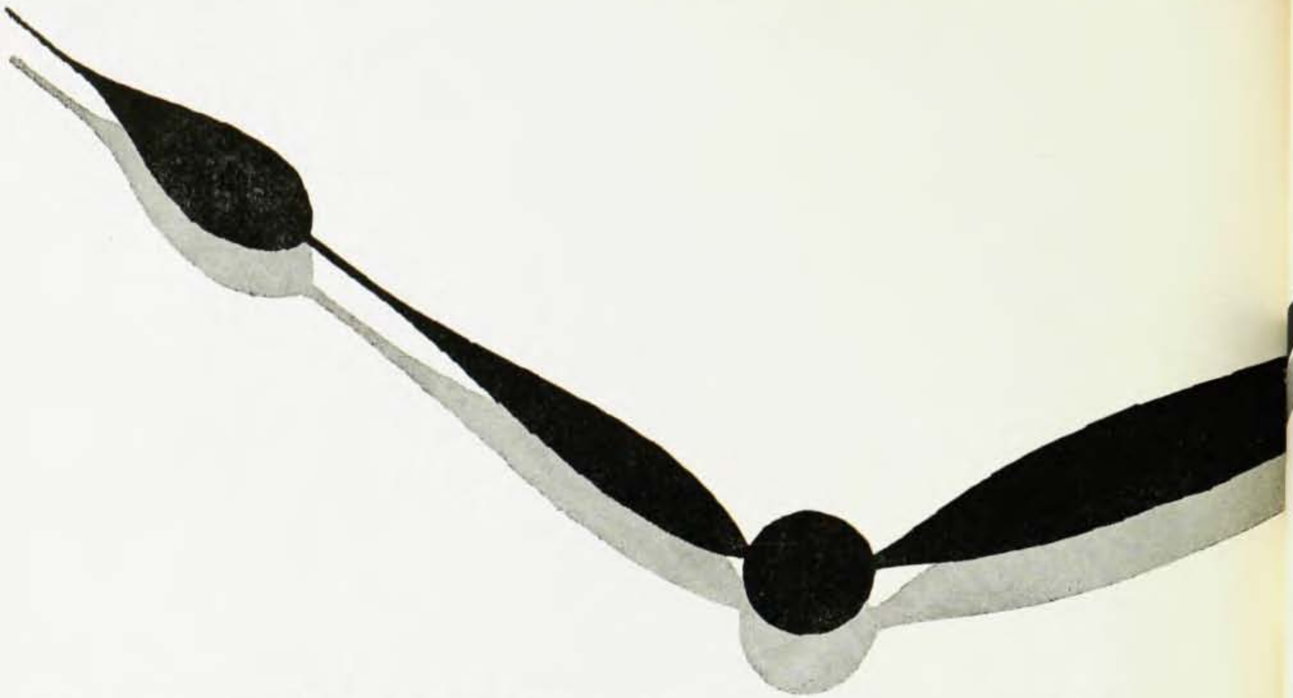
PHYSICS in the WATCH



To the philosopher, time is one of the fundamental quantities. To the average man, time has something to do with dinner. Both find it incapable of definition but subject to measurement, and to the latter at least, the measurement is of importance. Moreover, the importance of the measurement and correspondingly of its accuracy has increased as the complexity of life has increased, so that he no longer finds an estimate from the sun's position satisfactory. Instead he not only wants but needs a portable device for measuring time intervals, which device he calls a watch and upon whose accuracy he sets requirements which are astounding when compared to the accuracy of other instruments.

Although the exterior of a watch is completely familiar to most people, the functioning of the mechanism is not. It is difficult to pick up one piece of time and lay it alongside another for comparison. A less direct measurement is possible in terms of another quantity such as distance, and some equation relating this factor with time. One such equation is the definition of velocity and if the velocity be constant this has the very desirable characteristic of linearity in distance and time. An early application of this relation was in the use of a burning candle as timepiece, but the assumption of constant velocity was ill-founded, and the same difficulty has been met in all attempts to apply this invitingly simple formula.

Another linear relationship, and one which proved more useful, depends upon the attainment of a uniform time interval instead of a uniform velocity. Then the time between the two events can be described in terms of the number of repetitions of the uniform interval between these events and the description will have meaning to the extent that the standard interval is constant and reproducible. For long intervals, a year is a convenient standard. One of the notable contributions of physics to horology was Galileo's discovery that the swings of a pendulum were nearly enough constant in time to serve as a standard for shorter intervals. A pendulum, however, is not adaptable to a watch, and it was left for another famous physicist, the irascible Dr. Hooke, to discover in 1676 that a spiral spring (nearly) follows the law which bear his name, and hence that the rotary oscillations of a mass controlled by such a spring have the same property as the swings of a pendulum. It is this property of isochronism, the independence of the period from the amplitude of oscillation, that makes possible the accurate measure of time by this method.

