

Clock and Watch Escapements

Clock and watch escapements are a special class of intermittent motion mechanism designed for a single task; to measure time. Although they are designed for just one purpose from an historical point of view, they are probably the most important intermittent motion mechanisms ever devised. Mechanical timekeepers made accurate navigation possible and so aided significantly the expansion of Western civilization. The measurement of time was also of pivotal importance to the development of science, and all time measurement until recently was accomplished by mechanical devices (or celestial observations). Timers were considered such an important tool of the scientist, in fact, that some of the greatest scientists of all time, men like Galileo; Huygens; Robert Hooke; and Wheatstone all devoted a portion of their professional lives to the improvement of clock and watch escapements.

We will be considering mechanical escapements primarily (with one or two electro-mechanical escapements thrown in for good measure) since our topic is intermittent motion mechanisms and not clocks and watches. The more recent electronic timers will not be considered at all, even though these are rapidly gaining in popularity and will probably soon replace mechanical devices in a great many situations. The cost of excellent mechanical clocks and watches has been reduced to a point that will be very hard for electronics to beat, however, thus mechanical timers will be with us for a long, long time to come.

Basic Requirements For a Mechanical Timekeeper

The basic requirement for any timekeeper is some phenomenon that can be used as a measure of time or "time base." The earliest clocks used the flow of water or sand through a fixed orifice; or the steady burning of a measured candle was used to track the passage of time. Sundials, of course, were also used. These basically analogue time bases were eventually replaced by systems in which a mechanical oscillator was used to measure the passage of time. Two basic mechanical oscillators quickly gained favor and are still in use today; the pendulum and the rotating-mass-spring oscillator.

A good mechanical oscillator has a cyclical motion which is relatively constant over a long period of time as long as energy lost to friction is replaced. In a clock or watch, the motion of the oscillator is used to regulate the velocity of a gear train which, in turn, drives hands or dials that indicate time. In effect, the clock mechanisms count the beats of the oscillating element (or integrate them) to convert "number of oscillations" to hours, minutes, seconds, etc. The clock or watch escapement is the mechanism that couples the rotating-spring-mass or pendulum to the gear train, and time indicators.

There are some severe restrictions on the escapement if it is to function correctly. It must accurately sense the motion of the mechanical oscillator (mass-spring or pendulum) and use this information to control the motion of the gear train; which is con-

tinuously urged forward either by a large mainspring or falling weights. Since the escapement is generally controlled by the oscillator, it inevitably takes energy from the oscillator in order to function. If it takes out too much energy or takes it out at the wrong time, however, it will disturb the vibration of the oscillator and will affect the accuracy with which the oscillator measures time.

The escapement, furthermore, must also put energy back into the oscillator to keep the oscillator in motion. If this were not done, the oscillations would rapidly die down; thanks to viscous or coulomb friction, as in Figs. 3-16 or 3-18. The amount of energy introduced to the oscillator must be just about equal to that taken out by the escapement and by friction losses in the oscillator, or the oscillations will tend to increase in amplitude. This would destroy the accuracy of the time base (or would destroy the clock!). Thanks to the efforts of generations of superb designers, all of these things are accomplished easily by relatively simple and low-cost clock and watch escapements. We do not have room to go into all of the ramifications of the design of a good timekeeper, or even of a good escapement, but later on we will discuss some of the ways several of these things were accomplished, as we look at examples.

Advantages and Disadvantages of Clock and Watch Escapements

Since this is a special class of mechanism, it would be unfair to consider its advantages and disadvantages relative to the other devices we have been discussing. Needless to say, timer escapements have no peer when the job to be done is to keep time. On the other hand, they have few advantages compared to ratchets, Genevas, clutches, stepping motors, etc., when the job to be done is anything other than keeping time.

This is not to say, however, that they cannot be useful to the designer of intermittent motion mechanisms for machinery. As we will see in a later chapter, there are such things as machine escapements and they bear a strong family resemblance to clock and watch escapements, from which they were, no doubt, derived. Some of the forms and ideas developed for timekeeping might very well find application in heavy-duty machinery.

The first clocks as a matter of fact *were* heavy-duty machines, with escapements only a foot or more in diameter easily controlling weights weighing tons.

Some of these designs gave excellent service for centuries, with only routine maintenance. Even small timer escapements are surprisingly rugged devices and should find more application in other instruments than they do at present. Mechanical delayed bomb fuses of World War II, for example, would withstand decelerations of 30,000 times the acceleration of gravity and still go on ticking accurately. Try dropping your high-speed business machine or machine tool with their Genevas, ratchets, stepping motors, etc., out of an airplane sometime and see if the machine will still function! Even though the timer escapement is a very small, lightweight device, its strength-to-weight ratio is very high, and it will stand a remarkable amount of abuse.

Another typical characteristic of good clock and watch escapements is very long life (see Fig. 5-2); almost zero wear in some applications. Disadvantages include the requirement for precision manufacturing techniques and correct lubrication, intolerance of dirt, etc., at least where precision timekeeping is required.

BASIC TYPES OF CLOCK AND WATCH ESCAPEMENTS

There are literally hundreds of different clock and watch escapements. Only a few of the more important ones will be considered in this text, however.

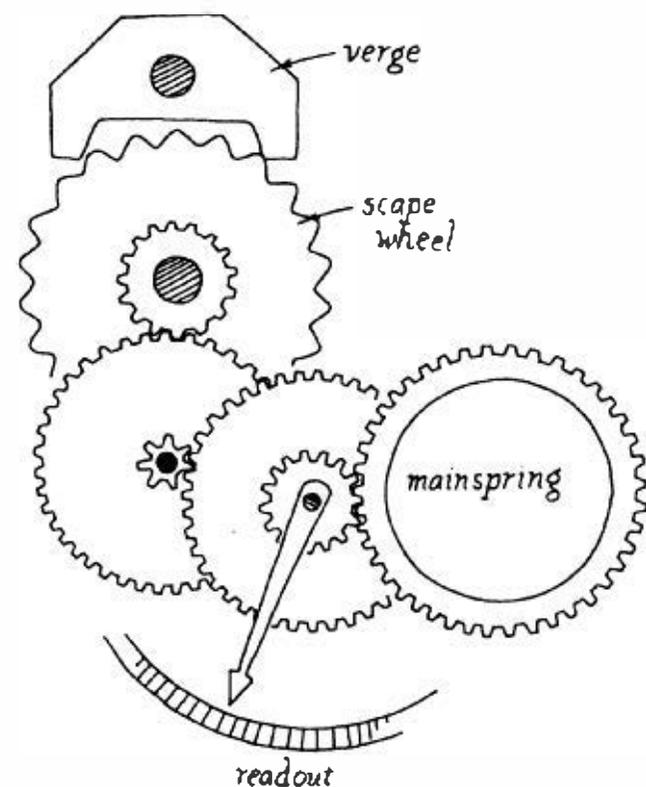


Fig. 11-1. Complete timer mechanism, showing drive spring, gear train and runaway, or verge, escapement.

