FEATURE

By Mark V. Headrick

Origin and Evolution of the Anchor Clock Escapement


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Horologium, solo naturae motu, atque ingenio, dimetiens, et numerans momenta temporis, constantissime aequalia.
(A clock that, by natural motions alone, indicates regularly equal divisions of time.)
—Mateo de Alimenis Campani (1678)

The escapement is a feedback regulator that controls the speed of a mechanical clock. The first anchor escapement used in a mechanical clock was designed and applied by Robert Hooke (1635-1703) around 1657, in London. Although there is argument as to who invented the anchor escapement, either Robert Hooke or William Clement, credit is generally given to Hooke. Its application catalyzed a rapid succession in clock and watch escapement designs over the next 50 years that revolutionized timekeeping. In this article, I consider the advances this escapement design made possible and then describe how horologists improved on this escapement in subsequent designs.

Before continuing, it is important to stress that the development of the escapement by generations of horologists was largely an empirical trial-and-error process. As will be seen, this process was remarkably successful despite being based on only an intuitive understanding of physics and mechanical engineering principles. Even today, the understanding of the dynamics

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of linkages under impact, friction, and other realistic effects is incomplete. Consequently, the explanations I give in this article concerning the evolution and operation of the clock escapement are based largely on kinematic, geometric, and energy transfer principles.

An escapement mechanism is a speed regulator, and it uses feedback to obtain precision operation despite imperfect components. The presence of feedback is realized by the interaction between the escape wheel and the escape arm, which interact according to their relative position and velocity. This interaction can be seen in [1] and [2], where the verge-and-foliot escapement, one of the earliest escapements, is analyzed. It is with this escapement that I begin this description of the evolution of the anchor escapement.


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Prior to the Anchor Escapement

The earliest record of a mechanical clock with an escapement, which is believed to date around 1285, was a reference to a payment for a hired clock keeper at St. Paul's in London. All the early mechanical timepieces are believed to have had a verge and foliot as the control mechanism for measuring the passage of time. The verge-and-foliot design was clearly based on the alarum (the alarm mechanism, with a hammer and a bell instead of a foliot), which was invented several centuries earlier. No one knows exactly when the mechanical clock was invented or by whom.

The Graham escapement has been the escapement of choice in almost all finer pendulum clocks since 1715.

First, let us consider a clock consisting of a set of gears and a driving weight, using the force of gravity (see Fig. 1). In such a clock, the gears would spin uncontrollably unless a control mechanism was applied at the other end of the gear train. The control mechanism consists of an oscillating device that prevents the gear train from rotating, except at specific intervals, when it releases one tooth of the last gear in the train. By controlling the rate of rotation of the gears, it is possible to use this device to measure time by incorporating an indicator and a scale at the end of the shaft of one of the gears.

The verge-and-foliot control mechanism consists of a shaft, called the verge, and a crossbar with a weight attached at each end, called the foliot (Fig. 2). The weights can be moved to different positions on the crossbar, so that the radius (or distance) of the weights from the center determine the period of oscillation. The control mechanism is an escapement because the energy is allowed to "escape" each time a gear tooth is released. The stored energy of the system is the potential energy of the driving weight, which falls slowly during operation. In early clocks, the driving weight could weigh as much as 1,000 lb, and large towers were constructed to accommodate its range of motion.

It is important to understand how the verge escapement works to appreciate the circumstances that led to the invention of the anchor escapement. The oscillator consists of the foliot, suspended at its center by a string, often made of silk. For the foliot to oscillate, accelerating and decelerating forces must be acting on it.

When a tooth of the escape wheel escapes, this wheel rotates freely by about 2° (called drop) until another tooth strikes an arm protruding from the vertical shaft that is attached to the crossbar. The vertical shaft has two arms, called pallets, located with about 100° of angular separation and with a vertical separation equal to the diameter of the escape wheel. The pallets rotate by about 100° until a pallet releases an escape tooth. An instant later, another escape tooth strikes the other pallet. As the pallets rotate, the escape tooth slides across the surface of the pallet, exerting a force on it. The work done on a pallet is therefore the applied moment times the arc through which the escape tooth moves during contact, and it is this moment that causes the foliot to accelerate and rotate in one direction. In horology, the moment applied during contact is traditionally called impulse, although the applied torque is not necessarily impulsive in the usual engineering sense.

After another tooth strikes the other pallet, the foliot continues to rotate in the same direction (as it was rotating in before the tooth struck the other pallet), causing the other pallet to push the escape wheel backward as the foliot rotates. Since the escape wheel exerts a force on the pallet, the pushing of the escape wheel backward causes a decelerating force, which is opposite and equal in magnitude, to act on the pallet until the foliot stops. This backward action, called recoil, is equivalent to winding the clock by a small amount; in other words, energy is stored rather than wasted. After the foliot has stopped, it changes direction, since the escape wheel continues to exert a force on the pallet, and the foliot begins to accelerate in the opposite direction, continuing to do so until it has rotated by about 100° and the pallet allows the tooth to escape again. The escape wheel rotates freely again by about 2° until another tooth strikes the other pallet. This process is repeated indefinitely.

Since it was difficult to control many of the factors that affected the period of oscillation of the foliot, the early clocks were poor timekeepers, with errors exceeding several hours per day. The greatest problems were caused by changes in temperature and levels of friction. When the temperature increases, the crossbar becomes longer due to the thermal expansion of the wrought iron, so the period increases, and the clock loses time. Similarly, the clock gains time in colder temperatures.

A warmer temperature causes the lubricants to become thinner so that they create less resistance or drag, which results in more energy reaching the foliot, and the clock gains time. The lubricants used in early clocks were primitive (animal fats and fish or vegetable oils, especially olive oil) and did not have preservatives. Clocks needed to be lubricated frequently because the lubricants were not hostile to bacteria, which accelerated their deterioration by causing the formation of fatty acids that corroded metal parts and resulted in the formation of sludge, increasing resistance. (Since the foliot rotates by about 100° in each direction and the pallets are almost continuously in contact with the escape wheel, the action of the escapement is rather violent and requires a lot of energy to keep going. To reduce the required power, it is necessary to reduce the levels of friction involved, and thus there is a need for lubricants.)