Inside the Modern Watch

In the case of either the pendulum or balance wheel it is necessary to count the number of swings and to restore the energy lost by the oscillating

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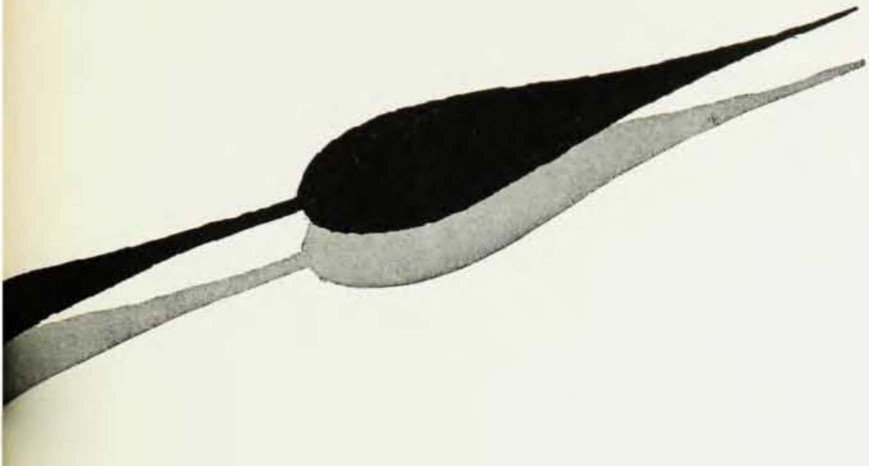


It is sometimes forgotten that physics remains physics even when it is applied. The present article has been written by a physicist who has to wrestle with the physical problems besetting watchmakers in their effort to mass produce ever smaller and more accurate time pieces.

By J. A. Van Horn

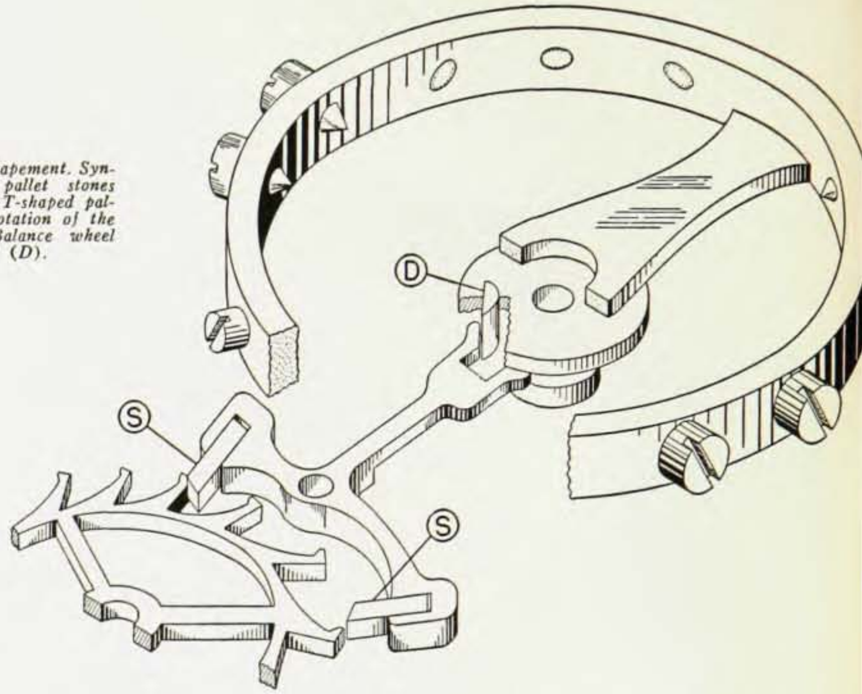
mechanism. Both of these duties are fulfilled by a highly ingenious mechanism called the escapement. In the high quality watch the jeweled lever escapement is exclusively used. As may be seen in the diagram on page 8, the T-shaped unit, or pallet, carries a beam "S" near each end of the cross bar. These are called the pallet stones and are made of a material such as synthetic sapphire which is very hard and capable of taking a high polish. As shown, the one of these rests alongside a tooth of the escape wheel, preventing its rotation in the direction in which it is forced by the mainspring. The balance wheel, which during most of its swing is free from any connection with the rest of the watch except the bearings in which its pivots rest, also carries a piece of sapphire, the jewel pin, D.

As the balance nears the rest position, this pin engages a notch in the other end of the pallet, forcing it to rotate and thus withdrawing the pallet stone which is holding the escape wheel, so that this wheel is temporarily free. However, the other stone has been pushed down by this same action and brings the escape wheel to an abrupt stop after it has turned through half the distance separating adjacent teeth. The balance now swings freely through the other half of its path, and upon its return to the center a similar cycle is accomplished, so that the state of affairs is as it was originally except that the escape wheel has advanced one tooth. Since the train of gears connecting it to the mainspring also engages the hands of the watch, these also advance, serving to count the oscillations.