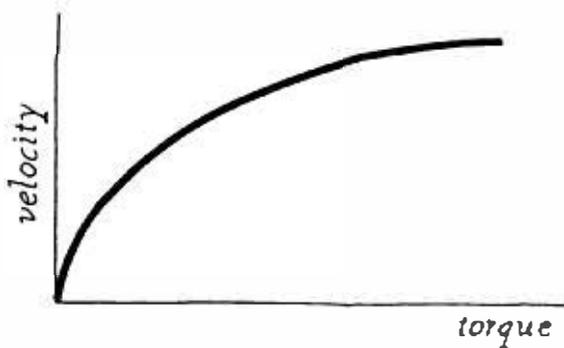


Fig. 11-2. Torque-speed curve for a runaway escapement.

Runaway Escapement

The simplest escapements use a non-resonant oscillating mass rather than an oscillating spring-mass as the basic timekeeper. A modern version of this type of escapement is shown in Fig. 11-1. The verge is the oscillating mass. It interferes with the rotation of the escape wheel as the latter attempts to rotate under the influence of a mainspring-driven gear train. One tooth or pallet of the verge is always positioned to interfere with the motion of the escape wheel or "scape" wheel, as it is sometimes known, so the latter is never allowed to rotate freely.

If the torque applied to the escape wheel is increased, the mass will oscillate more rapidly and the wheel will rotate more rapidly, since the verge is not a true oscillator. Hence the name "runaway" escapement for this type of mechanism. Figure 11-2 shows a typical torque-speed curve for a verge escapement. This type of escapement, incidentally, has a very high "beat rate." It sounds more like a bumblebee than a watch. The runaway finds a great deal of application in such things as portable range timers, parking meters, and in military products such as bomb fuses, rockets, and the like, because it is very rugged and economical. Furthermore, it is a self-starting escapement, which is necessary in many military situations. Also, its characteristics are similar to those of the fluid damper, and the runaway escapement is often used as a mechanical damper for speed control.

Pendulum Clock Escapement

Figure 11-3 shows the clockworks from a typical pendulum clock. The pendulum is hung from a knifeblade by a thin spring or strap, to reduce bearing friction effects. A yoke fastened to the escapement engages the pendulum near the top. As the pendulum oscillates, it moves the scape (escape) lever, which in turn releases the scape wheel. This latter is con-

stantly urged to rotate by the gear train which is driven by the large falling weight. Further gears couple the weight to the output indicator; in this case, a single hour hand. The motion of the pendulum, then, controls the motion of the falling weight; which motion is indicated by the rotation of the hour hand. At some point during each cycle of the pendulum (the maximum velocity, or vertical, position is preferred) the scape wheel pushes on the scape lever which in turn, pushes on the pendulum, replacing any energy lost through bearing supports, air friction and the like. Different types of clock escapement accomplish this transfer of energy in different ways.

Watch Escapement

A typical watch mechanism is shown in Fig. 11-4. The pendulum has now been replaced by an oscillating springmass—the mass being called a "balance wheel," and the spring being called the "hairspring." The motion of this oscillator controls an escapement

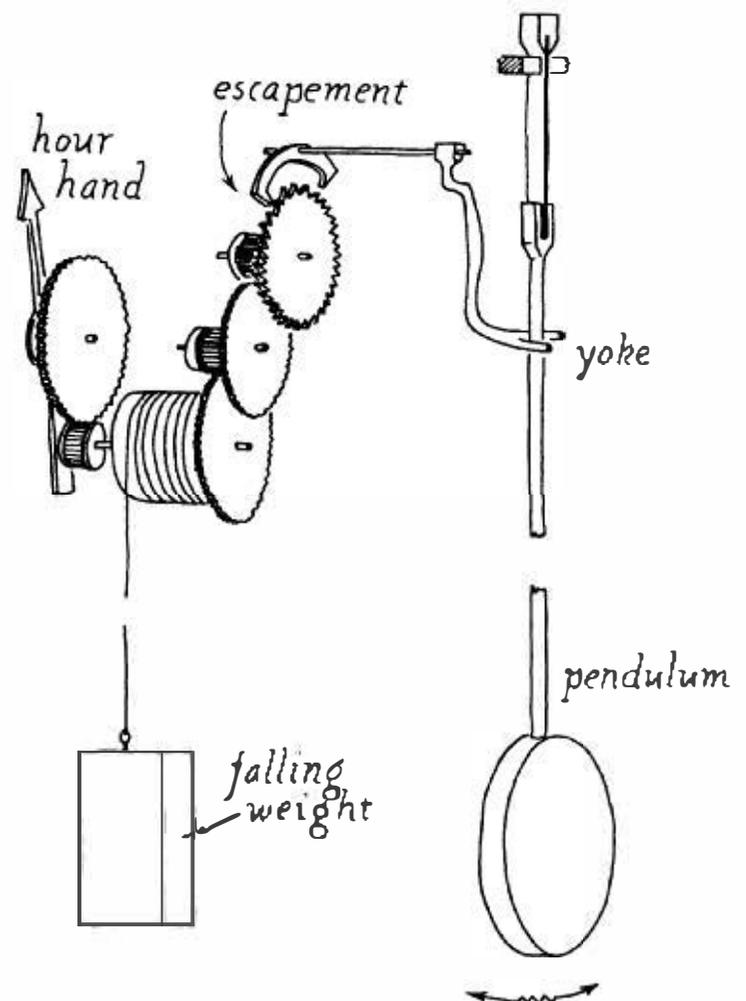


Fig. 11-3. Pendulum clock. Shows the relationship between mechanical oscillator (the pendulum); the clock escapement; the input power source (a falling weight); and the output indicator (hour hand).