The first modification of the verge-and-foliot clock was the replacement of the foliot weights with a wheel in smaller (nonchurch) clocks. By distributing the weight evenly around the perimeter of a circle, the foliot design was made more aerodynamic. More importantly, changes in temperature had less effect on timekeeping. In warmer temperatures, the crossbar expanded, causing the circle to become distorted, rather oval shaped. This means that, although part of the circle had a greater diameter than before (causing the clock to lose time), other parts of the circle were pulled in and had smaller diameters than before (tending to make the clock gain time and partially offsetting the effect of time loss). This could be seen as a crude form of temperature compensation. The wheel, or metal ring, that replaced the foliot is called a balance wheel, and it was introduced around 1400. The foliot continued to be used as well, however, until around 1650.

Another modification was the replacement of the weight with an elastic steel ribbon, called the mainspring. Its introduction around 1500 by Peter Henlein (1480-1542), a locksmith from Nürnberg, is most significant because it made possible the production of smaller and portable clocks (or very large pocket watches). It was extremely difficult to make a steel ribbon by hand with the production methods available at that time.

Mainsprings were relatively short and did not provide constant power. Power levels were high when the clock was fully wound, decreasing gradually as the mainspring unwound. Early spring-driven timepieces were extremely erratic timekeepers because they gained time drastically at the beginning of the wind and lost time drastically toward the end of the wind. Several devices were designed to improve the moment-versus-angle curve of the mainspring, but the spring-driven timepiece always remained an inferior timekeeper compared to an equivalent weight-driven timepiece.

A major improvement was the use of brass in clocks and watches, beginning around 1560. Although the production of brass can be traced back to Roman times, it was scarce before 1500, and more so in England than on the European continent. The use of brass in making timepieces increased as it became more available. Brass is an alloy of about 60% copper and 40% zinc. Its properties, especially its resistance

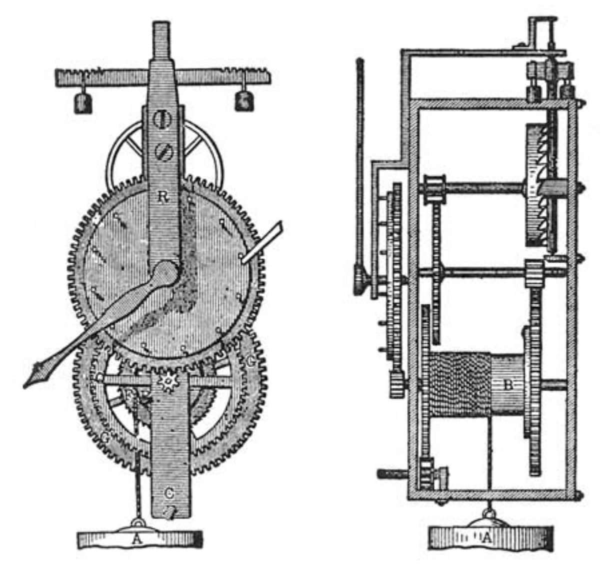

Figure 1. *An early clock (from [4]).*

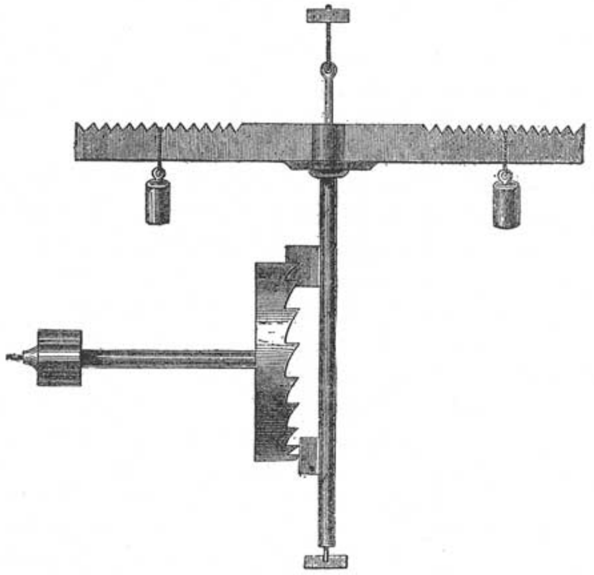

Figure 2. *The verge escapement with foliot (from [4]).*

to corrosion, make its use very beneficial. The corrosion of iron products has always been a major problem. Surfaces affected by corrosion lose their smoothness, increasing friction. Corrosion is accelerated by the abrasive action of iron oxide mixing with the lubricants. By fabricating the rubbing surfaces of dissimilar metals, the coefficient of friction can be reduced considerably.

The reduction of friction has to do with the lattice structure of the metal atoms. When the lattice structures are different, the two surfaces do not fit together perfectly, and so there is less surface contact between the two rubbing surfaces and hence less friction. Brass-with-iron (or steel) has a much lower coefficient of friction than iron-with-iron or brass-with-brass. Adding a small percentage of lead to the brass alloy also reduces friction levels, making the brass surface self-lubricating to some extent. The main reason brass resists corrosion is that the surface develops a layer of copper and zinc oxides (mainly zinc oxide, since zinc is more reactive than copper), protecting the metal underneath. In very humid conditions, zinc carbonate and sometimes copper sulphate can form, with the zinc carbonate providing a protective layer. Iron oxides do not protect the iron metal underneath, so corrosion can continue unabated, particularly in humid conditions.

Clocks made of iron and brass parts were considerably more durable than those made entirely of iron. The parts that would experience more severe wear were made of iron (they were later made of steel), and those that would experience less wear were made of brass. The larger gears were therefore made of brass, but the smaller gears (called pinion gears) were made of iron. The escape wheel was made of brass, but the pallets were made of iron. Brass is also softer than iron, so brass parts are easier to make, a very important point in an age, before the Industrial Revolution, when all parts were made entirely by hand.


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The Swiss lever design has been used in virtually all Swiss, American, and Japanese watches of quality, probably several hundred million watches.

The Pendulum

The first clock to use a pendulum instead of a foliot or balance wheel was produced by the Dutch mathematician Christian Huygens in 1657 (although it is claimed that others invented the pendulum clock before he did). His clock was a considerably better timekeeper than any clock before it, the reason for which is actually quite simple. Every escapement needs a driving force, provided by a suspended weight, and a restoring force, which makes the timekeeping device (i.e., the pendulum, balance wheel, or foliot) change direction. In previous designs, the only restoring force was recoil. As discussed earlier, a lot of recoil action was needed, and it created a lot of friction. Huygens' clock, however, used both recoil and the force of gravity as restoring forces.