The other function of the escapement, the restoration of lost energy to the balance wheel, is accomplished by properly shaping the ends of the pallet stones and the escape wheel teeth. As the diagram shows, these are placed at an angle such that when the corner of the stone, as it is withdrawn, reaches the corner of the escape tooth, the rotating escape wheel presses against the end of the stone and forces the pallet to rotate faster than the balance. The pallet then drives the balance, instead of being driven by it, and in the steady state supplies just as much energy as the balance has lost in half a cycle.

The watch, then, consists of a source of power, the *mainspring;* a means of transferring this power, the *train* (that collection of gears called wheels by the watchmaker); a means of recording, the *dial* and *hands;* and a means of controlling the flow of power, the *escapement, balance wheel,* and *hairspring*. It may be seen that this mechanism is a

John A. Van Horn, senior physicist in the watch research department of the Hamilton Watch Company, writes that he made a gesture towards chemistry to the extent of a bachelor's degree but eventually found himself receiving the doctorate in physics from Penn State. After some further indecision about the relative desirability of industrial or academic life, he joined the Hamilton staff. This indecision, he adds, was not the result of any belief that a piece of work is inferior solely because it is immediately useful.



Typical watch escapement. Synthetic sapphire pallet stones (S) are set into T-shaped pallet, controlling rotation of the escape wheel. Balance wheel also carries jewel (D).

fairly simple one; moreover it is one whose basic design has not been altered for nearly two hundred years, although during this time an accumulation of refinements has increased its precision and decreased its size.

Accuracy and Size

Not only the mechanism itself, but also the basic problems connected with it have been unchanged for a long time. The problems arise principally from two somewhat contradictory requirements. One of these is the accuracy demanded of a watch. Being an integrating mechanism, it carefully sums not only the time but also the errors made in measurement. Therefore, in order to attain a precision which appears quite modest under the circumstances of actual use, it is necessary to build into the instrument a precision far beyond that of most instruments. That is to say, from the viewpoint of a man who thinks he has five minutes to catch a train, an error of seven minutes is a very considerable one, but seven minutes per day is an error of only ½ of 1 percent, which is that expected in a good electrical meter. A good pocket watch will have an average error of ± 5 seconds per day, which is ± .006 percent. Comparison of this figure with the tolerances in other apparatus is of interest. A commercial broadcasting station, for instance, is required by law to maintain its frequency to within 20 cycles per second (although in practice it is held closer than this). For a station operating at 1000 kilocycles per second this is an accuracy of ± .002 percent. If the man responsible for maintaining this accuracy has a very good but not extraordinary watch, he has another oscillator good to within the Federal Communication Commission's percentage limits. This second oscillator, however, demands much less attention, operates satisfactorily over a wide range of temperatures and in any position, is impervious to moderate shocks, and needs only to be wound daily and cleaned and oiled every year or so.

The characteristic of a watch which creates most of the rest of the problems is its small and ever smaller size. High accuracy demands close manufacturing tolerances which become doubly difficult to attain as the sizes of the parts decrease. Not only does the same ten-thousandth of an inch represent a greater percentage error when the dimension itself is halved, but also it becomes more difficult to hold the same numerical tolerance. The loss in rigidity as the diameter decreases is not compensated by the increase in rigidity as the length decreases, a fact that plagues the tool designer in most of the manufacturing operations. An indication of the problem represented by such small dimensions is given in its intensification in the smaller watches. In general, the smaller the watch, the poorer will be its timekeeping qualities. Thus, the tiny piece of jewelry on a woman's wrist may have an accuracy of ± 30 seconds per day, which is about .04 percent, whereas a man's wrist watch may be good to .01 percent and a pocket watch, as already stated, should be good to not worse than .006 percent.

This last figure suggests than Michelson's unfortunate remark that the future of physics lay in the seventh decimal place was too demanding, for the watch manufacturer would be happy—at least temporarily—to reach the sixth decimal place, and in attaining this goal expects aid from other physicists than Hooke.