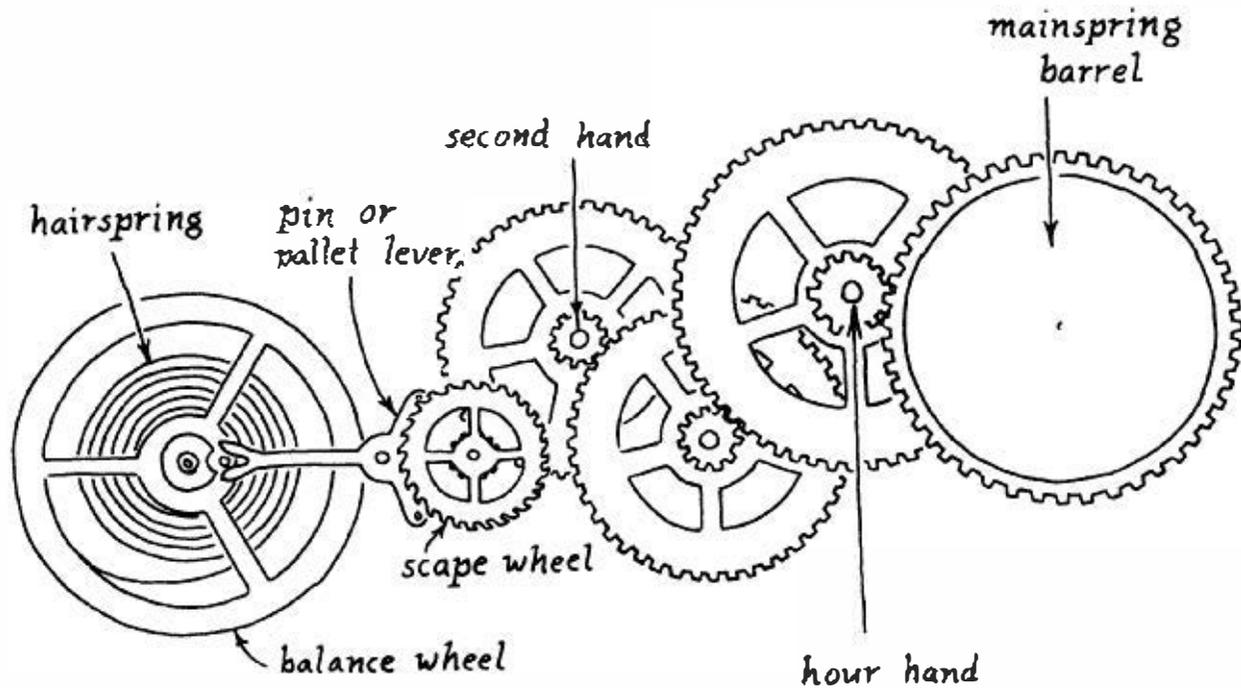


Fig. 11-4. Pocket watch showing the relationship between power source (mainspring), gear train, escapement, mechanical oscillator (balance wheel and hairspring) and indicators (second and hour hands). The minute hand is driven by additional gears (not shown) from the hour hand spindle.

which in turn regulates the motion of a gear train. In this case, however, the gear train is driven by a large mainspring rather than by a falling weight. Hour and second hands are in turn driven by the gear train, as shown in the illustration. The minute hand would be mounted on the same shaft as the hour hand but would be driven by different gears. I have omitted it for clarity. Again, energy must be delivered from the main power source, the mainspring, to the oscillating balance wheel, by the escapement, at some point during each cycle of oscillation.

And, again, it is best to introduce such energy at the maximum velocity point since an impulse on the balance wheel at this point will have the least effect on the frequency or period of oscillation. Different watch escapements accomplish this energy transfer in different ways. Watch escapements designed for maximum timekeeping accuracy (i.e., minimum interference with the oscillator) inherently tend to be weak in selfstarting, but the handling they receive when they are wound is generally sufficient to get them going.

Motion Curves

Figure 11-5 shows typical motion curves; angular acceleration, α ; angular velocity, ω ; and angular displacement, θ for the scape wheel (and, therefore for any element of the gear train) in a clock or a watch. This picture is also a reasonably correct

description of the motion of the gear train in a runaway escapement, although, in this case the velocity ramps would appear "heel to toe" with essentially no sustained dwell periods.

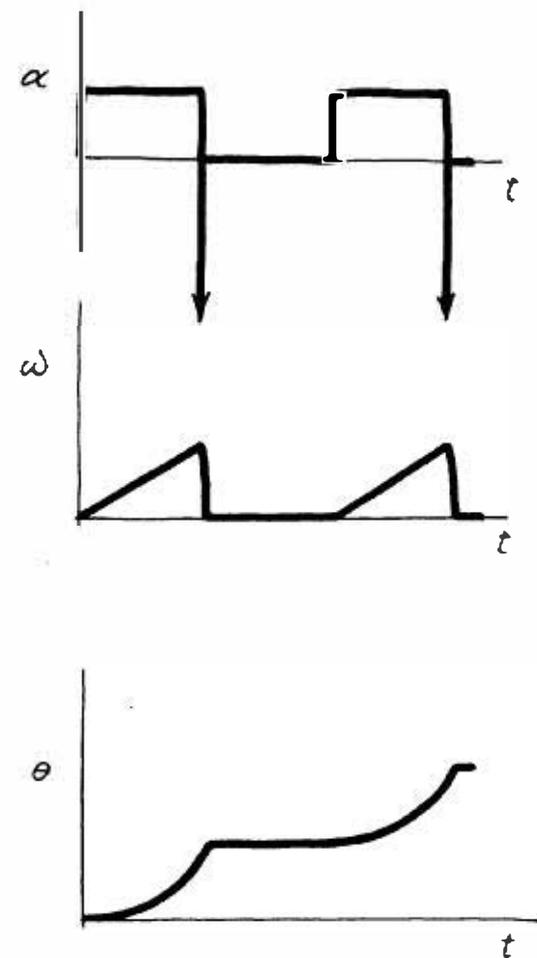


Fig. 11-5. Motion curves for a clock or watch escapement for one complete cycle of a pendulum or balance wheel (a tick and a tock).

As can be seen, a net torque (from the mainspring or falling weight) is suddenly applied to the scape wheel when the latter is released by the scape lever or verge. The wheel then moves until striking the other tooth (or pallet, as it is called) of the escapement; this suddenly stops the entire system. Motion recommences when the escapement permits. Two steps (a tick and a tock) are shown in Fig. 11-5.