If the lubricants failed and there was a lot of friction between corroded pallet and escape wheel tooth surfaces, the force from the escape wheel may not be enough to cause the foliot to change direction once it stopped. Therefore, the verge-and-foliot clocks were unreliable. In the pendulum clock, the pendulum could be seen as wanting to change direction and return to a downward position because of gravity. Pendulum clocks were more reliable and much more consistent as timekeepers.

Many of the earliest pendulum clocks had very wide pendulum swings because of the verge escapement. Early pendula were short and light to minimize the amount of energy needed to keep them in motion. Furthermore, the wide swing, combined with changing conditions such as increased friction and drying of the lubricants, caused changes in the angle of swing and resulted in variations in timekeeping because of a phenomenon called circular error by horologists. This error is caused primarily by the fact that the restoring effect of the gravitational force increases as the sine of the angle of swing. The restoring force causes the period of oscillation to decrease as the amplitude increases. Since the verge escapement had a very wide pallet swing, a new escapement design was required.

The Anchor Escapement

As mentioned earlier, Hooke invented the first anchor escapement around 1657. The date is only approximate, the important point being that the anchor escapement was invented soon after the pendulum clock, perhaps even in the same year.

The anchor escapement has several advantages over the verge escapement, the most important of which is a much smaller angle of swing. The anchor is a steel lever with two limbs, called pallets, rotating about a pivot shaft. The two pallets have impulse faces that interact with the escape wheel's teeth. Instead of requiring a pendulum swing of about 100°, the anchor escapement reduces the pendulum swing to as little as 6°, requiring much less energy to keep it in motion. The pallets of the anchor escapement are positioned much farther away from the axis of rotation, thereby requiring a much smaller angle of rotation to obtain the same arc. Less driving weight means less friction in the bearings of the gears, less friction between the gear teeth, and less friction between the brass escape wheel teeth and the iron pallet surfaces.

A smaller swing made it possible to use a much longer and heavier pendulum. A longer pendulum reduces wear in the escapement. Although a heavier pendulum entails more friction, it has more angular momentum, and thus its motion is less affected by interaction with the escape wheel. Therefore, a long and heavy pendulum has a swing that more closely resembles simple harmonic motion, despite contact with the escape wheel. Energy transfer and recoil take place in the same manner as for the verge escapement.

The anchor escapement allowed new designs for the escape wheel and pallets that were much easier to manufacture. The ability in the 19th century to mass-produce rough copies of pallets and escape wheels that could easily be fitted and finished by the clockmaker substantially reduced the overall cost of producing a quality clock.

The design principles were remarkably simple. The escape wheel teeth needed to be tall and pointed, and they needed to be tapered to maximize strength. A shape such as a right-angled triangle could be used, although many designs had a curved front side and a straight back side, as shown in Fig. 3. The height of the teeth and the spacing between them needed to be such that the pallets could enter the space far more deeply than they did under normal running conditions (with a typical amplitude of oscillation of about 10°); in other words, there needed to be plenty of clearance. The radial length of each tooth (i.e., the distance from the center of the escape wheel to the tip of each tooth), as well as the angle between each pair of teeth, needed to be identical. A tooth that was too short or unevenly spaced teeth resulted in irregular action of the escapement, detrimentally affecting timekeeping.

The design of the pallets was similarly straightforward. Of critical importance was the impulse face. The angle of each impulse face was such that the desired angle of swing of the pendulum was achieved between the pallet's point of contact with the escape tooth and the point at which it released the tooth. In other words, if a wider swing was desired, the clockmaker created a steeper angle on the pallet. If a smaller swing was desired, the clockmaker created a shallower angle on the pallet.

Another issue in pallet design was symmetry. Each pallet must cause the pendulum to swing by the same angle. Each pallet must therefore have the same steepness or shallowness; otherwise, the effect of the pallets would be asymmetric. Timekeeping is improved as the actions of the pallets are increasingly equalized.

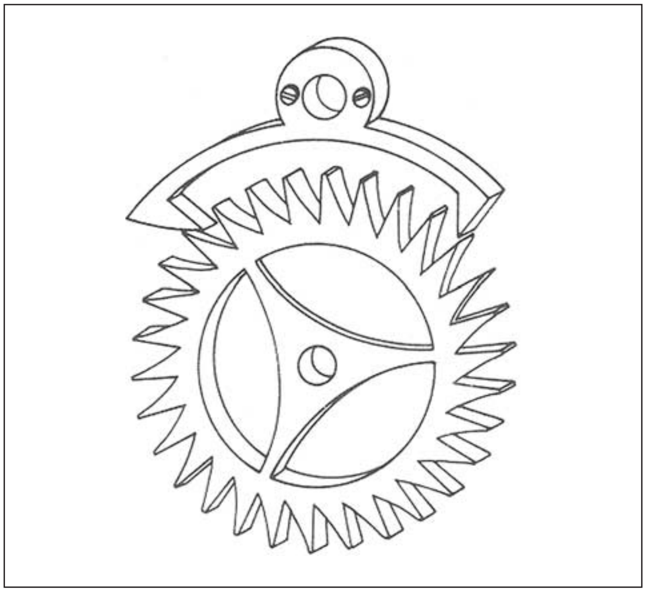

Figure 3. *An anchor escapement.*

The distances from the midpoint of each pallet impulse face to the axis of rotation of the pallets need to be the same or else the actions would be asymmetric. The weight of the pallet assembly (two pallets plus two pallet arms) needs to be as low as possible. The other details of the pallet's design could be created as the clockmaker desired, and there are many different styles of this escapement. An example of one style is shown in Fig. 3.

Most clocks with anchor escapements have pallets that were designed as outlined above. However, a few clock designs demonstrate the superior knowledge of the clockmaker, especially with regard to the energy transfer efficiency of the escapement. For the force applied by the escape tooth on the pallet at the point of impulse to be applied at a right angle to the force received by the pallet at its point of impulse and in its direction of motion at that point, the pallet impulse face must lie at a right angle to a line that lies halfway between the two force vectors (in this case, at 45°). This geometry was needed to maximize the transfer of energy from the escape wheel to the pendulum. Clockmakers needed to understand vector analysis, at least intuitively, to design an escapement with maximum efficiency.