Precision Testing Instruments

In rendering this aid, part of the physicist's function, as in any industry, is to devise tests, and instruments for the performance of those tests by relatively unskilled personnel, which will help to maintain control over the characteristics and behavior of material through the various stages of manufacture. This task is possibly of greater importance in the watch industry than in many others because of two factors. One, obviously enough, is the precision demanded in the finished product. The other is the orphan status of the industry. It is sufficiently different from most of the rest of science or industry that much of its equipment is highly specialized, and it offers a market too limited to justify much attention from instrument makers. For example, the period of the balance wheel, which is to say the rate of the watch, is dependent on the moment of inertia of the balance, and this in turn is adjusted by means of tiny gold screws in the rim. In order to attain the necessary accuracy in the rate, it is necessary to know the weights of these screws to not worse than $\pm$ .02 mg. As any chemist knows, it is no feat to weigh a small object to this accuracy, but cost is also an important consideration. If a standard analytical balance were used the time required for all the necessary weighings would be enough to add several dollars to the retail price of a watch. The current solution to the problem is a sensitive spring balance which weighs the screw to about the required accuracy and requires only a few seconds for the operation. However, it has all of the defects common to spring balances, and it requires the full attention of the operator. A vastly superior method would be to dump the day's production of screws into a hopper of a machine which would separate them according to weight with no further attention. In developing such a piece of equipment, an instrument maker could probably count on the sale of three units for his reward, one to each of the present American manufacturers of fine watches. In the absence of such philanthropy the Hamilton Watch Company has recently attacked the problem itself and has produced the first half of the apparatus, a scale which will automatically weigh screws of from one to six milligrams to within five thousandths of a milligram, and is proceeding on the second half.

In the present form of the instrument, the screw to be weighed is placed in a pan on the end of an aluminum rod fastened at right angles to a straight piece of spring wire (Elinvar), both in a horizontal plane. This wire acts as an axis, about which is a hairspring of the same material. A torque can be applied through the hairspring by rotating the outside coil, which counteracts the torque caused by the weight of the screw and restores the rod to its rest position. This restoring torque is supplied by a synchronous motor operating through a high ratio train of reducing gears, and the number of revolutions of the motor (read on a properly calibrated dial) gives the amount of torque and hence the weight of the screw.

The motor is controlled through a photocell. A beam of light is reflected from a mirror mounted on the wire with its normal parallel to the rod. When the rod reaches its rest position the light strikes the photocell, whose output actuates relays which cut the power from the motor, send a surge of direct current through it to act as a brake, and remove the screw from the pan. Auxiliary circuits control the direction of rotation of the motor so that whatever the initial position of the rod the approach to the rest position is from the same direction. This eliminates the effect of backlash.

The entire cycle takes about fifteen seconds. Since the operator needs only to place the screw on the pan and later to read the weight, another operation, such as inserting a previously weighed screw in a balance wheel, can be performed simultaneously. The cost of weighing a single screw is pretty nearly zero, and to that extent the apparatus is satisfactory. To make it sort screws automatically will require the addition of a device to put the screw on the pan and substitution of a set of bins for the calibrations on the dial and of a chute for the pointer.

It might be noted that in designing this one machine a little familiarity with several fields was required. Although the problem was essentially a mechanical one, the solution involved the use of some circuit theory and some optics. In the watch industry, as in other industries, the wide range covered in the physicist's training forms part of the basis of his usefulness.

Although most of the problems center about the balance wheel, the problems there are simplified if the torque at the escape wheel is reasonably constant, so that the prime source of power, the mainspring, deserves some attention. In the watch it is contained in a short closed cylinder called the barrel. The outer end of the spring is fastened to the edge of the barrel, the inner end to an arbor (or axle) which in winding rotates to wrap the spring around it; in unwinding the barrel turns to drive the watch.

In investigating the properties of this mechanism at Hamilton, two instruments were constructed, each illustrating one of the functions of an industrial laboratory. The first was intended principally for the collection of fairly complete data on a large number of springs in the laboratory. In it the barrel is secured coaxially to a vertical disk whose rotation is prevented by a cord from its rim to the end of a horizontal beam below. The beam is pivoted near its other end and counterbalanced. On the beam there rides a car which, carrying a weight appropriate to the size of spring, can balance at some point on the beam any torque supplied by the spring. It is driven along the length of the beam by a lead screw turned by a reversible motor. The direction of rotation is determined through a sensing mechanism on the end of the beam so that the weight is driven in a direction that will restore equilibrium. The motor is in continuous operation and the car oscillates about the equilibrium point, but the hunting is restricted to a small enough distance that the resultant uncertainty is unimportant, and it gives a desirable assurance that the car has not fallen behind in a state of changing equilibrium.

Through a Selsyn transmitter and follower this motor also controls the rotation of another lead screw which carries a recording pen along the length of a drum, so that the pen follows the motion of the weighted car. The drum is turned by another motor which also winds and unwinds the spring. The apparatus goes through its whole cycle, requiring about an hour, without further attention after the spring is mounted and the starting switch thrown. Results are presented in the form of a completed graph of torque versus angle of wind. The device has provided a mass of information not only about springs, but also about barrels, since not only the spring but a whole unit is tested.