Miscellaneous Problems

A mechanical clock or watch can be a superb timekeeper if sufficient attention is paid to design details. In addition to the problems already discussed, great care must be taken to be certain that the bearing friction in the balance wheel, scape wheel and scape lever shafts does not change significantly during the useful life of the device. In the best timepieces, furthermore, provision is made to compensate for temperature effects (which would cause oscillating masses to increase in size, springs to increase in length, etc.). For those clocks and watches subjected to shock, vibration, or moisture, etc., attention must be given to shock-loaded pivot bearings, careful selection of assembly techniques, sealed cases, etc. And, of course, cost is always a factor, with the designer striving for maximum performance at minimum cost. The extent to which cost reduction has been carried in the watch industry is really amazing.

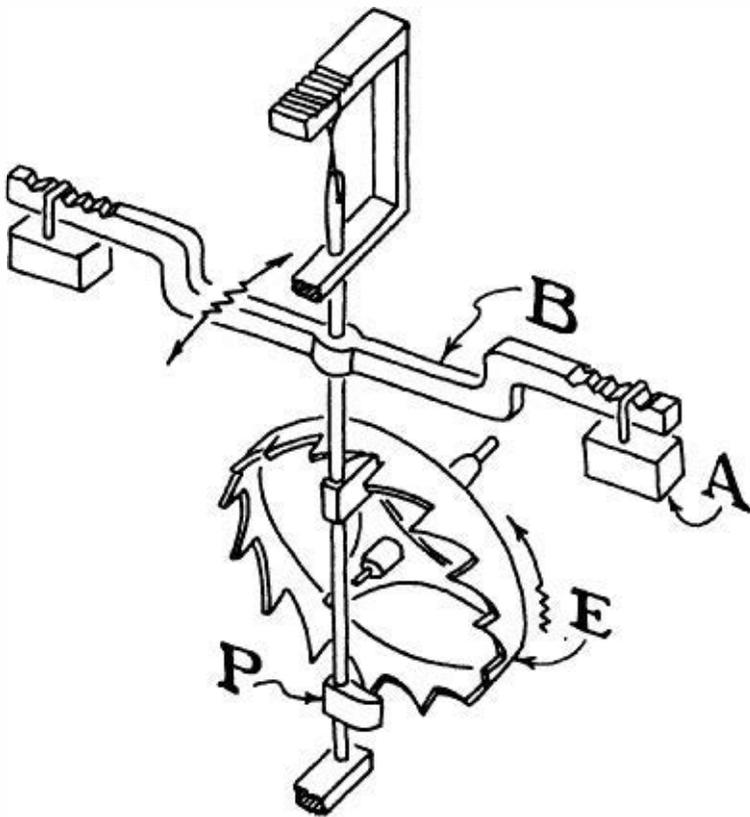


Fig. 11-6. Foliot verge runaway escapement.

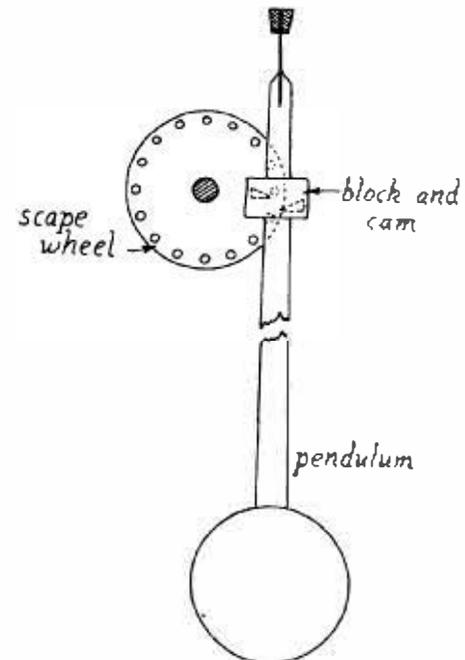


Fig. 11-7. Block and cam runaway escapement.

Varieties of Escapements

Let us look at some escapements. The first, the Foliot verge runaway in Fig. 11-6, is one of the oldest known. Probably the first successful clock escapement, it was widely used in steeple clocks for over three centuries (until the pendulum clock was invented about 1650 AD). This is a runaway escapement, there being only an oscillating mass (the arm *B*, and small weights *A*) to control the motion of the scape wheel (*E*), through the action of the pallets, *P*. There is no oscillating spring-mass combination. This device was, therefore, very torque sensitive; its speed would change if the applied torque changed; a serious problem in steeple clocks which are usually exposed to extremes of weather. Nevertheless, this was a very successful device in its day. The escapement used as a model for this drawing was about two feet high.

Figure 11-7 shows a block and cam runaway escapement, another ancient runaway escapement for a pendulum clock, nearly as old as that in Fig. 11-6, but far less popular. Pins (not teeth) on the scape wheel encounter small wedge cams on the block mounted on the pendulum. These impacts between pins and cams control the speed of the scape wheel, and deliver impulses to the pendulum to keep it swinging.

The small military timers shown in Fig. 11-8, left, are direct descendents of the early devices shown in Figs. 11-6 and 11-7, and use a modern verge escapement such as that shown at the bottom of the drawing at the right. This type of escapement is used in

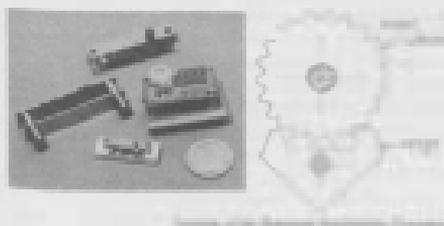


Fig. 11-4. Small military timer with modern verge escapement.

lance, bomb, rocket systems, and so forth, because it is rugged, low-cost, self-starting, and reliable.

The Jungkern cylinder escapement (Fig. 11-9) is another mechanism directly descended from those in Figs. 11-6 and 11-7. It has some of the characteristics of the gun-train-impaling-watch escapement shown in Fig. 11-4, in that it, too, uses locking in conjunction with a control—in this case, a balance arm—pushes-on, then pulls, then steers to a specific beat frequency. Note that the escapement of Fig. 11-4, detaches the balance mass from direct engagement with the escape lever, giving rise to greater accuracy. In effect, “detached lever” escapements represent an evolutionary refinement of the “tuned” cylinder escapement typified here. Escapements of the Jungkern type provide considerably better accuracy than a runaway escapement, if not quite the accuracy of a good detached-lever mechanism. Like the verge, the Jungkern escapement is rugged and unsophisticated and is used in military problems. The main use is between those of a verge and the pocket watch.