The Hairspring and the Suspension Spring

In about 1660, Robert Hooke discovered his law of elasticity, which states that for relatively small deformations of an object, the deformation is proportional to the applied force. Hooke applied a spring to the balance wheel of a watch with a verge escapement. This balance spring, made of tempered spring steel, was straight. A spiral form, however, which we now know as the hairspring, was developed simultaneously by Christian Huygens and the Abbé d'Hautefeuille. The hairspring was thin and relatively short, although adequate for

Figure 4. *The balance and hairspring.*

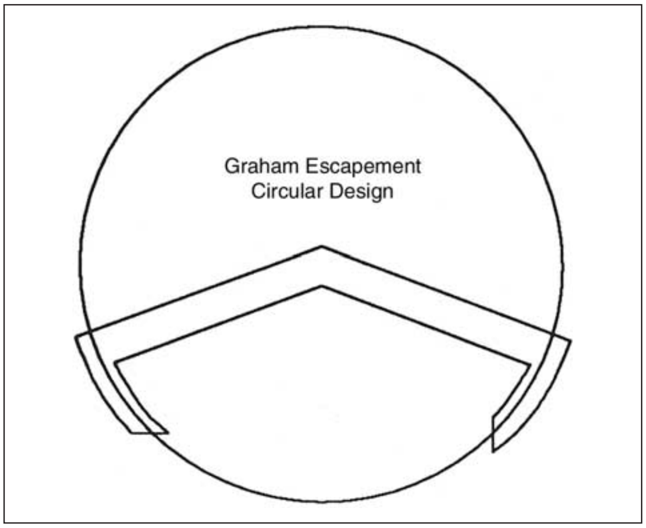

Figure 5. *The Graham pallets.*

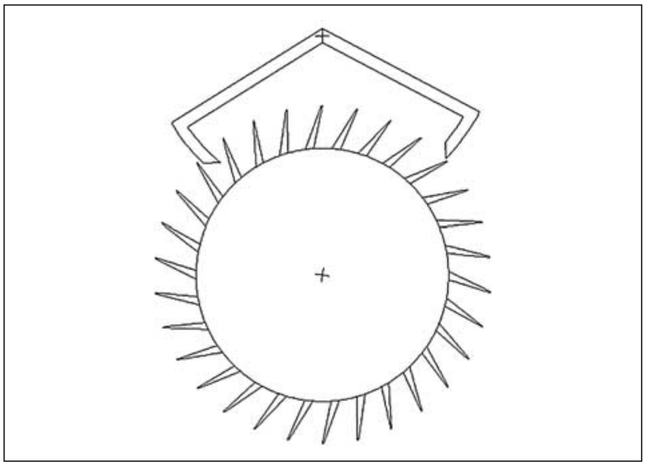

Figure 6. *The Graham escapement.*

use with the verge escapement because the angle of swing of the balance wheel was about 100°.

The addition of the hairspring dramatically improved the timekeeping and reliability of the watch because the hairspring stored elastic energy to act as the restoring force. This restoring force brought the balance wheel back to the midpoint of its oscillation and thus allowed it to change direction and to oscillate back and forth. The hairspring caused the action of the balance wheel to resemble simple harmonic motion more closely than before. Adding a hairspring to a balance wheel or to a foliot dramatically improved the timekeeping and reliability of the watch or clock. Fig. 4 shows a balance wheel and hairspring from an English pocket watch, circa 1820. The hairspring is typical of earlier hairsprings, with a few coils.

A flat suspension spring, which is a thin sheet of elastic spring steel, similarly benefited a pendulum clock with either a verge or an anchor escapement. This is particularly true for an anchor escapement because of the narrow swing of the pendulum. A narrow swing means that the returning force (which is proportional to the sine of the swing angle) caused by gravity is small. It also means that the pendulum requires much less weight to keep it oscillating, compared to an identical pendulum with a wide swing, so there is less recoil. If the returning forces caused by gravity and recoil were small, then most of the force that acts to change the direction of the pendulum would be caused by the elasticity of the suspension spring. The energy is not lost in friction or stored as gravitational potential energy. It is stored as elastic energy instead. Furthermore, virtually no energy (save for that lost to internal heating) is lost at the axis of rotation of the pendulum compared to other forms of suspension that involve sliding friction. Since the advent of the suspension spring around 1660, virtually every quality clock made with a pendulum has been equipped with a suspension spring. The importance of the suspension spring increased when the anchor escapement was modified to eliminate recoil action.

The Graham Escapement

In 1715, George Graham (1673-1751) of London is said to have modified the anchor escapement to eliminate recoil, creating the deadbeat escapement, also called the Graham escapement. This has been the escapement of choice in almost all finer pendulum clocks since then. Graham modified the arm of each steel pallet so that the lower portion of each limb was based on the arc of a circle with its center at the axis of rotation of the pallets (see Fig. 5). The tip of each limb had a surface, the angle of which, based on force directions (as outlined above), was designed to provide an impulse to the pallet as the escape tooth slid across the surface of each tip. The escape tooth strikes the pallet above the tip on the lower portion of the limb (see Fig. 6), where the escape wheel is rotating clockwise and is about to strike the entrance pallet on the left side, above the impulse face. The surface that the escape tooth strikes is the locking face, since it prevents the escape wheel from rotating farther.

When a pallet releases an escape tooth, the escape wheel rotates freely with about 2° of drop, until another tooth strikes the other pallet on its locking face, just beyond the tip. If the pendulum continues to swing after the drop has taken place, the escape tooth slides up the locking face until the pendulum stops. The escape wheel is not pushed backward (recoil) as the tooth slides up the locking face because each point along the locking face is at the same radial distance from the axis of rotation (pivot shaft) of the pallets. The pendulum stops at the end of each swing, to some extent because of gravitational force but mostly because of the elasticity of the suspension spring, which serves to change the direction of motion of the pendulum and start it moving again. The pendulum would behave similarly, however, if recoil were present. Recoil interferes with the action of the pendulum and causes it to stop sooner, reducing its amplitude of oscillation. It is preferable to minimize interference in the action of the pendulum to exploit the natural pendulum dynamics.

The escape wheel teeth in a Graham escapement are slightly different from those in a recoil escapement. In the Graham escapement, the teeth lean forward, in the direction of rotation of the escape wheel, to take advantage of the curved locking faces of the pallets and thus achieve no recoil. In the original recoil anchor escapement, the teeth may lean backward to avoid being at right angles to the pallet surfaces and reduce the risk of accidental damage to the tips of the teeth. Which way the teeth lean, however, is less important than the clearance they provide to allow the pallets to enter between teeth as the pallets swing in and out.