This instrument proved useful in the laboratory and may be applied to spot inspection, but it obviously is not suitable for inspecting the production of a million or so springs each year. Information secured with the first instrument showed that the value of the torque supplied by a spring at a quarter turn less than full wind would serve as a criterion for the acceptability of the spring. The laboratory was instructed to develop a simple instrument which would make this measurement rapidly and semiautomatically. In the resulting "torque-tester" the operator simply inserts the spring assembly and presses a starting button. A motor winds the spring until at full wind the spring torque overcomes that of a weight on a pivoted beam. At this point the end of the beam lifts which breaks an electrical contact, whereupon the motor backs off to unwind the spring by a quarter turn and then stops. Meanwhile another motor starts unreeling a chain from a calibrated drum. The end of this chain is supported by the beam at the other end from the weight, so that the increasing length of chain restores the torque by unwinding the spring. When equilibrium is again established the second motor stops, the operator reads the value of the torque and presses another button which starts both motors, the one unwinding the spring, the other rewinding the chain. The whole operation requires about twenty seconds.

It may be objected that these are examples of that applied physics which is called engineering. If (as sometimes seems to be the case) present-day physics is to be limited by definition to nuclear problems, only one minor application can be cited. This is the use of polonium coated foil to ionize the surrounding air so that the static charge on unmounted jewels is dissipated, making it possible to handle them individually without their either sticking together or flying into space. The high ratio of surface area to volume of the tiny jewels (it takes seven of the smallest ones to weigh a milligram) gives them the ability to hold enough of a charge under some weather conditions to make them quite unmanageable without such a discharging system.

Friction Physics

However, there is also other work done in which the instrumentation is a means rather than an end in the laboratory. One example of this "purer" research is the investigation of friction. Friction is objectionable in a watch principally in the balance unit. There is, of course, friction wherever there is motion, but the train is surprisingly efficient, transmitting about 80 percent of the energy at the barrel to the escape wheel, so that the only improvement to be expected from a general decrease in friction is an inconsequential decrease in the size of the mainspring. In the oscillating system the effects of friction are not all inconsequential. In the ideal case, a balance whose moment of inertia is I and which is acted upon by a restoring torque equal to a constant, k, times the displacement θ, has an equation of motion $I\ddot{\theta} + k\theta = 0$, an equation which as every sophomore knows (or ought to know), describes a simple harmonic motion with a period

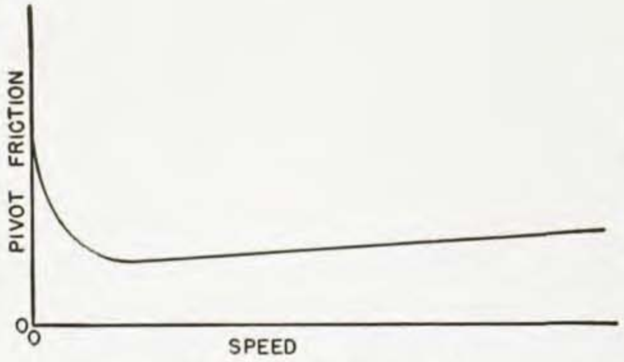
The plates and bridges of this watch have been made of plastic so that the entire train may be clearly seen.

T, given by $T = 2\pi\sqrt{I/k}$. In any actual case, factors such as the escapement action alter the situation, but ignoring such further complications, the presence of friction changes the original equation to $I\ddot{\theta} + k\theta + F = 0$ where F is an unknown function of velocity and possibly of other variables also. The period of such a system will differ from that of the ideal system and—much worse—may be a function of the amplitude and of parameters in F which may change slowly with time or with temperature or pressure.

The energy losses lumped together in F are due to losses in the spring material itself, to air resistance, and to rubbing of the balance pivots against the jeweled bearings. Lubrication aids in alleviating the ills caused by the last of these, and the chemists have made some progress toward better oils, so that the jaw of the porpoise is no longer the best source of supply. But this phase of the problem remains unsolved, a fact attested by the availability of a couple of thousand brands of watch oils. Even the best of these eventually gum or evaporate or run away and the watch shows a losing rate or stops running. As a matter of fact, the oil introduces about as many troubles as it eliminates, but until someone makes an oilless bearing suitable for watch use it is indispensable.

A correction of the errors due to friction appears more likely as more information becomes available, and it would be highly desirable to have a description close enough to determine a good approximation to the function F above. On this basis, the Hamilton Laboratories have improved an apparatus originally built for the investigation of the relative merits of various oils and are now using it for a more general study of the whole problem of friction under conditions similar to those in a watch. The method used is the measurement of the deceleration of a balance running free in its jewel bearing. A beam of light incident on a photocell is interrupted by the arm of the balance so that the output of the cell contains two pulses for each revolution of the balance. These pulses are amplified and by means of the plunger in a solenoid are used to move a pen across a paper tape running at constant velocity. An accurate time base is obtained from another set of marks made by a pen actuated by the second ticks of the standard clock. From this data the angular velocity and acceleration for any velocity are easily found. The moment of inertia of the balance wheel is measured by observing its period when coupled with a hairspring with a known torque constant, and now the frictional torque can be calculated. If the apparatus is in a vacuum so that the only forces are those at the bearing, a measurement of the weight of the balance and the diameter of the staff permits a calculation of the coefficient of friction.