The next seven illustrations, Figs. 11-10 through 11-16, show various types of pendulum clock escape-

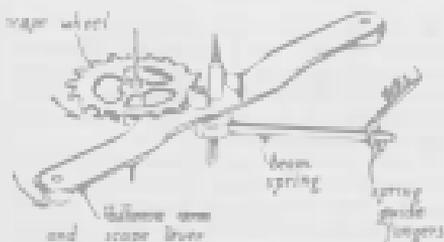


Fig. 11-9. Jungkern cylinder escapement.

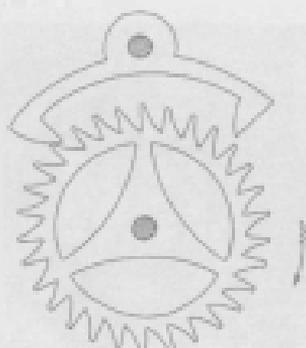
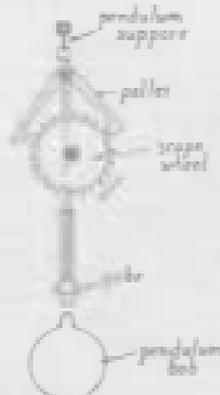


Fig. 11-10. Round escapement from a pendulum clock.

ments arranged roughly in the order of their antiquity. All of these mechanisms were good timekeepers with the last one in this group being the best single-pendulum escapement ever devised.

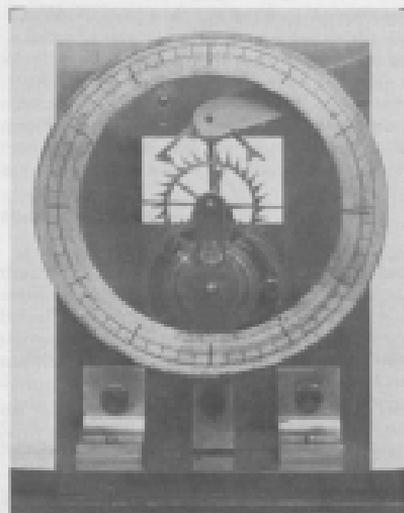
A round escapement from a pendulum clock, shown in Fig. 11-10, was the earliest form of pendulum escapement. The scape wheel backs up each time an escape-lever tooth is entrained from the wheel. This caused some timing errors, but the round escapement was very popular in its time.

Figure 11-11 shows a round clock escapement and



Operating action of a round clock escapement. (See 11-10.)

Fig. 11-11. Round clock escapement.



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Fig. 11-13. Working model of an "anchor" recoil escapement.

the relationship between the escapement and the oscillating pendulum.

A working model of a recoil escapement is shown in Fig. 11-13. This type of escapement is often called

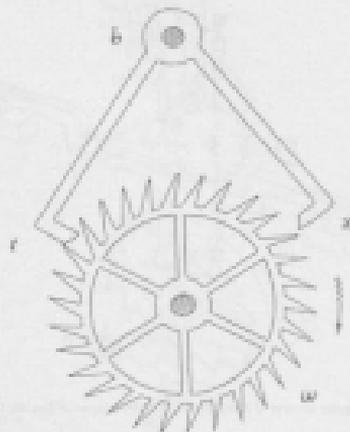
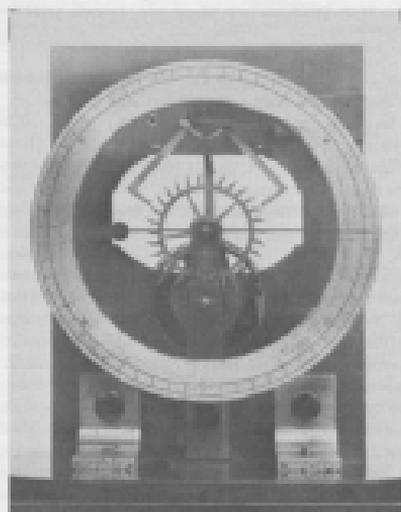


Fig. 11-15. Deadbeat clock escapement, ca. 1715.

an "anchor" escapement. Historians believe it was invented by Robert Hooke around the end of the 17th century.

Figure 11-14 illustrates the deadbeat clock escapement invented by George Graham, around 1715. This is an improved pendulum escapement in which the escape wheel does not back up as the escape-lever teeth are contacted. The device resulted in a considerable improvement in accuracy over that obtained with a recoil escapement.



British Crown copyright, Science Museum, London.

Fig. 11-14. Working model of Graham's deadbeat escapement.

A working model of a deadbeat escapement is shown in Fig. 11-14. This device was one of Graham's many contributions to the design of clocks and watches. His contributions were considered to be so important that he was honored by his nation with burial in Westminster Abbey.

Not all "clockworks" are as small and "delicate" as those we usually encounter, as seen in Fig. 11-15, which is Lord Grimsharpe's three-legged gravity escapement, invented in 1824, and used in the Big Ben of that time. The gravity arms are lifted by three pins on the scape "wheel" and are subsequently

released by the pendulum. This controls the motion of the three-legged scape wheel which periodically impacts small stops or blocks on the gravity arms. The scape wheel, of course, is urged to rotate by a gear train, which, in turn, is powered by falling weights as in other pendulum clocks. A great advantage of this escapement is that all the impulses to the pendulum are derived from the gravity arms, rather than from the scape wheel, through a yoke as in the recoil or deadbeat escapements. This means that the impulses to the pendulum are constant even if the load on the gear train varies, as it usually does in turret clocks that are exposed to the weather. The gravity arms, incidentally, are about one-foot long on this design; to give you some idea of the size of the escapement.