The energy that the escape wheel provides to the pendulum is needed to maintain the motion of the pendulum. The clock is not self-starting. You must start the pendulum swinging. The anchor escapement is not self-starting since the energy that is transferred from the escape wheel to the pallets is only sufficient to overcome the effects of friction but is not sufficient to make the pendulum start oscillating. In contrast, the verge-and-foliot escapement *is* self-starting.

Temperature Compensation

As timepieces became more accurate, the effects of changes in temperature on timekeeping became more noticeable. In 1721, George Graham invented the mercury pendulum, which used a vessel with mercury instead of a pendulum bob. The quantity of mercury in the vessel could be adjusted such that the expansion of mercury offset the lengthening of the pendulum upon warming, thereby maintaining a constant center of gravity for a wide range of temperatures. A weight-driven clock with a Graham escapement and a mercury pendulum could achieve accuracy to within a few seconds per day!

In 1726, John Harrison (1693-1776) is believed to have invented the gridiron pendulum. This pendulum had a set of nine alternating brass and steel rods, framed together and adjusted so that the temperature effect on one metal offset the temperature effect on the other. Both the mercury and the gridiron pendula were based on the same principle of thermal expansion of metals.

The Grasshopper Escapement

No one can write about horology without mentioning the most brilliant horologist of all time—John Harrison. He devoted almost his entire life to solving the problem of measuring longitude, in pursuit of a £20,000 prize offered by the British Government in 1714. Harrison built four clocks, the first three of which were not suitable for use at sea, although they performed well on land. His first clock was tested at sea, but the motion of the ship affected the timekeeping of the clock.

These clocks had an entirely different escapement, not related to the anchor escapements, called the grasshopper escapement because of its action. Its limbs are fixed in a position that is offset from the pendulum (see Fig. 7), and they are free to rotate about their axes, appearing to jump in and out of the escape wheel teeth. While engaged with the teeth, they rotate with the escape wheel and with no sliding action until they are released, so there is virtually no friction in this escapement.

When the pallets are released, the counterweight at the other end of each pallet causes the pallets to jump up. The vertical shaft in Fig. 7 is the upper portion of the pendulum. The grasshopper escapement has rarely been used because of the complexity and fragility of the design. I do not consider the grasshopper escapement to be related to the anchor escapements because it does not really have an anchor, despite having two limbs. The structure of the grasshopper escapement is sufficiently different and unique to merit placing it in a class of its own. The main characteristics of Harrison's designs were the prevention of rust, the reduction of friction, and the elimination of the need for lubrication by use of self-lubricating and oil-rich woods, lignum vitae in particular. Harrison also attempted

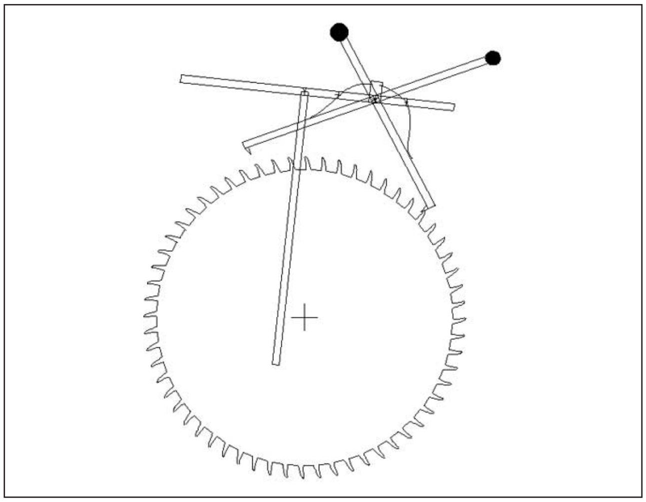

Figure 7. *The Grasshopper escapement.*

to compensate for temperature by using a bimetallic strip to counteract the effects of temperature on the hairspring. If the temperature became warmer, for example, the hairspring would become slightly longer, and the bimetallic strip would displace the end of the hairspring away from the regulating pins by a similar amount.

Harrison won the Longitude Prize with his fourth timepiece, which was actually a very large watch he had built to his own specifications. What is particularly noteworthy about this watch is that it had a verge escapement with a balance wheel, demonstrating that very accurate timekeeping was actually possible with this escapement. The balance wheel had a hairspring with an attachment at the outer end that compensated for temperature. The pallets on the verge were made of highly polished rubies to minimize friction. The gear train had a remontoire between the third and fourth wheels. The remontoire consisted of a secondary spring and a lever that served to provide approximately constant force to the escapement, despite the varying torque of the mainspring as it unwound. One reason why this watch was able to perform well despite turbulence at sea was because of its hairspring. The hairspring provided the main restoring force to the balance wheel by storing its kinetic energy as elastic energy and restoring the energy to the balance wheel when it changed direction of rotation. Another reason was frequency. By designing a watch that oscillated more quickly, the watch was less affected by the motion of the ship because resonance was avoided.