This method of determining the torque or the coefficient of friction is reasonably precise. That is, under identical conditions, measurements can be repeated to within less than 1 percent. Maintenance of these conditions is something else again, as is their alteration in controlled fashion. Frictional forces are dependent on almost everything from temperature to the headlines in the morning paper. The approximations of Coulomb, that these forces are independent of velocity and surface area and directly proportional to pressure between the slid-



Frictional torque in a lubricated bearing as a function of speed.

ing surfaces, if they are true at all, are indeed approximations even for the case of the friction between two solid surfaces. They are not applicable to the fluid friction of the air or the oil.

A long series of measurements made in vacuo with a lubricated bearing have shown that the fluid friction is dependent upon velocity as shown in the accompanying sketch. The low velocity end of the curve is of interest. It shows no discontinuity for the static case, but rather a coefficient which decreases sharply with increasing speed until a minimum is reached at a comparatively low speed and then increases again along a nearly straight line. In the oscillatory motion of the balance in a watch a range of angular speeds from zero to about 14 revolutions per second is covered in each quarter cycle, so that the continuity is welcome. The fluid friction has been found to decrease with increasing temperature, as would be expected. The change is small with silicone oils, but unfortunately these are poor lubricants.

Measurements in air are made under conditions which do not quite duplicate the conditions in a watch. In the experimental apparatus, the balance wheel is mounted between the pillar plate (base) and the balance cock, but the rest of the movement and the case are missing, so that conditions approach those in free space. In a watch the balance is contained within a small, closed, irregular volume. The interference supplied by the air will be greater in the latter case, particularly since the motion there is oscillatory. In this respect also, the experimental conditions do not duplicate operating conditions, since the balance motion is unidirectional experimentally. On account of both of these factors, the air friction is probably greater in a watch than is shown by experimental results. None the less, some of the results are meaningful and interesting, although the work to date is far from giving a definitive description of frictional forces.

At normal pressures, the effect of velocity is somewhat more complex than in a vacuum, the friction increasing more rapidly at higher speeds. The measurements are more difficult at these higher pressures and correspondingly less accurate. The oil collects tiny bubbles of air which decrease the coefficient and which are present to an extent dependent upon the recent previous history of the oil. Also, the frictional effects have been found to be dependent, in an unreliable sort of a way, upon the amount of water in the atmosphere. The coefficient increases in approximately linear fashion with the absolute humidity.

The Effects of Temperature

A well-known example of the application of physical research to timekeeping is given by the Nobel Prize (1920) work of E. C. Guilliaume. In his researches on nickel alloys, Guilliaume produced not only Invar with its very small dependence of length on temperature, but also Elinvar, with an unusual relationship between elasticity and temperature.

Most materials, including steels, show decreasing values for Young's modulus with increasing temperatures. Hence, a steel hairspring supplies a smaller restoring force at higher temperatures, which tends to make the watch run slow. This effect is increased by the expansion of the balance wheel, which increases the moment of inertia of the system and also lengthens the period of oscillation. As a result of these effects, principally the first, a watch with a steel spring and a copper balance wheel has a temperature error of about ten seconds per day for each Centigrade degree.

The problem of correcting this error, or of supplying temperature compensation, is a historic one. The first solution was supplied by John Harrison in 1759 and was a major factor in winning for him the 20,000 pound prize offered by an Act of Parliament in 1714 for a method of determining longitude on shipboard. (Twenty thousand eighteenth century pounds compare favorably with a twentieth century Nobel Prize. It might be noted, however, that a reluctant Admiralty delayed eleven years before paying the whole sum.) Harrison's method of correction depended upon the warping of a bimetallic strip with changing temperature. This strip carried a pair of curb-pins through which the hairspring passed and was arranged so that with increasing temperature the pins moved in a direction to decrease the effective length of hairspring and increase the rate of the watch.

This device was soon superseded by another which is still described in many beginning physics texts, although it is not used in many modern watches. In this second solution the bimetallic strip is again found, but this time it makes up the rim of the balance wheel, the material with the higher coefficient of expansion being on the outside. The rim is cut through at the two ends of some diameter, so that it is made up of two semicircles, each of which is free to warp inward as the temperature increases. The moment of inertia is decreased by an amount which can be made to nearly compensate for the decreased spring constant and increased length of arm.

