides the input signal frequency in half. Two flip-flops will divide the frequency by 4. Three will divide by 8, and so on. Fifteen flip-flops will divide the frequency by 32,768.

The Time Accumulator Mechanism

In the quartz analog watch gears will reduce the speed of the second hand to turn the minute and hour hands just as in any other mechanical clock. In the quartz digital watch, the integrated circuit contains the counters that drive the digits of the display.

The analog watch has a small stepper motor that typically is geared down to drive the second hand. The stepper motor rotates one half revolution—180°—each second and drives a second gear that rotates 36° per second. The last gear drives the watch’s second hand. It rotates 6° per second which is exactly 1/60 of a revolution, or equivalently, one second on the watch dial.

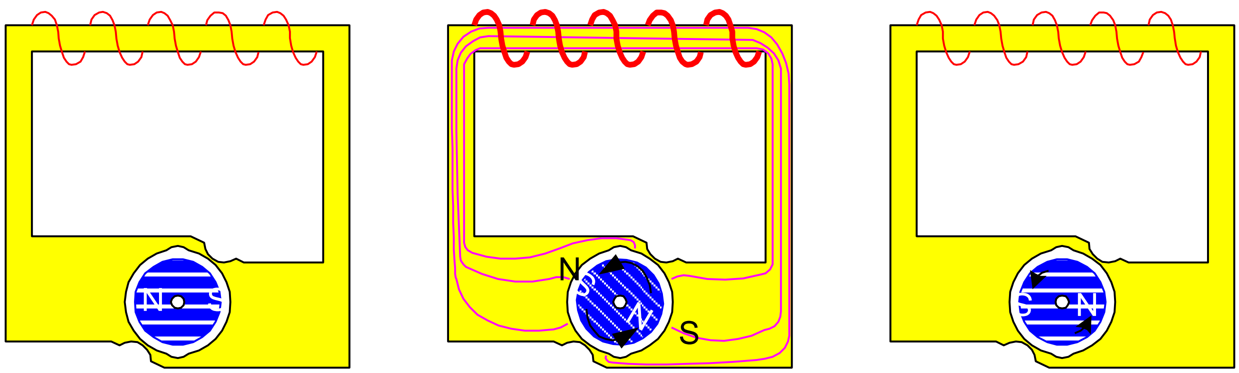


Some watches that do not have second hands advance the minute hand one third of a minute every 20 seconds.

The stepper motor operates with a single-coil electromagnet. This coil is pulsed once each second with a tiny electric current for a fraction of a second. This causes the rotor of the motor to revolve one half of a 360° rotation. Between pulses the coil is not energized and no power is consumed.

The stepper motor has a small permanent magnet rotor surrounded by a pole-piece that is coupled to the electromagnet coil. When the coil is *not energized* (no current flowing in the coil) the rotor magnet’s north-south pole axis aligns horizontally as shown in the first drawing below. This is due to the construction of the pole-piece which is made of soft iron that does not remain magnetized when the coil is not energized. Notice that there are two small voids—one directly at the top and one at the bottom—in the round opening where the rotor resides. The voids create two places in the round opening that do not attract the rotor magnet. The voids force the rotor to align with as much of the *nearby* pole-piece as possible, which happens to be horizontally in the diagram, below. The rotor is stable in either of the two possible horizontal positions (north poll on the left or north pole on the right) and will always rotate into one of these two positions when the coil is not energized.

When the coil is *energized* with a pulse of current, a strong magnetic field is created which is aligned at the 10 o’clock and 4 o’clock positions of the rotor, as shown in the center diagram below. In the case shown the polarity of the pole-piece is north (N) on the left and south (S) on the right. This field is at a non-horizontal angle in the diagram because of the narrow constrictions near the 1 o’clock and 7 o’clock positions near the rotor. The constrictions cause the magnetic field of the *energized* pole-piece to align at this angle because the magnetic force is concentrated at the two constrictions.