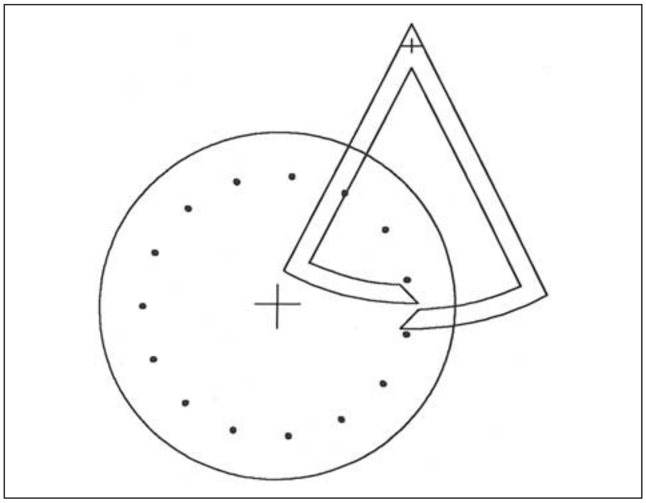

Figure 8. *The pinwheel escapement.*

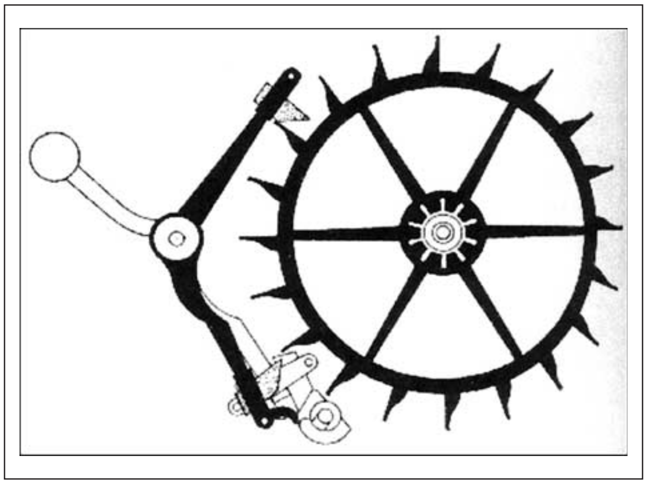

Figure 9. *Mudge's detached lever escapement.*

The Pinwheel Escapement

The first notable descendant of the Graham escapement was the pinwheel escapement, invented by Lepaute in 1753. The main objective of this design was to reduce the angle of swing of the pendulum. The pinwheel escapement was used in a few of the finest clocks, which were called jewelers' regulators. However, this design is not superior to the Graham escapement. If both escapements were designed on the same geometric principles (so that the angles of their respective impulse faces were the same), the amplitude of pendulum swing would also be the same, thereby failing to reduce the circular error in the motion of the pendulum. The pinwheel escapement has the disadvantage of being particularly difficult to make because of the pallets: they must be nearly perfect or the escapement will not work at all! The clearances are so small that any sizable error would result in binding of the parts. The pallets are also asymmetrical, with one pallet located farther from its axis of rotation than the other. This design places the pallets next to each other, rather than on opposite sides of the escape wheel. As can be seen in Fig. 8, the escape wheel rotates clockwise and the upper entry pallet is closer to the pallets' axis of rotation than the lower exit pallet. In contrast, the pallets in a Graham escapement are symmetric.

The most efficient anchor escapements are the Graham and pinwheel escapements. The tooth or pin of the escape wheel slides across the impulse face, transferring energy from the escape wheel to the pallet and thus to the pendulum. Since the force vectors of the tooth and pallet are designed to be at right angles, the maximum achievable efficiency of these escapements is actually less than 50%. The sliding surfaces require lubrication because of friction.

The Detached Lever Escapement in Watches

Thomas Mudge (1717-1794) invented a new escapement for watches around 1750. He appears to have adapted the Graham escapement for use in a pocket watch, creating what became known as the detached lever escapement. The vast majority of all watches made since then were based on Mudge's design. Whereas the pallets and the balance wheel of the verge escapement were attached and interdependent, they were detached and independent of one another in the detached lever escapement. This means that the balance wheel could oscillate back and forth freely and independently of the pallets, interacting with the pallets only near the midpoint of its oscillations. The pallet assembly has three arms, one for each of the two pallets and a third arm with a slot in the end, called a fork. The balance wheel has a pin under it that enters the slot in the fork as it goes by. The pin unlocks the pallets, and energy is transferred from the escape wheel to the pin. The pallet releases the escape wheel, and the pin exits the fork. The pin continues to rotate with the balance wheel until it changes direction and returns to engage the fork again. The balance wheel is free to rotate up to about 300° before the pin strikes the fork on the other side.

The balance wheels of most watches are set up to rotate between 180° and 270° in each direction. The balance wheel's pin interacts with the pallet fork in about 16°, less than 10% of the total oscillation. The balance wheel is no longer restricted to rotating by only about 100°, enabling the watchmaker to make increased use of the elastic property of the hairspring for improved timekeeping. Since the balance wheel has much greater amplitude of oscillation, a longer hairspring is required, like the one shown in Fig. 4. Harrison's watch would have been even more accurate if it had been equipped with a detached lever instead of a verge escapement!

Mudge's watch included a safety pin to prevent the pallet fork from moving over to the wrong side of the balance wheel while the balance wheel rotated. If the pallet fork was on the wrong side of the balance wheel, the balance wheel's pin would not engage with it correctly to unlock the pallets and receive energy from the escape wheel. However, this design did not include a means for preventing the fork from accidentally rubbing against the side of the balance wheel shaft (the part known to horologists as the roller table), interrupting the freedom of rotation of the balance wheel.

Notice that a fourth arm with a weight, shown with a circle in Fig. 9, was added for poise. The pallet assembly is poised when the weight of the parts is evenly distributed about the axis of rotation, so that the assembly is not heavier on one side than the other. The weight of the corresponding parts of the pallet assembly needs to be equally distributed for symmetric behavior. The word *poised* is used instead of *balanced* to avoid confusion with another part, the balance wheel (which, by the way, should also be poised).

The most important advantage of detached lever escapements in watches, including the English lever, the Swiss lever, and the pin-pallet escapements, is that these watches were essentially self-starting. If the movement of the balance wheel was interrupted for any reason and the watch stopped, a slight movement of the watch in the pocket or on the wrist would start the watch ticking again.

The English Lever Watch Escapement

Other watchmakers did not adopt Mudge's design until about 1820. Technology was slow to change, and the verge escapement was still widely used in watches until about 1840. Around 1820, a new design, based on Mudge's detached lever escapement, emerged in the English Midlands. This new design, now called the English lever, slowly gained