Both of these mechanisms are workable, but they are unsatisfactory in that a difficult fabrication is required to give a compensation which is still imperfect. Guilliaume's Elinvar, which has since been improved, permits a solution which is at once simpler and more accurate. This alloy can be made to have a positive, negative, or zero temperature coefficient of elasticity, and in particular to have such a coefficient that the change in elasticity of the spring and the change in moment of inertia of a mono-metallic wheel just counteract instead of adding. The correction thus secured is very nearly perfect over the normal range of temperatures, and the manufacture is very much simpler than that of the bimetallic wheel.

Gravitational Interference

A problem with which Dr. Guilliaume was not greatly concerned, but which has increasing importance, is the effect of magnetic field upon the rate of a watch. The magnetization, induced and residual, of the hairspring when placed in a field of a magnitude no longer uncommon in everyday experience, is enough to alter greatly the rate or even to stop the watch. Despite "non-magnetic" advertising claims, no watch completely free from this effect has been built, and indeed there is reason to believe that a spring cannot be made to be both temperature-compensated and non-magnetic. However, there are varying degrees of failure, and a great deal of research on magnetism is being conducted in this country and abroad. Results so far do not justify a report, but rather only indicate the necessity of fundamental research on this problem.

Another pair of problems exist which are classic to the watchmaker, the problem of poising the balance wheel and the problem of shaping the end section of the hairspring. The first is again a problem in instrumentation. It is easy enough to see that a balance wheel oscillating about a horizontal axis and having its center of gravity displaced from the axis will be subject to another restoring force than that supplied by the spring, and that this will affect the period. It can be shown that the change in the period depends upon the lack of poise, the location of the excess weight, and upon the amplitude of vibration, the last entering in a Bessel function. These facts are of little interest to the practical watchmaker who is all too familiar with the fact that the rate of a watch with an imperfectly poised balance depends upon the position of the watch and the "motion" or amplitude of balance vibration. He knows these things to be out of his control, and he wants not an analysis of the problem, but an end to it.

The present method of poising is nearly as old as the balance. It consists of placing the ends of the staff on a pair of parallel knife edges, carefully levelled and very hard and smooth. If the balance shows no tendency to rotate in any direction, it is poised so far as this test is concerned. If it is not in poise, the mass is redistributed, making use of the same screws as are used to alter its rate, until it is satisfactory. Evidently such a test will also detect any out-of-round condition in the pivots, although it will not distinguish between the two causes. Even under the best conditions, the error represented by an excess of .01 mg on the rim of a small balance is just detectable by this method. Unfortunately, the rate of the watch provides a much more delicate test, so that a balance perfectly poised on the poising tool may have a considerable position error. Hence, in a good watch a second and indirect method of poising must be used—the finished watch is timed in several positions, and if the variation in its rate is outside the tolerance the balance is removed and further screw changes made as judged necessary from the position error. Obviously such a method is slow and expensive, so that a position adjusted watch costs more to make or buy. Also, in altering the poise the rate may be inadvertently changed, or in bringing a watch to time the poise may be destroyed.

The necessity for a precise balance of a moving part is not uncommon. The wheels of an automobile or the rotor of a generator are often poised by rotating them at a high speed and observing with a crystal pickup the vibrations due to lack of balance. Such a method is very sensitive and results in the dynamic balance which is required in a three dimensional rotating piece. The nearly lamellar balance wheel will be in dynamic poise if it is in static poise, but the method looks attractive until the magnitude of the force is calculated. The balance in a small watch has a diameter of less than a quarter inch and to be even as good as the present method, an out of poise amounting to .01 mg must be detected. At 1800 rpm this gives a centrifugal force of less than .09 mg, which is not much gain.

In addition to having an insufficient sensitivity, the knife edge method of poising is defective because it must be applied to the balance wheel and staff before the spring is attached. The spring is not fastened directely to the staff but is pinned into a collet, a small collar split so that it can be friction-fit on the balance staff. Several years ago Hamilton investigated the effect on poise of the collet and the inner terminal of the hairspring. It was found that an improvement in the position rate could be obtained by counterpoising the collet, that is, by cutting away a small portion of it so as to counterbalance the asymmetry introduced by the cut in the collet and by the first bit of the spring.

Hooke's Law Torque

The problem of the proper shape of the end of the spring is of another type altogether, and one which should be resolvable by the theory of elasticity. However, some very able theoreticians have performed some elaborate analyses ". . . but evermore came out by that same door wherein I went".