We will next describe what the rotor does in response to the magnetic fields. (We will focus our attention on the left side of the pole-piece, but the same phenomenon occurs on the right side of the pole-piece, but with names of the poles reversed.) The N pole field on the left side repels the N pole of the rotor and pushes the rotor counterclockwise about 1/3 of a full 360° rotation as shown in the middle diagram. Because opposite magnetic poles attract, the N pole of the pole-piece attracts the S pole of the rotor and holds the rotor there. Finally the short current pulse is removed from the coil and the pole-piece is no longer magnetized. Therefore the rotor continues to turn in the shortest direction to again align itself horizontally with the pole-piece. The resulting position is shown in the last diagram where the S pole of the rotor is now near the left of the pole-piece. The rotor turned counterclockwise one half rotation.

The current in the next pulse to the coil would have to be in the opposite direction to again generate an opposing magnetic field. The step pulses alternate in polarity each half rotation.

Setting and Adjustment Mechanism

In the analog quartz watch a winder stem is the usual setting mechanism, although on some watches, buttons will turn the stepping motor faster to advance the hands. In the digital quartz watch there are usually some buttons that cause the minutes or the hours digits to advance rapidly for setting. There is also a button or mode to clear the seconds counter so that the watch can be set against an external time signal.

Quartz crystal oscillator circuits usually have a trimmer capacitor connected across the crystal for small frequency adjustments. More sophisticated circuits have adjustable taps in the divider chain to add or remove counts as necessary to make the output exactly one pulse per second.

Display

The analog quartz watch has gears and hands, although some watches have separate stepping motors for each hand, in which case the integrated circuit controls each stepping motor rather than gears. Digital watches first used light emitting diodes—LEDs. These devices consumed lots of power so there was a button on the watch that would turn on the LEDs for only a few seconds, then turn them off again. Users disliked having to push a button every time they wanted to see what time it was. The liquid crystal display—LCD—supplanted the LED in digital watches. LCDs require very little power since they do not generate light, they merely control the reflection of ambient light. Some watches have a button that turns on a back-light for night use.

Some electronic watches have LCD analog hand displays—no moving parts.

Power Source

Small silver oxide or lithium batteries power most electronic watches. Some watches have solar cells that recharge a built-in rechargeable battery so it never has to be replaced. “Self-winding” electronic watches have a moving weight that swings with the user’s daily wrist movements. The weight is linked to a tiny generator by gears and the generator charges a battery.

11. Electric

The Time Base or Time Keeping Mechanism

The electric clock that runs on household AC power is not really a time keeper at all. The timekeeping mechanism is external. The electric clock relies on the precise frequency of the sinusoidal AC power, usually 60 or 50 Hz. The power station receives a time signal from a frequency standard and the generators are synchronized to that signal. The AC power frequency is very accurate and therefore so is an electric clock.

In analog clocks the 60 Hz AC power runs a small, synchronous motor. The motor's speed is directly related to the frequency of the sinusoidal AC power. In digital clocks a circuit divides the 60 Hz signal by 60 to generate a 1 cycle per second pulse stream which runs the seconds counter.

The Time Accumulator Mechanism

The accumulator in the analog electric clock is the gear train. A reduction gear reduces the motor speed to one revolution per second to run the second hand. Subsequent gearing runs the minute and hour hands. In digital clocks the accumulator is a series of counters made up of flip-flops as in the quartz watch.

Setting and Adjustment Mechanism

A knob on back of an electric clock moves the minute hand, and the hour hand follows through the 12:1 gearing. On the electric clock there are usually some buttons that cause the minutes or the hours digits to advance rapidly for setting. The seconds timer is often set to zero so that the clock can be set against an external time signal.

There is no adjustment for an electric clock because there is no time base in it. The time base is back in the power station.

Display

Standard analog or digital displays are used in electric clocks.

