HANDBOOKS OF THE SCIENCE MUSEUM

Time Measurement

17th Century French Column Sundial.

PART I—HISTORICAL REVIEW

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HANDBOOK OF THE COLLECTIONS ILLUSTRATING

TIME MEASUREMENT

By F. A. B. WARD
M.A., Ph.D.

Part I.—Historical Review

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PREFACE

THE formation of a Museum of Science was first proposed by the Prince Consort after the Great Exhibition in 1851, and in 1857 collections illustrating foods, animal products, examples of structures and building materials, and educational apparatus were brought together and placed on exhibition in South Kensington. The collections of scientific instruments and apparatus were first formed in 1874, but it was only after 1876 that they became of importance. The Special Loan Collection of Scientific Apparatus which was exhibited in that year in the Museum brought together examples of all kinds from various countries, and a large number of these were acquired for the Museum. Subsequently many additions were made, including in 1884 the collection of machinery formed by the Commissioners of Patents, in 1900 the Maudslay Collection of machine tools and marine engine models, and in 1903 the Bennet Woodcroft Collection of engine models and portraits.

Until 1899 the Art Collections and the Science and Engineering Collections together formed the South Kensington Museum, but in that year the name was changed to the Victoria and Albert Museum, which included both Collections until 1909, when it was restricted to the Art Collections ; those relating to Science and Technical Industry have since then formed the Science Museum.

The aim of the Science Museum, with its Collections and Science Library, is to aid in the study of scientific and technical development, and to illustrate the applications of physical science to technical industry.

This is effected by the informative display of objects, diagrams, and photographs—so arranged as to illustrate in each Section the development which has taken place from past to modern practice.

Many of the exhibits are so arranged that they can be operated by visitors or demonstrated to them. Others have been sectioned so that the internal structure can be clearly seen. A detailed descriptive label is placed by each object.

The Collections have been augmented from time to time by loans and gifts from many sources, including many scientific and technical institutions, industrial firms, and also private individuals.

In the Museum there are collections illustrating :—

Textile and Agricultural Machinery.
Hand and Machine Tools.
Papermaking, Typewriting, Printing.
Lighting and Illumination.
Mining, Ore Dressing, Metallurgy.

Glass and Pottery.
Electrical Engineering.
Telegraphy, Telephony, Radio.
Carts, Carriages, Cycles, and Mechanical Vehicles.
Railway Construction, Locomotives, and Rolling Stock.
Roads, Bridges, Lifting Appliances.
Power Transmission, Pumps, Fire Protection.
Building Construction, Heating, Water Supply, Sewage Disposal.
Metrology (Weighing and Measuring).
Steam and Internal Combustion Engines.
Boilers.
James Watt's Workshop.
Marine Engines and Boilers, and Auxiliary Machinery.
Harbours and Docks.
Sailing Ships, Merchant Steamers, Steamships of War, Small Craft.
Aircraft, Aero-Engines, and Aircraft Instruments.
Mathematics, Astronomy.
Chemistry, Photography and Kinematography.
Optical Instruments.
Geodesy and Surveying.
Meteorology.
Terrestrial Magnetism, Seismology, Gravity, Atmospheric Electricity and Tidal Phenomena.
Applied Geophysics.
Electrical, Magnetic, Acoustical, and Thermal Instruments.
Time Measurement.
Physical Phenomena, Properties of Matter, and a collection of Historical Apparatus formerly the property of the late Lord Rayleigh.

There is also an extensive Science Library of books and periodicals, dealing with all branches of pure and applied science. The literature is available to the public for consultation in the reading room, or obtainable on loan through the medium of an approved Institution or industrial organisation.

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(The illustrations marked with a star (*) represent exhibits in the Science Museum)

INTRODUCTION

THIS handbook is intended to serve as an introduction to the Time Measurement Collection of the Science Museum. The first two chapters deal with the subject from the scientific standpoint: they are intended to suggest an answer to questions such as " How is Greenwich Time determined by observations on the stars ? " or " Why does a clock possess a swinging pendulum ? " In the succeeding chapters an account is given of the historical development of each of the main types of time-measuring instruments.

The earliest of these instruments which have survived to the present day are the water-clocks and primitive sundials of ancient Egypt. Instruments of similar type were in use throughout the periods of the Greek and Roman empires and together with the sand-glass were still the only timekeepers employed throughout the Dark Ages and the early Middle Ages.

It seems probable from our present knowledge that the first mechanical timekeeper was constructed during the first half of the fourteenth century. Towards the end of this century and in the first half of the succeeding one public clocks were set up in many towns, while a few domestic clocks were also made. The first watches were introduced about the year 1500. The accuracy of these early clocks and watches was very low, and an error of a quarter of an hour a day would not be unusual ; it was, in fact, customary to employ a sundial for the purpose of checking a watch when opportunity offered.

With the revival of scientific learning two inventions of outstanding importance were made about the middle of the seventeenth century—the application of the pendulum to the clock and of the balance-spring to the watch. These inventions gave a great improvement in timekeeping, and transformed clocks and watches into instruments of real utility. Further improvements were introduced in fairly rapid succession, and by the year 1800 observatory clocks were being made which were accurate to a few tenths of a second per day.

The need for accurate portable timekeepers had become urgently felt about the end of the sixteenth century, when long sea voyages had become common. On their coastwise voyages the early navigators could find their way from landmark to landmark, but on long voyages out of sight of land they could find their position only by measurements of their latitude and longitude, and to find their longitude they required to know the time accurately. The first instruments which kept sufficiently accurate time on board ship were constructed between 1728 and 1759 by Harrison, whose fourth timekeeper was less than a minute in error after five months spent mainly at sea.

During the nineteenth and early twentieth centuries important progress has been made in the distribution of time, through the perfection of electrical systems whereby a single clock is able to control and synchronise a large number of distant subsidiary clocks, and by the aid of wireless time-signals. Improved methods of manufacture have greatly reduced the prices of clocks and watches so that their use has become extremely widespread. The science of very accurate time measurement has also advanced still further, and whereas a hundred years ago the best clocks obtainable were accurate to about one-tenth of a second per day, present-day observatory clocks keep time to an accuracy of a few thousandths of a second per day.

This high accuracy is of great value to astronomers, but is, of course, far beyond what is necessary for daily life, where accurate time measurement is required mainly to enable a number of individuals to meet together at the same time for a common purpose. Nevertheless, with the growing complexity and organisation of civilised life punctuality to within a few minutes at the most is frequently essential, and business and social activities on the scale now prevalent in civilised countries would be difficult or impossible without accurate timekeeping.

I. ASTRONOMY AND TIME

The subject of time measurement is closely bound up with astronomy, since the natural sub-division of time on a large scale is given by the rotation of the earth on its axis and its motion in an orbit round the sun. The orbital motion, which goes through a complete cycle once in a year, is of course responsible for the changing seasons, while the rotation on its axis gives rise to the regular succession of day and night.

To a terrestrial observer the earth appears fixed, while the whole of the stellar system appears to rotate round the earth's axis, the rate of this rotation being equal to that of the true rotation of the earth itself relative to the fixed stars. If a clock is regulated so as to record exactly twenty-four hours for a single rotation of the earth, the time by this clock at which a given star crosses the meridian should therefore be the same every day. The time recorded by such a clock is termed sidereal time, and the period of a complete rotation is termed a sidereal day.* The sidereal day is chosen by astronomers as the unit of time as it is constant in length and can be accurately measured by astronomical observations of great precision, but it is not suitable for general use, as the ordering of civil life is governed not by the stars but by the sun.

To an observer on the earth the sun appears to take part in the general rotation of the stellar system, but to have in addition a slower motion of its own through the stellar system, performing a definite orbit once in a year—this apparent motion is of course due to the earth's revolution in an orbit round the sun. The sun's motion is not quite uniform and in consequence the intervals of time between successive transits of the sun across the meridian are not exactly equal: the length of a true solar day is not, in fact, quite constant. For the purposes of time reckoning an imaginary sun termed the " mean sun " is therefore invented which apparently rotates round the earth's axis at a uniform rate, equal to the average rate of rotation of the true sun. The mean sun is sometimes in advance of the true sun, sometimes behind it, the maximum difference amounting to a little over sixteen minutes in November. The difference between mean solar time indicated by the mean sun and true or " apparent " solar time indicated by the true sun is termed the " equation of time " and is due to the combination of two separate effects. Firstly, the earth's orbit is an ellipse, not a circle, and in consequence the velocity of the earth's motion is not uniform, being greater when it is nearest the sun in January than when it is farthest away in July. The sun therefore appears to move through the stars faster in January than in July.