Riefler's escapement, shown in Fig. 11-16, is considered to be the best, purely mechanical pendulum escapement ever designed, because the impulses are imparted to the pendulum through a supporting spring only (by flexing the spring as the pallet lever oscillates). The pendulum is otherwise completely free and is, therefore, a superb mechanical oscillator. The only pendulum clocks which have been found

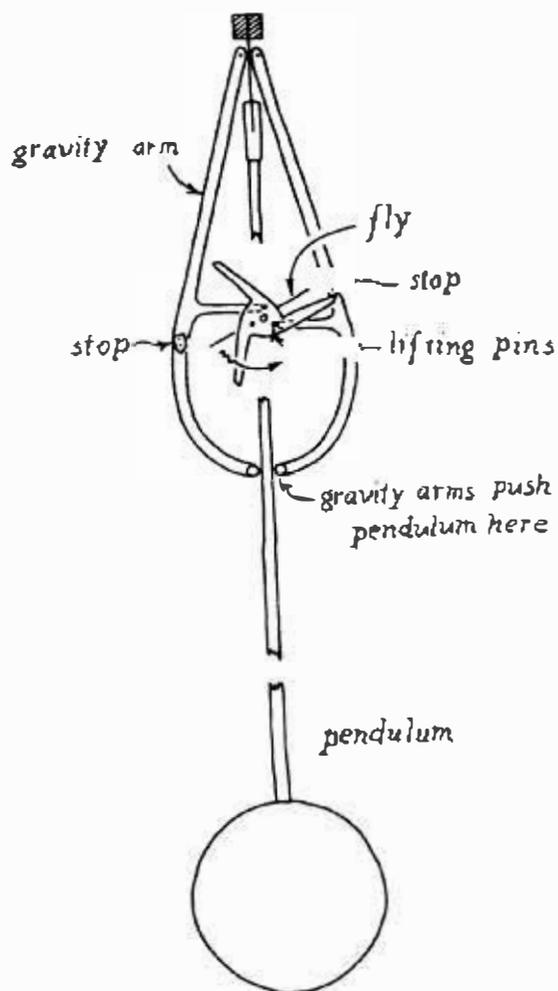
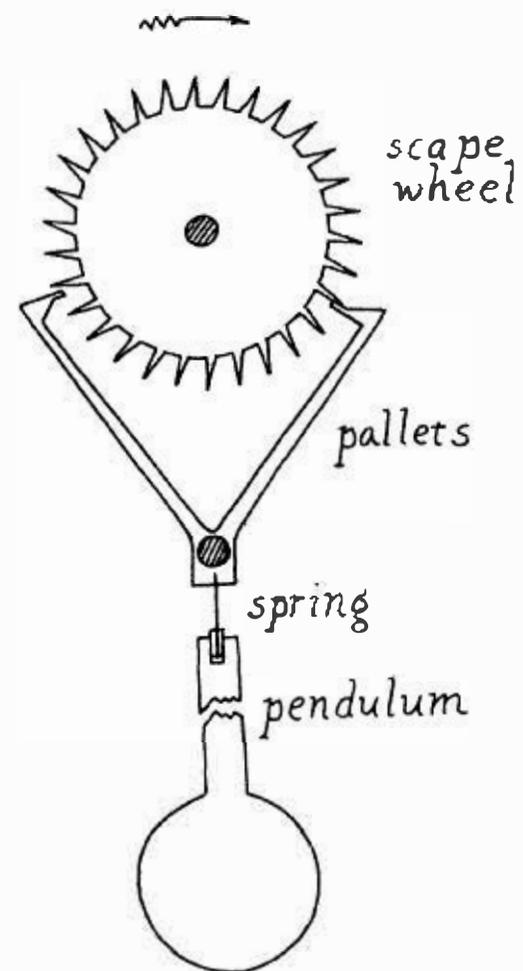


Fig. 11-15. Lord Grimthorpe's three-legged gravity escapement, ca. 1854.



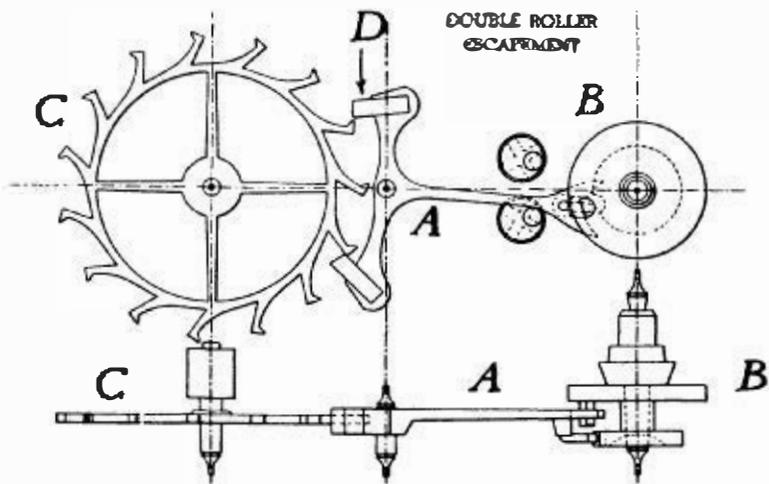
Drawing courtesy of MACHINE DESIGN Magazine; Dec. 25, 1965; p. 121 f

Fig. 11-16. Riefler's escapement.

to be more accurate than this use electro-mechanical escapements with slave and master pendulum systems.

Following are six illustrations showing various types of watch escapements. The main difference between clocks and watches is that the latter are portable. The former usually use pendulum oscillators to keep time, while the latter rely on balance wheel-spring combinations.

This detached pallet lever watch escapement (Fig. 11-17) is one of the most accurate and popular of all time. It is called a detached lever escapement because, like the typical watch escapement of Fig. 11-4, the scape wheel and balance wheel (oscillating mass) are connected by a lever that does not touch the balance wheel at all except for an instant in the middle of each oscillation (maximum velocity point), leaving the mechanical oscillator free during most of each cycle. This results in a great improvement in timing accuracy. Impulses to the balance wheel are delivered by the detached lever, which, in turn, is impulsed by the scape wheel at the end of each

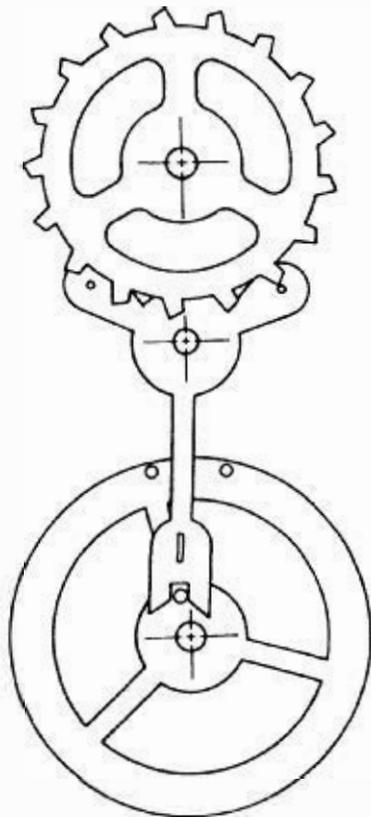


Courtesy of the Waltham Precision Instrument Company

Fig. 11-17. Detached pallet lever watch escapement.

motion. The escapement is not self starting, although the slightest motion in handling will get it going. The following elements can be identified in the illustration: *A.* Detached lever; *B.* Balance wheel roller (mounted under the balance wheel—not shown—and on the same shaft); *C.* Scape wheel; *D.* Pallets.