Figure 10. *An English lever escapement.*

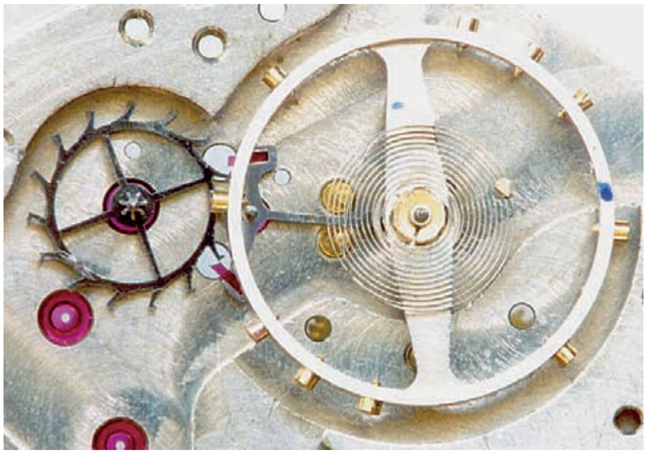

Figure 11. *A Swiss lever escapement.*

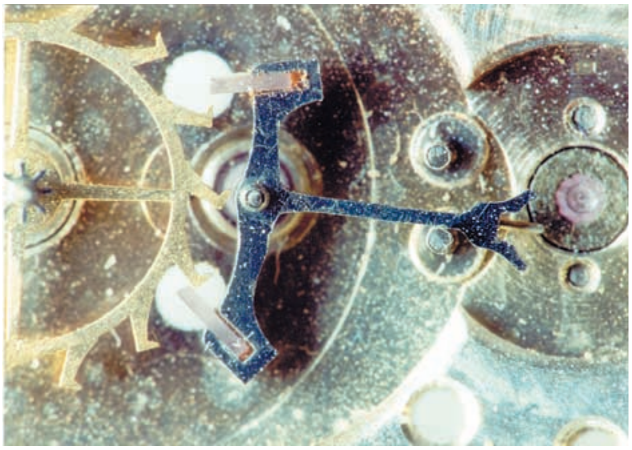

Figure 12. *Another Swiss lever escapement.*

popularity until the verge escapement was phased out around 1840.

The English lever incorporated a major improvement over Mudge's design. To keep the fork away from the balance wheel until the pin returns to engage the fork, force is necessary to prevent the fork from rotating, keeping it in its desired place. Whereas Graham's pallets had curved locking faces to prevent recoil, the English lever had flat locking faces that leaned forward by about 15° to allow the escape wheel to rotate forward by about 1° during lock (see Fig. 10). When the pin (known to horologists as the roller jewel) on the balance wheel engages the fork to unlock the pallet, the escape wheel must be pushed in the opposite direction (backward), requiring a little extra force to unlock. This extra force is known as draw. You could say that this force serves to draw the fork away from the balance wheel between engagements. Draw is critical in watch design to ensure consistent timekeeping, although it was not included in the early lever designs.

The English lever escapement was used until the end of watch production in England, around 1900. This end was caused by less expensive imports from the United States and Switzerland and by the failure of English watchmakers to adapt to changing technologies and markets.

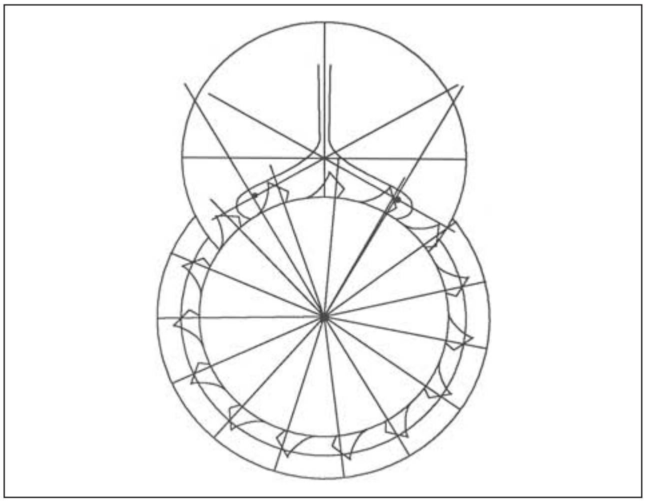

Figure 13. *The pin pallet escapement.*

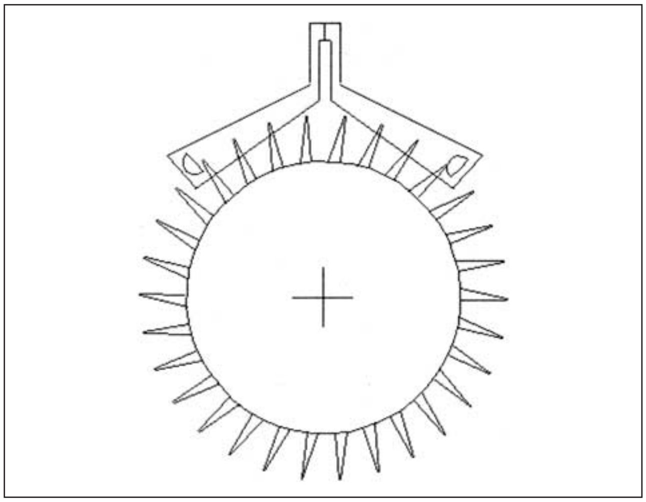

Figure 14. *The Brocot escapement.*

The Swiss Lever

There are two major differences between the Swiss lever and the English lever. As shown in Fig. 11, the axes of rotation of the escape wheel, the pallets, and the balance wheel all lie on a straight line. This design feature makes it much easier to fabricate this escapement so that it is symmetric. It is desirable to make the design of the pallets as symmetrical as possible so that the energy the balance wheel receives from the pallet fork would be of the same magnitude for both directions. If there was asymmetry, the balance wheel would rotate more in one direction than the other, which would make the timekeeping inconsistent, particularly if there was a change in the amplitude of oscillation of the balance wheel, contributing to isochronal error. In theory, the period should be the same for all amplitudes. In reality, the period decreases slightly as the amplitude increases, causing the watch to gain time. This difference is called isochronal error: *iso* meaning "same" and *chronos* meaning "time." Isochronal error of balance wheels should not be confused with the circular error of pendula, caused by gravitational forces. Gravitational forces do not affect a properly designed balance wheel.

Fig. 12 shows the second major difference between the Swiss and the English lever escapements. The teeth of the escape wheel in the English lever are pointed. The escape wheel in the Swiss lever, called the club-tooth escape wheel, has a slope added to the end of each tooth for added strength and to reduce drop. The ruby pallets are slightly narrower because of this design change, so that the impulse faces of the pallets are shorter. Each escape tooth has an impulse face as well, however, making the total length of impulse face equal to the sum of both the pallet's impulse face and the tooth's impulse face. A reduction in drop increases the transfer of energy from the escape wheel to the balance wheel for every revolution of the escape wheel. The Swiss lever escapement is therefore more efficient. The pallet assembly is as light as possible and is not poised, relying on draw to keep the fork away from the balance wheel. A very small number of high-grade watches do have poised forks, however.

The Swiss lever design appeared between 1860 and 1870. It has been used in virtually all Swiss, American, and Japanese watches of quality produced since then (probably several hundred million watches), and it is still being produced today.