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* Neglecting, for the purpose of this discussion, the small corrections due to the precession of the equinoxes and to nutation.

The contribution of this effect to the equation of time is shown in Curve I of Figure 1, and is seen to reach a maximum of nearly eight minutes in April and October. The second component of the equation of time is due to the fact that the sun's apparent motion is not along the celestial equator but in a plane inclined to it at an angle of $23\frac{1}{2}°$ and the component of its velocity parallel to the equator is therefore variable. The effect of this variation on the equation of time is shown in Curve II of Figure 1 and is seen to reach a maximum of ten minutes four times a year. The equation of time is due to the combination of these two separate effects and its amount is shown by Curve III of the figure.

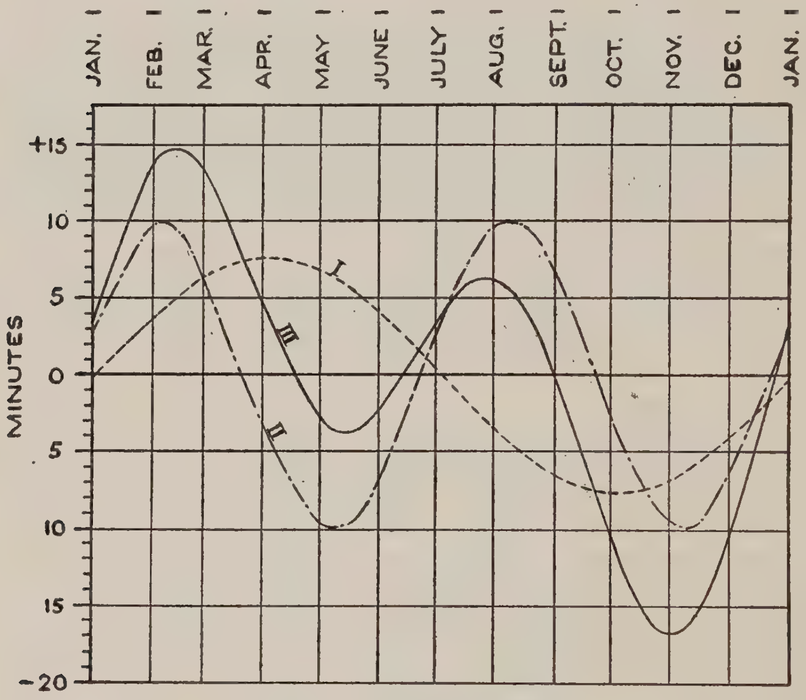

FIG. 1—The Equation of Time.

Since it is essential to employ an invariable unit of time, the mean solar day is chosen as the practical unit of time, and timekeepers are regulated so as to record twenty-four hours in a mean solar day. The only important practical consequence of abandoning apparent solar time in favour of mean solar time is that the times of sunrise and sunset vary somewhat less regularly, and, as is well known, the shortest winter afternoons occur in mid-December in the northern hemisphere, whereas the shortest mornings occur at the beginning of January.

Local time and standard time.—The mean solar time at any given place on the earth's surface is termed its local mean time. On account of the curvature of the earth local time varies from place to place, the local time of a given event being earlier as we move westwards and later as we move eastwards. There is very simple relation between change of local time and change of longitude, one hour of time corresponding to 15 degrees of longitude. Thus, for instance, when it is noon at Greenwich it is after sunset and late in the evening in Australia, in New Zealand it is nearly midnight, while in New York the sun is still low in the east or even below the horizon (in mid-winter) and the time is 7 a.m. Even in Bristol, 112 miles west of Greenwich, local time is ten minutes behind Greenwich time. In former days every individual place in a country used its own local time, but soon after the introduction of railways the inconvenience of this system began to be felt. For a short period " local time " and " railway time " were both used concurrently, and some clocks were even fitted with an extra hand to show " railway time," but local time gradually fell out of use, and in small countries a universal standard time is now used throughout the country. Thus, for instance, the whole of Great Britain and Ireland now uses the standard time of Greenwich. In large countries such as the United States of America, where local time differs by as much as three hours between New York and California, it is not practicable to employ a single standard time throughout the country, and so the country is divided into " zones " throughout each of which a uniform standard time is observed, each zone time differing from the neighbouring one by a whole hour.

At an international conference held in Washington in 1884 the entire world was divided into a series of time zones differing by a whole number of hours from Greenwich time, the time for each zone being that of the meridian passing fairly centrally through it. During the ensuing years the plan was gradually accepted by one nation after another. For greater convenience a few zones were introduced having a time differing from that of Greenwich by an odd number of half-hours, but substantially the original plan was followed. It is now adopted by the great majority of countries, though a few still retain the local time of some important city, while a few backward countries have not yet adopted a uniform standard time.

Following the lead given by Great Britain during the war, certain industrial countries now employ during the summer months a special " summer " time, one hour faster than their normal time ; this practice is designed to economise in the use of artificial light and to provide an extra hour of evening daylight for the outdoor recreations of urban workers. Countries adopting this scheme move away from their normal time zone into the next one to the east during the summer months.

The determination of standard time.—The standard time of Great Britain and Ireland is that of the meridian passing through Greenwich Observatory. It is one of the main functions of this National Observatory to check its standard clocks—daily if possible—by means of observations on the stars, and to supply accurate time-signals for distribution throughout the country by radio or line telegraphy.

The standard sidereal clock at the Observatory is checked by observations on the stars and the mean solar time is then calculated from the sidereal time. The two times should agree exactly at the moment at which the mean sun is at the autumn equinox, and from this instant onwards the mean solar clock becomes increasingly slow on the sidereal clock until after the lapse of exactly one year the mean sun has returned to the autumn equinox and mean solar time has fallen exactly twenty-four hours behind sidereal time. The period taken for the mean sun to make a complete circuit of the heavens from one autumn equinox to the next is 366·2422 sidereal days or 365·2422 mean solar days. The mean solar clock must therefore be regulated to go $\frac{365\cdot2422}{366\cdot2422}$ times as fast as the sidereal clock, and since the two agree exactly at the moment when the mean sun is at the autumn equinox the difference between the two times at any subsequent date and hour can be accurately calculated and is, in fact, published in advance in tables in the " Nautical Almanac."

The actual procedure adopted for checking the mean solar clock at Greenwich is as follows : In the first place, the times at which certain selected stars cross the Greenwich meridian are observed with the aid of a special transit telescope, and are recorded on a chronograph, while the standard sidereal clock records itself automatically on the same chronograph. If the sidereal clock is accurate, it should always indicate the same time when a given star crosses the meridian, and by measuring up the chronograph record the amount by which the sidereal clock is in error can therefore be determined. The sidereal clock is then compared directly with the mean solar clock by means of a second chronograph. The difference between the two thus found experimentally is compared with the difference calculated in the way described in the preceding paragraph, and hence the amount by which the mean solar clock is in error can be found. This error is, of course, never more than a small fraction of a second and is carefully corrected by a refined method. Both the sidereal and the mean solar clocks at Greenwich are Shortt free pendulum clocks, and thus even if the weather is so cloudy that observations of the stars are impossible for a whole week the mean solar clock will not have varied from true time by more than about one-tenth of a second. The " six dot seconds " radiated from B.B.C. stations and the rhythmic time-signals radiated from the Rugby station of the Post Office are derived from electrical contacts on the Greenwich mean solar clock, and are therefore accurate to a few hundredths of a second.

A similar procedure is followed in the Observatories of most of the leading countries of the world for supplying their own time-signals.