Power Source

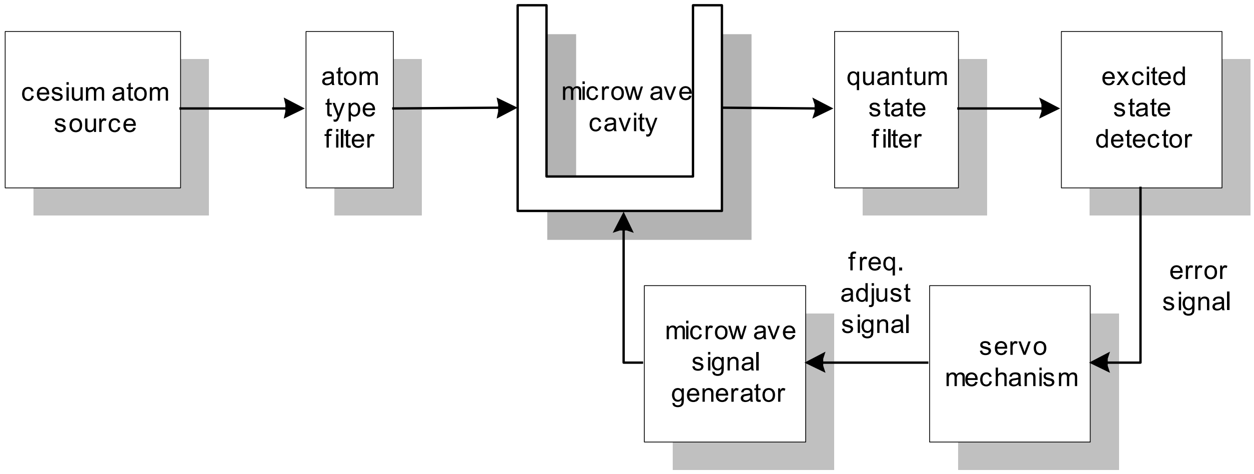
The power source is the same as the frequency source, namely the AC power line. In the analog clock, the motor runs the clock mechanism through gears. In the digital clock, the AC is converted to low voltage DC by a power supply to run the electronics.

12. Atomic

Atomic clocks depend on the precise excitation frequency that will cause a quantum state transition of atoms in an electromagnetic field.

The Time Base or Time Keeping Mechanism

Atoms of cesium are forced to transition from a so-called *quiescent*—or quiet—quantum-mechanical state to an *excited* state by an externally applied high frequency radio signal. There is only one frequency that forces this transition and it is always the same: 9,162,631,770 Hz. If the cesium atoms are excited by exactly this frequency, they will jump to the excited state. The atomic clock generates a microwave radio signal of this exact frequency and detects the occurrence of numerous excited state atoms. If the frequency generated by the atomic clock is only slightly too high or too low, the number of excited state atoms will decrease considerably.



The servo mechanism adjusts the frequency of the microwave signal generator to maximize the number of transitions detected. This exact frequency can then be counted down, similarly to the quartz clock described earlier—except that many more flip-flops will be required—and generate any sub-frequency and timing signals. In the diagram above the cesium source sprays atoms to the atom type filter which allows only atoms of the correct type to pass through. The microwave cavity is where the state transitions occur provided the microwave signal generator is producing exactly the correct frequency. The quantum state filter allows only atoms of the excited state to pass through to the excited state detector.

Atomic clocks are so accurate that they will gain or lose one second every 6 millions years (the warranty probably expires after 5 millions years!). This accuracy is needed to synchronize digital communications signals and for precise GPS navigation. Each of the 24 GPS satellites that circle our earth has four atomic clocks which are updated daily from ground stations. It is the difference in time of arrival of these GPS satellite signals that lets your $100 GPS receiver determine its location anywhere on the earth to within a few hundred feet. Most GPS receivers have a time display from which you can obtain atomic clock accuracy.

The Time Accumulator Mechanism

Once the microwave frequency is reduced by frequency division or frequency synthesis, the reduced frequency can be used to drive electronic counters or even an simple analog clock. For example if the frequency were reduced to 60 Hz it could drive a $5 electric clock, but that clock would be extremely accurate. Usually the atomic clocks are used for split second timing and therefore generate 10 MHz, 1 MHz, 100 KHz, and other intermediate signals.

Setting and Adjustment Mechanism

Atomic clocks have electronic inputs that allow them to be precisely synchronized with other time standards.