The Pin Pallet Escapement

The pin pallet escapement is another detached lever. It differs from the others in that the lock, draw, and impulse are all designed into the teeth of the escape wheel rather than the pallets. The pallets consist of small steel pins, as shown in Fig. 13.

The lowest grade pocket watches, such as the dollar watches, and the cheapest clocks, especially alarm clocks, had pin pallet escapements. Again, probably several hundred million timepieces were produced with several variations of this escapement. Some cheap mechanical alarm clocks are still being made with pin pallet escapements, using plastic escape wheels and steel pins in plastic pallet assemblies. Escapements with plastic parts should never be lubricated because the lubricants may react with the plastic. Besides, plastics are said to be self-lubricating.


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The Brocot Escapement

The Brocot escapement, invented by Achille Brocot (1817-1878) in Paris around 1860, is a pin pallet escapement that was designed for use with pendulum clocks. The teeth of the escape wheel do not have draw designed into the locking faces since they follow the radial lines from the escape wheel's axis of rotation, rather than appearing to lean forward (see Fig. 14). The impulse face is designed into the pallets rather than the escape teeth, which are pointed. The pin pallets consist of larger steel pins in the form of a half circle. Some ornamental clocks have Brocot escapements with ruby pins.

A well-adjusted Brocot escapement has no recoil, so it is much more efficient than a recoil escapement. The impulse surfaces of the pin pallets are curved, however, which means that the direction of the force vector, acting to push the pallet, changes as the escape tooth slides across the impulse face. This escapement is about 20% less efficient than a similarly proportioned Graham escapement, which has straight impulse faces. To design a similarly proportioned Brocot escapement, simply place Brocot pallets over the tips of Graham pallets, as shown in Fig. 15.

This comparison clarifies the similarity between the Brocot and Graham escapements. The escape wheel of the Brocot escapement should have perpendicular teeth rather than teeth that appear to lean forward, as in the Graham escapement.

The influence of the anchor escapements on horology is enormous. Nearly 90% of all pendulum clocks produced since 1660 have had anchor escapements of the recoil type.

Other Escapements

Estimates are that several hundred different escapements were designed in the 18th and 19th centuries. Most were minor variations of the anchor escapements discussed above. There is, however, a different family of escapements that should be mentioned briefly here. The cylinder, duplex, and chronometer watch escapements differ in that they have no anchors and no pallets. The balance wheel receives energy directly from the escape wheel teeth.

By far the most important of these three escapements is the chronometer. The escape tooth provides energy to the balance wheel while the tooth and the balance wheel's roller jewel roll together, in the same way the teeth in the gear train roll together. The direction of the tooth's and the roller jewel's force vectors is therefore the same at the midpoint of their engagement, so the efficiency of the energy transfer is nearly 100%. Since there is very little friction in this design, no lubrication of the escapement is required, an advantage for improved timekeeping.

High-grade marine chronometers, based on the chronometer escapement, have served for over 200 years at sea and are still being used for ship navigation. Their use has more recently decreased because of the new satellite navigation systems.

Conclusions

The influence of the anchor escapements on horology is enormous. As many as 90% of all pendulum clocks produced since about 1660 have had anchor escapements of the recoil type. Although there are dozens of different styles, the design principles are essentially the same. Mechanical clocks with re-

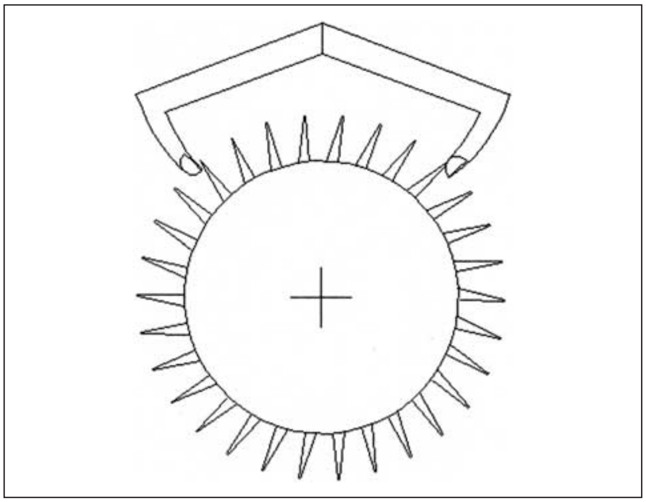

Figure 15. *Brocot pin pallets over Graham pallets.*

coil escapements are still made today. Almost all finer clocks have been equipped with Graham escapements.

All timepieces with anchor escapements can be seen as having three sets of components. There is the driving component, consisting of a gear train with a source of potential energy (gravitational energy with a weight or elastic energy with a mainspring). There is the controlling component, consisting of an anchor and an oscillator, which interacts with the driving component and allows the energy in the driving component to be expended in a controlled manner. The energy is used to repel the oscillator (the pendulum, balance wheel, or foliot) from its center of oscillation (or its rest position). The driving component serves to replace energy in the oscillator, energy lost due to friction. The third component is the restoring component.

The restoring component consists primarily of an elastic spring (suspension spring or hairspring) that stores kinetic energy from the moving oscillator. The spring causes the oscillator to decelerate until it stops and then uses the potential energy to accelerate the oscillator in the opposite direction (restoring the oscillator to its center of oscillation). Other restoring components include energy from the escapement, caused by recoil, and gravitation potential energy.

These three components interact to simulate simple harmonic motion as closely and as predictably as possible, with the objective of measuring the passage of time. The passage of time is shown by the rate of descent of the weight or by indicators (the hour, minute, and second hands) mounted onto the shafts of the gears.

The modern watch industry, after being overwhelmed by quartz technology, now produces mechanical watches to serve primarily a luxury market. All new mechanical watches, with a few extremely rare exceptions, have Swiss lever escapements. Modern methods of production have made it possible to mass produce these accurate (to within a few seconds per day) and reliable watches with little need for manual adjustment. The Swiss lever design evolved with the development of industrial machinery since the Industrial Revolution and has recently been optimized with the application of computer technology and computer-aided design programs.

Finally, as mentioned earlier, an escapement mechanism is a speed regulator that uses feedback to obtain precision operation despite imperfect components. Detailed analysis of this regulator, from mechanical and control engineering points of view, is incomplete. My hope is that this history of the origin and evolution of the anchor escapement will motivate continued research into the dynamics and operation of these fascinating, ubiquitous, and useful devices.

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