II. THE PRINCIPLES OF TIME MEASUREMENT

The passage of time is marked by change and by motion, and all methods of measuring time are based upon the utilisation of some form of regular motion, by means of which the passage of time is translated into the traversing of space. As described in the last chapter, a large-scale division of time is given by the revolution of the earth in its orbit round the sun and by the earth's rotation upon its own axis. It is the function of time-measuring instruments to sub-divide the mean solar day, *i.e.* to indicate the number of hours, minutes and seconds which have elapsed since the preceding midnight.

The day and night can of course be sub-divided by making use of the earth's rotation if astronomical observations of the sun and stars are made. By the use of sundials and nocturnals the time of day or night can be read off directly, but it is necessary to have some alternative method of time measurement for use in cloudy weather. The regular flow of water or sand through a small orifice and the regular burning of a lamp or candle were formerly employed for time measurement, but much greater accuracy has been attained by the use of some form of cyclic mechanical motion which repeats itself over and over again. The regular recurrences of a particular phase of this motion then correspond in the measurement of time to the regular recurrences of the inch marks upon a ruler or tape measure, which may be regarded as devices for sub-dividing the yard. It would be laborious when measuring a distance of, say, 27 inches with such a tape to be forced to count the individual inches, and so each inch is marked with its number. For the same reason a timekeeper incorporates some means of counting up the number of times its regular motion has recurred and indicating the number upon a dial. In an ideal timekeeper the regular motion would recur at exactly equal intervals and the whole history of mechanical timekeepers is the history of the attempts which have been made, with continually increasing success, to attain in practice to this ideal.

In the earliest mechanical timekeepers a pivoted beam or balance-wheel was pushed in one direction and then in the other by means of a toothed wheel driven by a weight. The regularity of this movement depended on the accurate shaping of the working parts, a constant driving force, and the maintenance of uniform conditions generally, so that it is not surprising that the accuracy of these early clocks was poor.

The first natural cyclical motion which was employed for time measurement was the oscillation of a pendulum swinging under the attraction of gravity. This motion approximates closely to the ideal type of motion known as " simple harmonic " in which the period of an oscillation is independent * of the extent of the swing.

The simplest type of pendulum consists of a small mass suspended by a light cord, and the period of swing of such a pendulum varies as the square root of the distance from the point of suspension to the centre of gravity of the mass, a fourfold increase in the distance being necessary to double the time of swing. The period of a simple pendulum of this type is independent of the amount of the mass. In the case of a rigid pendulum, such as is normally used in clocks, the period varies as the square root of the distance from the point of suspension to the so-called " centre of oscillation," a point which is near the centre of gravity of the bob but whose exact position depends upon the shapes of the bob and rod and their relative masses. The period of a pendulum of this type can be adjusted to the desired value by sliding the bob up or down the rod, and in practice the bottom of the rod is usually threaded and carries an adjustable screw upon which the bob rests.

A pendulum of constant length swinging entirely freely would be an ideal timekeeper, and in actual instruments attempts are made to approach this ideal as closely as possible. There are, however, many difficulties to be overcome.

In the first place, the length of the pendulum will change with changing temperature. As described in Chapter IV, various methods have been devised for compensating this change, and its effect can be reduced to an extremely small amount, while as an additional safeguard clocks of the highest accuracy are kept in a room whose temperature is maintained closely constant.

Secondly, whereas in an ideal timekeeper the pendulum would swing entirely freely, in practice there is always some frictional interference with its free motion, due chiefly to the resistance of the air, and this causes the arc of swing to die away slowly. In order to maintain the swing at a constant amplitude some power has to be applied to make up for the energy wasted in friction. This power must be supplied in such a way as to interfere as little as possible with the free motion of the pendulum. It was shown theoretically by Airy in 1827 that if the interference consists of a series of sharp impulses imparted to the pendulum exactly at the mid-point of its swing these impulses will not directly affect the timekeeping, though if they vary in strength the arc of swing will vary, and there will consequently be small corresponding variations in the period of swing.

Thirdly, some means must be found of counting the swings and recording their number. In mechanical clocks the two functions of counting swings and imparting impulses are both performed by the escapement mechanism. The escapement allows one tooth of a

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* The period of a free pendulum increases slightly with increasing arc, a change of arc from 2° on either side of the vertical to 3°, for instance, producing a loss of 8 seconds per day.

toothed wheel to " escape " at each swing of the pendulum, while in the act of escaping the tooth gives an impulse to the pendulum by means of some simple connecting system.

It is the aim of a good escapement to satisfy Airy's condition. The earlier escapements such as the verge and the anchor interfered with the pendulum throughout its swing, but as time progressed better types were evolved, culminating in Riefler's escapement in which the impulses to the pendulum were transmitted through the suspension spring, the pendulum being otherwise entirely free from interference apart from air friction.

It is not necessary to impart an impulse to the pendulum at every swing, and various methods have been devised for giving impulses at longer intervals. In some types of electric clocks, as described in Chapter VIII, the pendulum receives an impulse whenever its arc of swing falls below a given value, while in other types the pendulum operates a light counting mechanism and releases its impulse every half minute. In the Shortt free pendulum clock, the most accurate pendulum timekeeper yet devised (also described in Chapter VIII), both impulsing and counting are carried out by a subsidiary or " slave " clock, and the free pendulum swings entirely freely except for the fraction of a second every half minute during which it is receiving its impulse.

A second type of mechanical motion which has proved of great practical use for time measurement is the oscillation of a balance-wheel controlled by a spiral spring. This motion approaches very closely to a simple harmonic vibration, and has the advantage that, not being dependent upon gravity, it can be employed in portable timekeepers such as watches and chronometers. The angular acceleration of the balance-wheel is much greater than any ordinary accidental twists which might be given to a portable instrument, and so the timekeeping of a chronometer is not appreciably affected by the motion of a ship, and that of a pocket watch is only slightly affected by the normal movements of the wearer, though the highest accuracy cannot be expected from a wrist-watch.

The swings of a balance-wheel require maintaining and counting, and, just as in the case of a pendulum, it is desirable that the free motion of the wheel should be disturbed as little as possible and that any necessary interference should take place at the middle of the swing. The actual escapements employed differ from clock escapements because the total arc of swing of a balance-wheel may be nearly two whole revolutions, while that of a pendulum should not exceed a few degrees. The effect of temperature on a balance-wheel timekeeper is more serious than that on a pendulum clock, as the stiffness of the balance-spring changes markedly with temperature. The methods employed for compensating this change are somewhat elaborate, and are dealt with in Chapter VI.

The period of swing of a balance-wheel and spring depends on the ratio of the moment of inertia of the balance-wheel to the stiffness of the spring. The period can therefore be adjusted to the desired value by altering the effective length and hence the effective stiffness of the balance-spring, the outer end of the spring being made to pass between two pins the position of which is adjustable. For chronometers, in which high accuracy is required, this method is unsatisfactory, and the balance-wheels of chronometers are generally provided with small screws which can be screwed inwards or outwards to reduce or increase the moment of inertia of the balance and hence to achieve the necessary regulation.

The vibrations of crystals form a third type of cyclic mechanical motion which has recently been applied with success to the measurement of time. The elastic vibrations of quartz crystals are accompanied by small electrical effects, and these small effects can be magnified by a valve amplifier. The oscillating crystal can be made to behave like a tuned grid circuit used in wireless practice, and by employing a little " reaction " or feed-back from the anode circuit the oscillations can be maintained indefinitely. The frequency of these oscillations is sharply defined by the dimensions of the crystal and is very little affected by outside conditions such as changes of temperature and of barometric pressure, though for the highest accuracy these must be controlled. With crystals of manageable size the frequency of the oscillations is very high—some 100,000 vibrations per second—but it is possible by electrical methods to enable these high-frequency oscillations to control and synchronise another electrical circuit oscillating at a frequency of a few hundred cycles per second, and oscillations of this frequency can be counted and recorded automatically on a dial. Over short periods of a few hours to a few days the quartz crystal oscillator is the most accurate timekeeper yet devised, for its random errors can be reduced to only a few parts in one thousand million, but over longer periods of months slow changes take place, so that its accuracy is somewhat inferior, though still approaching or even equal to that of a Shortt clock. It appears possible that by very careful attention to design quartz oscillators may be constructed which will keep time over long periods to an even higher accuracy, and in fact Kohlschütter of the Geodetic Institute in Potsdam has recently described the performance of a quartz clock with which an accuracy ten times greater than that of any pendulum clock was maintained over a period of four months.