The atomic clock's frequency is based on quantum mechanics and so no frequency adjustment is necessary. The circuits used in the clock have adjustments for setting the open-loop center frequency of the microwave signal and other adjustments for optimizing the performance of the clock, but the 9,162,631,770 Hz frequency is immutable.

Display

The display can be digital, analog or some combination.

Power Source

The electronics in atomic clocks requires a number of different voltage levels that are generated by either an AC or DC powered supply.

Appendix—Historical clocks and watches and their five essential elements.

	Time base	Accumulator	Setting and Adjustment Mechanism	Display	Power Source
Sundial	Earth's rotation	Rotational position of the earth	Adjusting the slope of the plane (or dial) and the angle of the gnomon (or style)	Gnomon's shadow on the plane caused by the sun	Momentum of the rotation of the earth
Candle	Rate of burning of the wax candle	Amount of candle remaining	A new candle	Lines marked on the side of the candle	Wax to fuel the flame
Water clock	Rate of water dripping through a small hole from a source bucket into a collection bucket	Amount of water in the collection bucket which is used to catch the dripping water	Empty the collection bucket; adjust the orifice diameter	Amount of water in the collection bucket	Water lifted into the source bucket
Hourglass	Rate of sand falling through a small hole from a source bulb into a collection bulb	Amount of sand in the collection bulb	When the source bulb is empty, turn the hourglass over; no adjustment possible	Amount of sand in the collection bulb	Sand lifted into the source bulb by turning the hourglass over
Pendulum clock	Period of oscillation of a pendulum	Rotational position of gears	Turning the hands of the clock; adjust the position of the weight on the rod	Position of the hands in front of the dial	Lifting a weight or a winding a mainspring with a key or winding stem
Balance wheel, balance spring (hairspring) clock	Period of oscillation of the balance wheel and spring	Rotational position of gears	Turning the hands of the clock; adjust the anchor point—tension—of the hairspring	Position of the hands in front of the dial	Winding a mainspring with a key or winding stem

Tuning fork watch	Period of oscillation of a small tuning fork	Each cycle of the tuning fork with mechanical linkage to cause a small cog wheel to move one notch. Rotational position of gears	Setting the hands using a setting knob or stem; adjust small weights on tuning fork	Position of the hands in front of the dial	Battery
Quartz crystal watch	Period of oscillation of a small quartz crystal	Integrated circuit to divide the crystal frequency by 32,768 to obtain one pulse per second driving a stepper motor, and rotational position of gears	Setting the hands using a setting knob or stem; adjust a trim capacitor	Position of the hands in front of the dial	Battery
Digital watch	Period of oscillation of a small quartz crystal	Integrated circuit to divide the crystal frequency by 32,768 to obtain one cycle per second. Electronic counters to accumulate hours, minutes and seconds	Button or knob to change the values of the electronic counters; adjust a trim capacitor	Light emitting diodes (LED), electro-luminescent (EL) or liquid crystal display (LCD)	Battery
Digital clock	Accuracy of the AC power line frequency (Usually 50 or 60 Hz.)	Integrated circuit to divide the power line frequency by 60 (or 50) to obtain one cycle per second. Electronic counters to accumulate hours, minutes and seconds	Button or knob to change the values of the electronic counters; adjust at the power plant	Light emitting diodes (LED), electro-luminescent (EL) or liquid crystal display (LCD)	AC power line
Electric clock	Accuracy of the AC power line frequency (Usually 50 or 60 Hz.)	Rotational position of gears	Setting the hands using a setting knob or stem; adjust at the power plant	Position of the hands in front of the dial	AC power line
Atomic clock	Oscillating atoms or molecule, usually cesium or ammonia	Integrated circuit to divide the atomic oscillations to obtain one cycle per second or finer resolution. Electronic counters to accumulate hours, minutes and seconds	Button or knob to change the values of the electronic counters	Light emitting diodes (LED), electro-luminescent (EL) or liquid crystal display (LCD)	Any constant voltage source (battery or AC)