More specifically, an oscillating balance wheel controlled by a spring exactly obeying Hooke's law, and completely free from interference by the escapement or by friction, would be absolutely isochronous. In the presence of such interference, a spring which deviated from Hooke's law in the proper manner would restore isochronism. In either instance, an accurate knowledge of the function relating the shape of the spring to the torque developed in the rotation would be very useful. It has long been known that a spring which over the most of its length is an Archimedes spiral will very nearly follow Hooke's law—nearly enough that it is quite satisfactory in meters and almost satisfactory in watches. The inner end of the spring must be fastened to the finite cylinder of the shaft (more accurately, to a collet mounted on this shaft) and the outer end to a fixed point. If the spiral is simply chopped and the end points fastened so that in its normal position the spring is a spiral over its entire length, it is plain to see that as it is wound the increased length required by the increased angle is not available. The new spiral will be distorted, the body of the spring moving toward the outer fixed point. As the spring is unwound the reverse will be true. In either case, in addition to the couple there will be present a force which in general will have a moment about the axis. The spring "constant" will not be constant and the rate of a watch so constructed will vary with the amplitude of balance motion. If there is an integral number of complete turns in the unstressed spring the rate will increase slowly with increasing amplitude up to an amplitude of about 90° and then decrease rapidly. Over the range of motions possible, the maximum difference in rate will be about 50 seconds per day, about .06 percent.

About 1800, Breguet discovered that by altering the end section of the spring from its spiral form, bending it up and over the body of the spring in an "overcoil" and fastening it to a stud about half way out from center in the opposite quadrant, the error could be greatly reduced. Fifty years later, Edouard Phillips, a French engineer, published a classic memoir in which he showed that a sufficient condition for the attainment of the Hooke's law torque was that the spiral remain a spiral centered on the same axis. He also investigated the shape of the overcoil which would give this result and found the sufficient conditions to be two simple specifications on the position of the center of gravity of the overcoil, conditions fulfilled by an infinity of curves. It is an excellent paper, but a watch with a Phillips overcoil is not a good timekeeper, perhaps because of his neglect of friction and escapement error, or his assumption of perfect elasticity in the material itself. None the less, the problem has a solution, as is shown by the fact that a watchmaker, given sufficient experience, sufficient patience, and a trace of good fortune, is sometimes able to make a watch almost perfectly isochronous by manipulation of the overcoil and microscopic adjustments of it. The overcoils actually used in watches are thus determined experimentally and are better than those formed according to any of the theories offered to date. They are good but not perfect, and a solution to the problem would be most welcome.

The precision necessary in a satisfactory solution can be estimated from some facts on chronometers. A chronometer is very much like a watch although it differs in some important details. It is used, of course, to help determine the ship's location, and the advent of radio with its accurate time signals has not reduced the requirements on the ship's clock. Even in peace time, there are occasions when the radio is unreliable, and in war time the imposition of absolute radio silence, which applies to receivers as well as transmitters, may leave the ship with no time reference except its chronometer.

There are additional considerations, such as the possible destruction of power sources in battle, and the possible necessity of navigating a life boat, which make the chronometer essential. One of the details of difference between the watch and the chronometer is the shape of the hairspring, which instead of being a flat spiral is a helix wound on a circular cylinder. It has a terminal on each end and these can be shaped according to theory to give very good results. The historic practice has been to make final adjustments of the rate and behavior of the chronometer by slight alterations of the shape of the terminals of each individual spring. Also historic is the fact that a chronometer is subject to an aging process extending over several months, during which its rate is unreliable.

Until the recent war, chronometers were made only in Europe, principally in Switzerland. They were the largely handmade product of highly skilled craftsmen. During the war this source was cut off (and would in any case have been insufficient to supply the number of instruments needed in connection with the tremendous ship building program). But no ship sails without at least one chronometer and a battleship carries three, so that the magnificent accomplishment of the shipyards was futile unless chronometers were available. The Hamilton Watch Company was given the job of producing the first American made chronometers, producing them in unheard of quantity, and producing them instanter. There was no time for aging processes.

Ships sailed on schedule, and each one carried the proper number of timepieces, chronometers which came off an assembly line keeping the same excellent time which they still kept many months later. Hamilton had guessed that the necessity for aging was due to residual stresses set up in the last bit of spring when it was slightly reformed after hardening. A thirteen piece form was built and on this the spring was wrapped and heat treated so that it was properly shaped over its entire length, including the terminals. After hardening, the spring was never reshaped.

It is interesting to speculate upon how the course of the war may have been affected by this one small tool. It is also interesting to consider how precisely the terminals must be formed and how uniform the characteristics of the metal must be in view of this illustration of the large effects of small inhomogeneities.

In these somewhat more peaceful times there are other problems, a few of which have been described. Out of the host of others there is one which merits a paragraph, not because of its scientific interest, but because, according to legend, it would offer the ultimate in satisfaction to a large youthful segment of our population. Watches are sometimes dropped, and when dropped they may be injured. In order to learn how to build them stronger, it is necessary to first learn where and how they break. Across the hall in this laboratory a technician is busy obtaining such information (and offering some little hindrance to the writing of this paper). At irregular intervals and unexpected times he lets fall onto an anvil a steel bob containing a watch. Along with an impressive crash he gets data on the impact forces and the corresponding damage to the watch. From it may come a more shock-resistant watch, but however that may be, it would have been great fun when he was two years old.