III. SUNDIALS, WATER-CLOCKS AND OTHER EARLY DEVICES

The observation of the height or position of the sun in the heavens must have been the earliest of all methods of noting the passage of time during the day, and the observation of the corresponding change in the length or position of shadows would no doubt have followed. One can conjecture that at first the length of the shadow of a stick, pole or tree might be paced out upon the ground, or the position of the shadow noted with reference to some rough markings on the ground. This method of time indication was used by the Babylonians and by the Egyptians, and it is probable that the Egyptian obelisks were used for this purpose. The earliest time-measuring devices with actual time-scales which have survived to the present day are the shadow-clocks and water-clocks of Egypt. On account of the extremely dry climate of Egypt relics of many kinds have been preserved to this day, so that a good deal is known of the ancient Egyptian civilisation from about 3,500 B.C. onwards.

The earliest shadow-clock known is an Egyptian one of about the tenth to the eighth century B.C., which is now preserved in the Neues Museum at Berlin ; a copy of this instrument is shown in the Science Museum (*see* Plate I). The shadow of the cross-piece was allowed to fall upon the base, upon which a scale of " hours " was marked. These were not in general of the same length as our modern " hours." The present-day system of dividing a single day-and-night period into twenty-four equal hours was used by astronomers but was not employed in civil life until the fourteenth century ; previously to this time it was customary in practically all countries to divide the periods of daylight and of darkness each into the same number of " temporal " hours, usually twelve. The length of an hour of the day differed, therefore, from that of an hour of the night (except at the equinoxes) and both varied according to the season of the year. This system of reckoning by " temporal " hours, though strange at first sight, appears more natural when it is realised that in those early days artificial illumination was only of the poorest, and that dawn and sunset probably delimited most human activities. It should, moreover, be borne in mind that the early civilisations were in the neighbourhood of the Mediterranean, and in such latitudes the variation in length of the day is much less than in the higher latitudes of Great Britain. In Northern Egypt, for instance, in a latitude of 30° N., the period from sunrise to sunset varies only from 10 to 14 hours, whereas in London in a latitude of $51\frac{1}{2}$° N. it varies from $7\frac{3}{4}$ to $16\frac{1}{2}$ hours.

Various types of sundial used in ancient Egypt have been found in recent excavations. In the early form just described, the shadow fell upon a horizontal scale, while in others the shadow of a vertical wall fell upon a flight of steps, the time being known from the number of the step upon which it rested at a given moment. The scales of these sundials, instead of being constructed upon geometrical principles, were divided according to simple rules involving whole numbers; the lengths of the twelve day hours indicated were consequently by no means all equal, and since in the earlier examples the same scale of hours was used at all times of the year the errors varied at different seasons.

For finding the time by night the Egyptians used to observe the time of transit of selected stars across the southern meridian as they came into line with two plumb-lines.

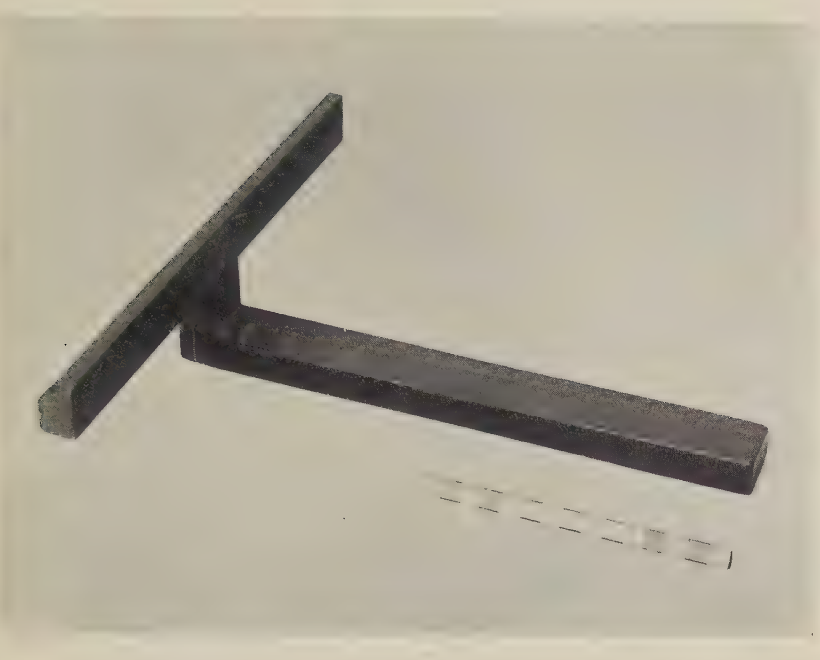
Several specimens of early Egyptian water-clocks have been found. All but one are stone vessels with sloping sides and in the shape of a truncated cone (*see* example on Plate I); the water was allowed to escape slowly from a small hole near the bottom of the vessel, and the time was indicated by the level of the water within. With this shape of vessel the water level falls fairly uniformly, for the more rapid flow when nearly full is compensated by the greater cross-section of the vessel near its top. Uniform scales of time were marked on the inside of the vessel, a different scale being provided for each month to allow for the variation in length of the hours. One cylindrical vessel has been found, and it is presumed that with this vessel time was measured by the steady inflow of water. These water-clocks were probably used for finding the hour of the night, but they may have been used by day as well.

Sundials and water-clocks were introduced into Greece, probably from Egypt, and were widely used in the Greek and Roman Empires. The sundials were of various types, a common one being the "hemispherium," which consisted of a block of stone in the horizontal upper surface of which a hemispherical hollow was made; from the bottom of this hollow a style rose, its point being in the plane of the surface. On any given day of the year the shadow of this point would describe a curve across the inner surface of the hemisphere, the actual curve followed depending upon the season of the year. Each curve was divided into twelve portions for the twelve temporal hours from sunrise to sunset, and the hour-marks for different seasons were joined to form a series of hour lines. A modification of this type was the so-called "hemicycle," said to have been invented by Berosus, the Chaldean astronomer, about 300 B.C., in which the useless part of the hemisphere was cut away (*see* Plate II). Many dials of this modified type have been found in Greece, Asia Minor and Italy. The first sundial appears to have been brought to Rome in about 290 B.C., while Vitruvius, writing in about 30 B.C., described no less than thirteen different types. In all of these the shadow of the tip of a pointer moved across a space on which hour-lines were marked, dividing the period from sunrise to sunset into twelve temporal hours.

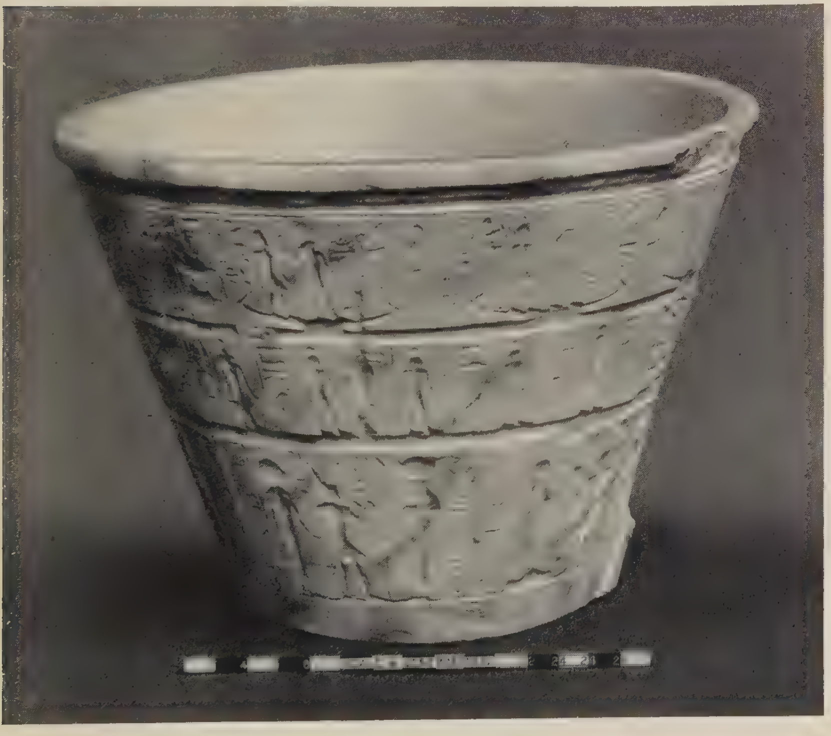
Water-clocks or "clepsydrae" were also used by the Greeks and Romans, and Vitruvius devotes considerable space to their description.