This detached pin lever escapement, Fig. 11-18, is very similar to the one shown in Fig. 11-17, except that the pallets on the detached lever have been replaced by small pins. Since pallets are usually

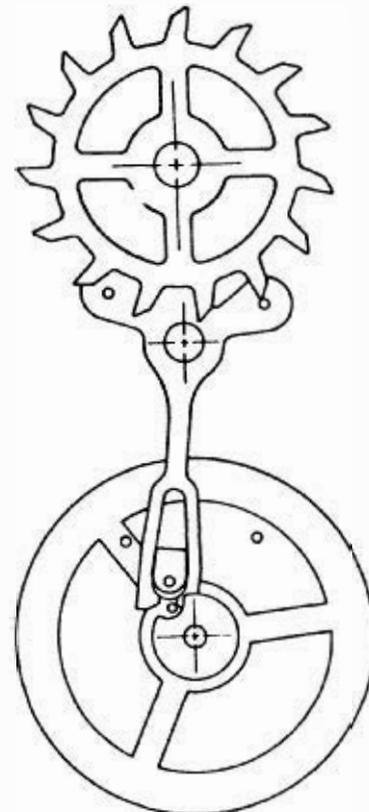


Courtesy of the Raymond Engineering Company

Fig. 11-18. Detached pin lever escapement.

jewels, the pin lever escapement is a much cheaper proposition. It is used in low-cost pocket and wrist watches, but is an excellent timekeeper; one that is cheap, rugged, and accurate.

In this semi-detached pin lever escapement, Fig. 11-19, the lever contacts the balance wheel at all times. The advantage of this is that the escapement is more nearly self-starting than is a fully detached mechanism which has only a weak tendency to self start. A semi-detached escapement, therefore, finds applications in military devices where reliability is



Courtesy of the Raymond Engineering Company

Fig. 11-19. Semidetached pin lever escapement.

essential and the device may not be handled (as is a pocket or wrist watch) to start it.

Schematic of an English lever escapement (*Top*, Fig. 11-20), invented by Thomas Mudge, about 1755. This is another detached lever design, not quite as successful as the ones shown in Figs. 11-17 or 11-18, but included here to show that a bewildering variety of escapements has been developed. The photograph is of a large working model of a similar Swiss lever escapement.

Figure 11-21 shows the Tavano cylinder escape ment. The scape wheel contacts a cylindrical and partially hollow shaft on the balance arm in this unusual design which incorporates a balance-arm suspension via a torsional hair spring located on the

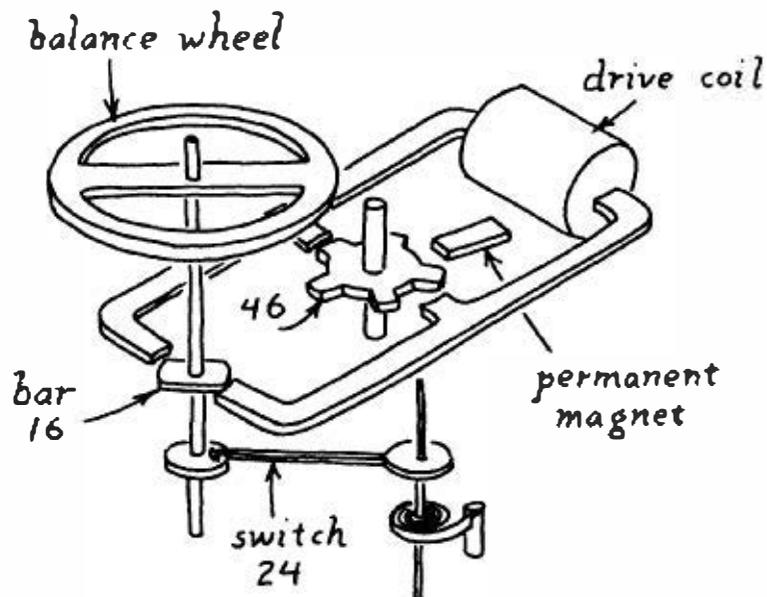


Fig. 11-27. An electro mechanical watch. (U.S. Patent 3,147,583; D. Fritsch.)

nometer escapement in The Science Museum of London, is shown in Fig. 11-26. This is an old form of chronometer escapement but it has most of the features of the modern escapement shown in Figs. 11-23 and 11-24.

Electro mechanical clocks and watches have been gaining popularity in recent years, thanks in part to the availability of small, efficient batteries. Also, designers have tried to replace tooth-to-tooth contact with magnetic forces to reduce friction in watch escapements. In the design (not necessarily typical) in Fig. 11-27 are shown the various elements required in an electrical-mechanical timekeeper. Magnetically transmitted impulses through bar 16 keep the balance wheel oscillating. Switch 24 on the balance wheel will time these impulses, and also time the magnetic forces that drive (not escape) the "scape wheel," 46. This latter is really part of a tiny variable reluctance stepping motor (see Chapter 14). Since considerable energy magnification (the ratio of the work required to close the switch, to the work available from the solenoid) is available here, it is not necessary to provide the mechanical advantage of an escapement; hence, the stepping motor approach. This is true of many electromechanical watch "escapements."