[*To face p.* 18.

PLATE I

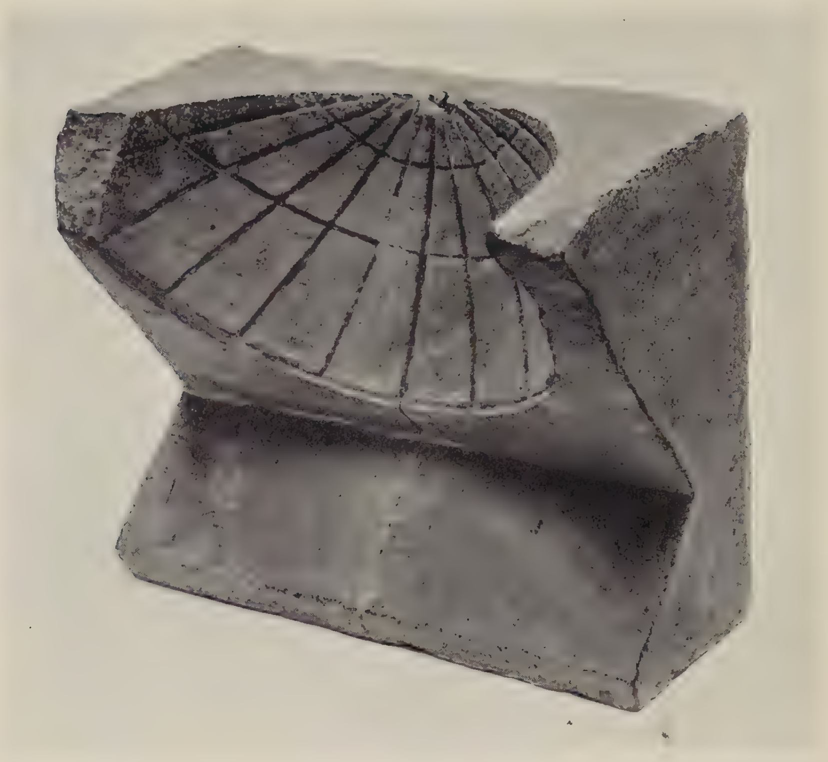


Cast of Egyptian Shadow-Clock (10th to 8th century B.C.). (*See* text, p. 17.)
(The cross-piece is a conjectural reconstruction.)



Cast of Egyptian Water-Clock (about 1400 B.C.).

PLATE II



[*By Courtesy of the British Museum.*

Roman "Hemicycle," found at Cività Lavinia. (*See* text, p. 18.)
(The gnomon is missing.)

[*By Courtesy of Messrs. G. Bell & Sons.*

Saxon Sundial on Kirkdale Church, Yorkshire (11th century).
(The gnomon is missing.)

In order to secure a uniform flow of water they were carefully designed so that the pressure head was kept constant, and in order to make them indicate " temporal " hours either the rate of flow or the scale of hours had to be varied according to the season of the year. During the centuries following the birth of Christ water-clocks tended to become more complicated and considerable mechanical ingenuity was displayed in their design ; some may even have been fitted with striking mechanism, and some operated shows of moving figures at the hours. None of these instruments has, however, survived, and our knowledge of them comes only from descriptions by contemporary writers. They appear to have been poor timekeepers, and had to be checked frequently by means of a sundial. At some unknown date in this period the sand-glass was invented, measuring time by the rate of flow of sand through a narrow neck between two bulbs of glass.

There is some evidence that about this period the regular burning of a lamp or candle was also used for measuring time. King Alfred's biographer, Asser, whose accounts are fairly well authenticated, relates that Alfred made use of candles as timekeepers in order to apportion out his day's work ; each candle burned completely away in four hours, and was enclosed in a lantern made of wood with windows of thin horn in order to protect it from draughts.

Some primitive water-clocks and sundials of Saxon times have been found in the British Isles. The water-clocks are of the " sinking bowl " type, in which the clock consists simply of a bronze bowl six to ten inches in diameter with a small hole in the bottom. The bowl was placed on the surface of water, which leaked in slowly through this hole, and after a definite interval of time the bowl sank ; this interval would be used as a unit of time. It is of interest to note that bowls of this type are still used in Algeria for timing the periods for which the various landowners are entitled to the supply of water for irrigation purposes.

Several sundials of Saxon times are still in existence, some fine examples being that on Bewcastle Cross, Cumberland, which dates from about 670 A.D., that on Kirkdale Church, Yorkshire (*see* Plate II), dating from about 1060, and that on Bishopstone Church, Hampshire, whose date is not known with certainty. Saxon dials are extremely simple in form and usually consist of a stone slab mounted on a south wall and engraved with a few hour-lines on the vertical face of the slab—a horizontal line for sunrise and sunset, a vertical one for midday, and two intermediate lines, which were drawn at about 45°. At the intersection of the hour-lines there is always a hole in which the gnomon was inserted, but no example of the gnomon itself has survived, though fragments of iron have in some cases been found in the hole. It is conjectured that the gnomon stood out horizontally, casting its shadow upon the wall, and dividing the period of daylight into four parts—the four " tides " into which the Saxons are known to have divided the daylight hours. The horizontal gnomon would show sunrise, sunset and midday correctly, but with the intermediate hour-lines at 45° the day would not be divided into four equal parts, the morning and evening " tides " being longer than the two midday ones, the difference varying according to the season. It is evident, therefore, that only a rough sub-division of the day was required at this period. In some Saxon dials the period from sunrise to sunset is divided into eight or twelve portions. These may correspond to differing systems of dividing up the day which were in use in different parts of the country, but it is also possible that the extra lines were cut at a later date.

Much more primitive dials of the same general type are found on very many churches from the twelfth to the fifteenth century. In these so-called " scratch " dials the hour indicators consist of lines or holes engraved on the actual stonework of the church. Frequently there are only one or two " hour " lines unequally spaced, and it is believed that these were intended to indicate not the hour of the day, but the time of celebration of one of the offices of the church ; these times were not definitely fixed, but were to some extent at the choice of the individual priest : hence the great variety which is found in the number and spacing of the lines.

The sundials so far described have all been fixed or heavy stone instruments, but portable sundials have also been constructed since fairly early times, and came into very general use during the sixteenth and seventeenth centuries. Portable dials can be divided into two main classes—those indicating time by the sun's *altitude* in the heavens and those embodying a compass and enabling the time to be found from the sun's *direction*. As the compass was not introduced into Europe until the thirteenth century, all portable dials prior to this date are of the first class and, in fact, the earliest compass dial known dates from 1451.

A few altitude dials of Roman times are still in existence ; these, with a single exception, are made to indicate temporal hours. As described in the next chapter, however, equal hours came into general use in European towns between 1350 and 1400, with the advent of mechanical clocks, and it is found that both portable and fixed dials constructed after this period are made to indicate equal hours.

The commonest types of altitude dials employ a horizontal gnomon, the tip of which casts its shadow upon a vertical plane, or upon the surface of a vertical cylinder, upon which curved hour-lines are marked, intersected by vertical lines corresponding to the different months of the year. The gnomon is moved until its tip is above the appropriate vertical line and turned to face the sun, the time then being indicated by the position of the shadow of the tip of the gnomon. A cylinder dial of this type is shown on Plate III. In another form, introduced about 1400 and afterwards widely used, the dial took the form of a ring similar to a serviette ring. A small hole was made at one point of the ring, and the sun's rays, after passing through this hole, fell upon a scale of hours marked on the opposite inner surface of the ring. A ring dial of this type is also illustrated on Plate III. Altitude dials of the above types could be used only in the latitude for which they

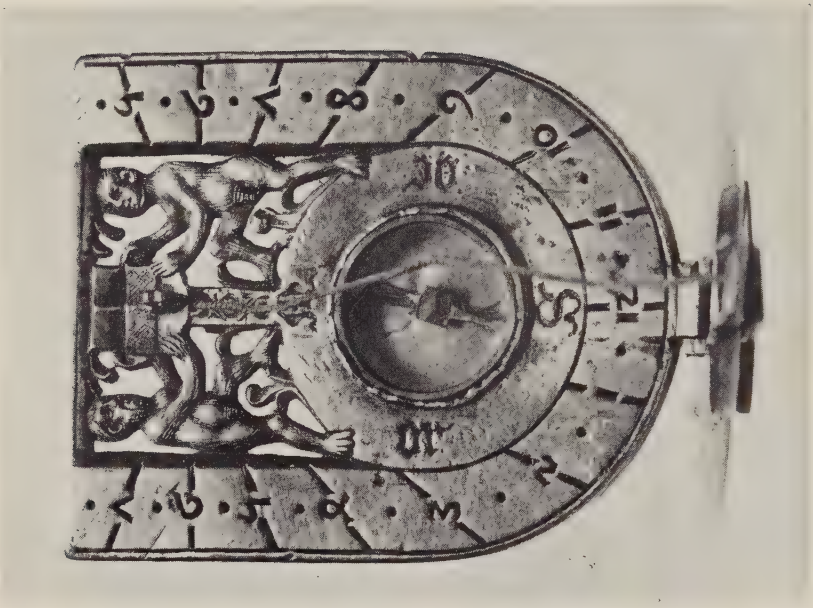
PLATE III

[*To face p.* 20.

Cylinder Sundial or " Shepherd's Dial."
(Modern primitive, from the Pyrenees.)

Portable Ring Sundial (1736).

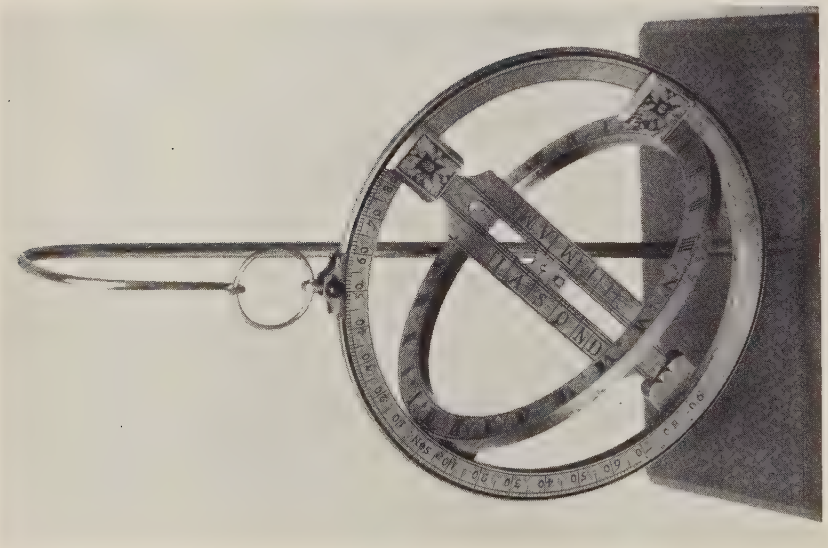
PLATE IV



[*By Courtesy of the British Museum.*

Compass Dial (1453).

(The shadow is cast by the string, which in use is kept taut.)



Portable Universal Ring Sundial (about 1700).

were designed, but, later, portable " universal " altitude dials were constructed which could be set for use in any latitude (*see* Plate IV). All altitude dials have the disadvantage that they cannot show whether the time is before or after noon, unless successive observations are taken at an interval of many minutes, while in the neighbourhood of noon their indications are somewhat uncertain, as the sun's altitude is then changing only very slowly.

The astrolabe, invented probably by the Greeks and re-introduced in Europe in the eleventh century, can be used for finding the time of day, in equal or temporal hours, from the sun's altitude, but it is not a direct-reading instrument, and could be utilised only by those possessing the necessary knowledge of its principles.

The earliest known compass dial, dated 1451,* is in the Landesmuseum Ferdinandeum in Innsbruck, and is also of special interest in being the earliest dial known in which the gnomon is set parallel to the earth's axis, though there is evidence that similar dials were constructed somewhat earlier by the Arabs and Egyptians. With this construction the same scale of equal hours serves for all seasons of the year. The great majority of subsequent compass dials embodied gnomons of this type, and many of them were either " universal "—*i.e.* adjustable for use in any latitude—or fitted with a small adjustment for latitude so that they could be used at different places in the same country.

The graduations of a few late " scratch " dials, such as that on Litlington Church, Sussex, are cut so as to indicate equal hours with a gnomon parallel to the earth's axis, though in most cases the gnomon itself is missing, while from the middle of the fifteenth century onwards fixed public dials with gnomons of this type began to be set up.

From about 1500 onwards great interest was taken in Europe in the theory and construction of sundials to indicate equal hours. At this period clocks and watches were much too expensive to be in general use, and hence the sundial was by far the most widely employed of all time-measuring instruments. Many fixed dials were set up in public places, and considerable ingenuity was shown in the design of portable dials which could be easily folded up and carried about on the person. Some idea of the great variety of forms which they took may be seen from the Museum collection, but even this is in no way representative of all the types.

Throughout the sixteenth, seventeenth and eighteenth centuries sundials continued to be very widely used, but as watches and domestic clocks became more numerous and less expensive the use of sundials gradually declined, until at the present day they have almost entirely disappeared from practical use, except in certain primitive districts.

A sundial indicates apparent solar time, and to obtain mean solar time from its indications allowance must be made for the equation of time. Before the advent of pendulum clocks the equation of time was of purely academic interest, since no foliot clock was accurate enough to distinguish between apparent and mean time. Between 1665 and 1670, however, the causes and amount of the equation of time were

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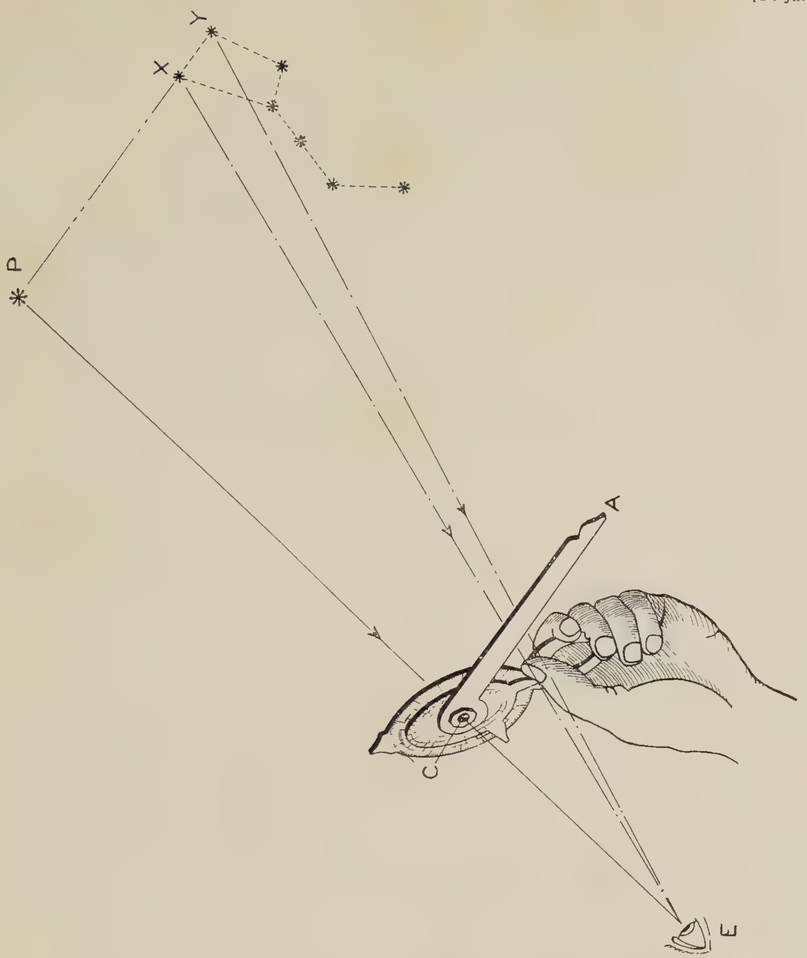
* A similar dial, dated 1453, is in the British Museum (*see* Plate IV).