Anatomy of a Watch Escapement

Let us now take a closer look at some of the design features (Fig. 11-28) of one of the best mechanical timekeepers ever invented, the detached pallet lever escapement:

A. Scape wheel, output—loaded by gear train and mainspring. It tries to turn con-

tinuously, but is prevented from doing so by the scape lever. The teeth on the scape wheel are very carefully shaped by generations of science and experience. They must not lock on the scape lever, yet must be held easily by the lever until the next step is desired. Furthermore, when escaping, these teeth must provide a tiny bit of energy to the lever (which energy is derived originally from the mainspring) to be passed to the balance wheel to keep that member oscillating; B. Output pinion—connects scape wheel to the rest of the gear train; C. Scape lever—in this case, a "detached" lever because it is not normally engaged by the balance wheel roller. This lever normally

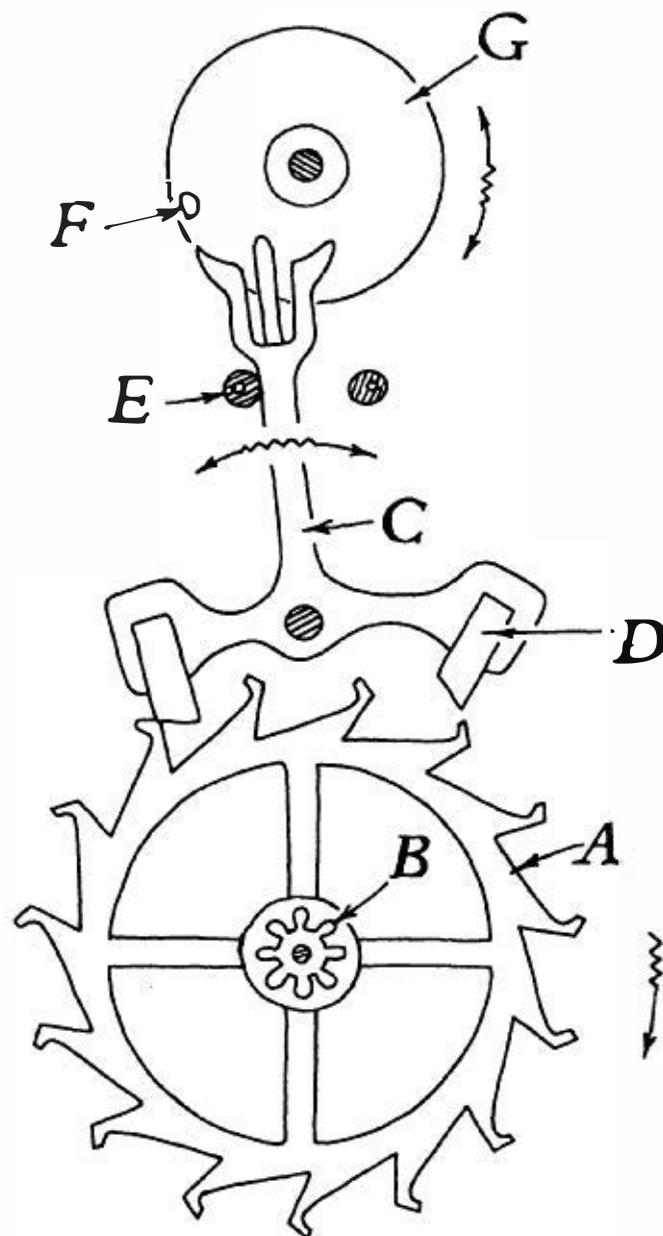


Fig. 11-28. Anatomy of a watch escapement.

rests against one of the two stop pins *E*, held (gently) by forces exerted on the lever, by the scape wheel *A*; *D*. Pallet—scape lever tooth—must be extremely hard, to operate with low friction for many years without benefit of lubrication (which would cause the pallets to stick to the scape wheel). In an expensive watch these are made of jewels and must be shaped to function properly together with the teeth of the scape wheel; *E*. Stop pins or banking pins—control length of throw of the scape lever (often eccentric for adjustment); *F*. Jewel impulse pin—provides the only contact between the balance-wheel assembly and the rest of the escapement. Periodically, it drives the lever from one stop pin to the other. As with the pallets, this pin must work a long time without lubrication; *G*. Balance-wheel roller—small cam mounted on the same shaft as the larger balance wheel. The latter, with the hair-spring, provides the “time base” on which the watch depends. It must not touch the lever except for a brief period at the center (maximum velocity point) of each swing. Although it is the balance-wheel roller which drives the lever back and forth, the lever succeeds in giving the roller a brief push during part of each swing to keep the mechanical oscillator going.

Historical Note

As has been pointed out, the intermittent motion mechanisms developed for the purpose of keeping time have had an immeasurable influence on the development of our civilization. Of course, this was

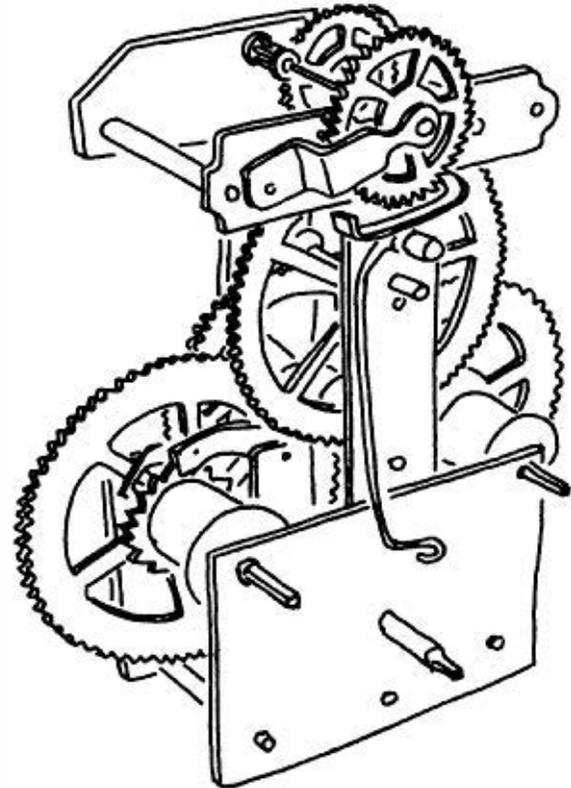


Fig. 11-29. Clock movement manufactured in Connecticut by Joseph Ives, ca. 1847.

said in considering their use as instruments and tools. However, less obvious but also very real, is the influence these devices have had on manufacturing practices throughout the world. Many precision manufacturing techniques were first developed for the production of clocks or watches, where precision is essential to performance. Furthermore, these products were among the first to be built by mass production techniques, which is ample evidence of their popularity and importance. The sketch, Fig. 11-29, shows a clock movement manufactured by Joseph Ives in Connecticut, about 1847.