systematically worked out by Flamsteed. During the eighteenth century many accurate clocks were fitted with a special dial indicating the equation of time, while on sundials tables were frequently inscribed giving its amount on different dates during the year. Various types of sundial have also been designed to indicate mean solar time directly. The allowance for the equation of time is made by specially shaping either the gnomon or the scale of hours upon which its shadow falls. Such instruments are capable of indicating mean solar time to within an accuracy of one or two minutes; higher accuracy cannot be attained, since the shadow is not perfectly sharp owing to the finite angular size of the sun.

Nocturnals or night dials (*see* Plate V) are instruments for telling the hour of the night by the aid of the fixed stars. Looking towards the north, the stars appear to make one complete revolution round the Pole Star in a sidereal day and any given star—for instance, one of the " pointers " of the Great Bear—may be regarded as the hour-hand of a clock indicating sidereal time on a twenty-four-hour dial. The stars can also be made to indicate mean solar time on an imaginary mean solar dial if this dial is rotated very slowly in the same direction, making one revolution in a year. Thus at 10 p.m. mean solar time in September the pointers of the Great Bear are low down on the northern horizon, while at 10 p.m. in December they are in the north-eastern sky and at the same hour in March high overhead. The necessary annual rotation of the solar dial is allowed for in nocturnals. A typical nocturnal is an instrument which is held in the hand, its centre being placed in a direct line between the Pole Star P and the eye E (*see* Plate V). An arm CA, pivoted at this centre C, is rotated by hand until it is in line with the " pointers " XY of the Great Bear, and the time is then read off on a dial mounted on the instrument. This dial has been previously rotated into the correct position for the season of the year, the rotation allowing for the apparent rotation of the imaginary celestial mean solar dial.

A primitive form of this method was employed by the ancient Egyptians for finding the hour of the night, but their method required the co-operation of two observers, each holding a plumb-line. The earliest true nocturnal, embodying the characteristic rotating dial, dates from about 1520, and nocturnals were probably fairly commonly used during the seventeenth and eighteenth centuries. Like sundials, they gradually went out of use with the more widespread introduction of clocks and watches.



A Nocturnal in Use.

Nocturnal or Night Dial (about 1700).

IV. MECHANICAL CLOCKS

The early history of mechanical clocks is still far from clear. The first mechanical clocks of which we have any definite evidence appear to have been made during the first half of the fourteenth century; these, however, were successful public clocks, well enough known to be described by contemporary writers, but of the early experimental clocks which must have preceded them nothing is known.

The evidence for the former existence of these early clocks is of various types. In some cases a description has been left by a writer or poet of the period: sometimes there may be an entry in church records of the payment of wages to a clock-keeper or of payment to a clockmaker for repairs; occasionally a record of payment for the construction of a clock. In certain instances it is uncertain whether a clock mechanism existing at the present day is the same as that referred to in records of this type or is a later replacement.

A great difficulty which is encountered in the investigation of records of early clocks of the fourteenth and fifteenth centuries is that at this period all time-measuring instruments—clocks, water-clocks, sand-glasses and sundials—were referred to under the same name—" horologium," or its equivalent in the language of the recorder. Before the advent of mechanical clocks, elaborate water-clocks were in use; some of these embodied trains of wheels, and may even have actuated alarm or striking mechanisms, so that it is often difficult to distinguish these from mechanical clocks in the somewhat inadequate and non-technical descriptions which have been left by contemporary writers.

The fundamental distinction between water-clocks and mechanical clocks is that in the former the timekeeping is governed by the rate of flow of water through a small orifice, while in the latter it is governed by a mechanical motion which repeats itself over and over again. The type of motion employed in these early clocks was a curious one in which a heavy bar or " foliot," pivoted near its centre, was pushed first one way and then the other by a toothed wheel, the wheel advancing through the space of one tooth for each double oscillation of the beam; this wheel was driven through simple gearing by a weight suspended from a drum. The rate of a clock of this type depends very largely upon the amount of the driving weight, and is also greatly affected by variations of friction in the driving mechanism. It is difficult to imagine how this type of escapement came to be invented, but it has been tentatively suggested that a mechanism of roughly the same type was originally used for ringing an alarm, and might have been afterwards adapted for the measurement of time. In spite of its many imperfections it was universally employed, and remained the sole controlling agent for mechanical timekeepers for over three centuries until the pendulum was applied to clock mechanism about 1660.

The first clock of which we have reliable knowledge is one which was set up in Milan in 1335, and there are fairly reliable records of three other clocks in Italy before 1350. From the results of recent researches it appears that from this time onwards mechanical clocks gradually spread northwards across Europe, the first clock in England being constructed about 1370. These would be mainly public clocks, most of them probably striking the hours. Nothing now remains of the early pioneer clocks, and it is probable that the oldest clocks still in existence are those of Rouen, Salisbury and Wells.

The records of Rouen show that a great clock was set up there in 1379, and there appears to be no reason to doubt that this is the actual clock still in existence. This clock possesses a going train, a striking train and a quarter-chiming train which are mounted in a large rectangular iron frame, some 6 ft. long, 5 ft. wide and 6 ft. high ; it is the earliest clock known which possesses a quarter-chiming mechanism. It is now controlled by a pendulum, but this is, of course, a later addition, while some of the wheels have also been renewed.

The mechanism of the Salisbury clock is now to be seen in the north transept of Salisbury Cathedral, while that of the Wells clock is in the Science Museum. The two clocks bear a remarkable resemblance to one another (*see* Plate VI). Both have at some date been modified so as to employ a pendulum to govern the timekeeping, but traces of the old foliot balance are clearly visible in both clocks. The Salisbury clock, to which a date 1386 has been assigned, possesses a going and a striking mechanism, while the Wells movement, which was probably constructed about 1392, has in addition a quarter chiming mechanism, although this may have been added in a later modification of the mechanism. Both clocks are mounted in large iron frames. No dial has survived at Salisbury, but at Wells an old dial, possibly not, however, the original, is still to be seen. It is an elaborate astronomical dial on which the hours of the day and the age and phases of the moon are shown, while at the hours a mechanism is released which actuates a number of moving figures on horseback. This elaborate dial and puppet show is typical of many of the early public clocks.

As described in the preceding chapter, it was customary in all countries until the fourteenth century to divide day and night each into the same number of " temporal " hours, so that except at the equinoxes the length of a day-hour differed from that of a night-hour, and both day-hours and night-hours varied according to the season of the year.

In Europe during the early fourteenth century the monasteries, which were then centres of learning of all kinds, used to divide the day into twelve hours from sunrise to sunset ; these were termed the " canonical " hours, and all times of day were specified according to them. It appears, however, that a change to the modern system of reckoning, in which day and night together are divided into twenty-four equal hours, took place in each country in Europe a few years after the

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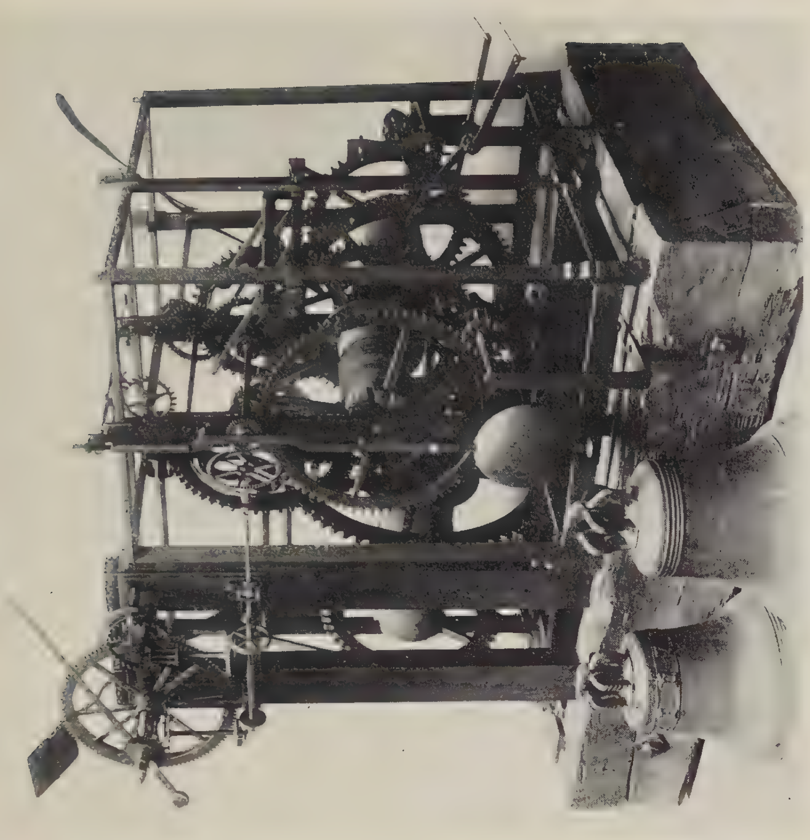
PLATE VI



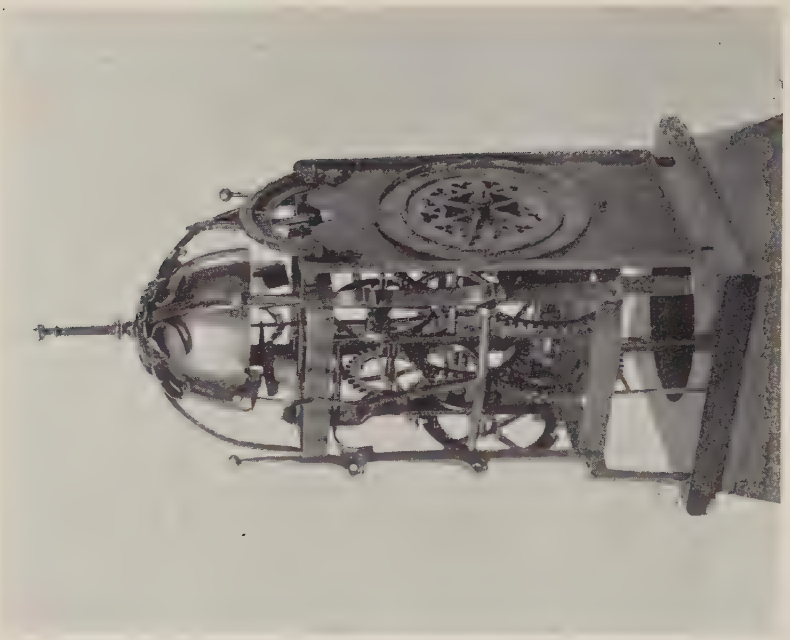
Wells Cathedral Clock (14th Century).

[By Courtesy of R. P. Howgrave-Graham, Esq.

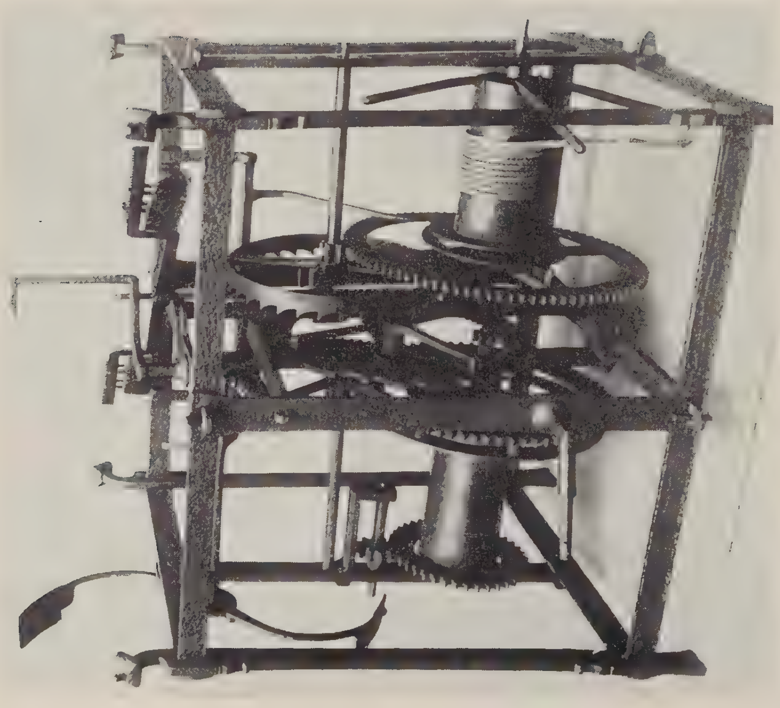
Salisbury Cathedral Clock (14th Century).

To face p. 25.]

PLATE VII



Weight-driven Domestic Clock (16th Century).



Dover Castle Clock.

introduction of mechanical clocks into that country. In England, for instance, where the new hours were counted in two sets of twelve from noon and from midnight, the first references to hours " before noon " or " after noon " occur about 1380, while, as described above, the Salisbury and Wells clocks which were constructed shortly afterwards strike on the 2 × 12 system.

In Italy, however, the new equal hours were counted from one up to twenty-four, starting from sunset. Early Italian clocks, in fact, such as that set up at Milan in 1335, struck up to twenty-four, and the twenty-four-hour system of reckoning persisted in Italy for several centuries, although the 2 × 12 system counting from noon and midnight had been adopted throughout most of the rest of Europe by the beginning of the fifteenth century.

During the fifteenth, sixteenth and seventeenth centuries cathedral and tower clocks continued to be set up in most towns of importance. They were essentially similar to the earliest clocks, but tended to become a little smaller. Among interesting clock movements of this period still in existence are those which have been found at Dover Castle, Cassiobury Park and Quickswood, Herts, respectively; these three resemble each other closely, and have been attributed to the same workshop. The Dover Castle clock (*see* Plate VII), which is in the Science Museum, was formerly attributed to a date in the middle of the fourteenth century, but recent research has cast some doubt on this, and it now appears probable that the three clocks may date from considerably later, although in their design and workmanship they resemble fourteenth-century clocks. The Dover and Cassiobury clocks are of special interest as being the only two public clocks in England which have still retained their original foliot balances.

Our knowledge of early domestic clocks is even more scanty than that of public clocks. There is slight evidence of their existence in the first half of the fourteenth century, but the first reliable record of a domestic clock is of a famous and elaborate one made by Dondi in Italy in 1364. A fairly full contemporary description by Froissart of a clock made for Charles V of France by Henry de Vic or Henry von Wieck in 1370 has come down to us. A technical description of de Vic's clock was found among the papers of Julien Le Roy, the eminent French horologist, at his death in 1759, but it seems probable from various sources of evidence that the clock described by Le Roy was not the original made by de Vic, but a very much modified and improved piece of mechanism.

From about 1400 onwards there are frequent records of the purchase of domestic clocks by kings and princes, but throughout the fifteenth and early sixteenth centuries they were great rarities and were possessed only by the very wealthy. Except in size, these domestic clocks (*see* example on Plate VII) were very similar to the large public clocks, but they were designed for mounting on a bracket projecting from a wall. They usually embodied a going and a striking train, with sometimes an alarm in addition; they were weight-driven and the mechanism was of iron and was mounted in a rectangular iron frame. Their timekeeping was governed by the verge and foliot escapement, but the foliot balance itself was often replaced by a balance-wheel. Brass was not used in the construction of clocks until about 1550, but its use spread rapidly, and the typical English domestic clock of the early seventeenth century was the so-called " lantern clock " whose wheels, frames and dial were all made of brass.

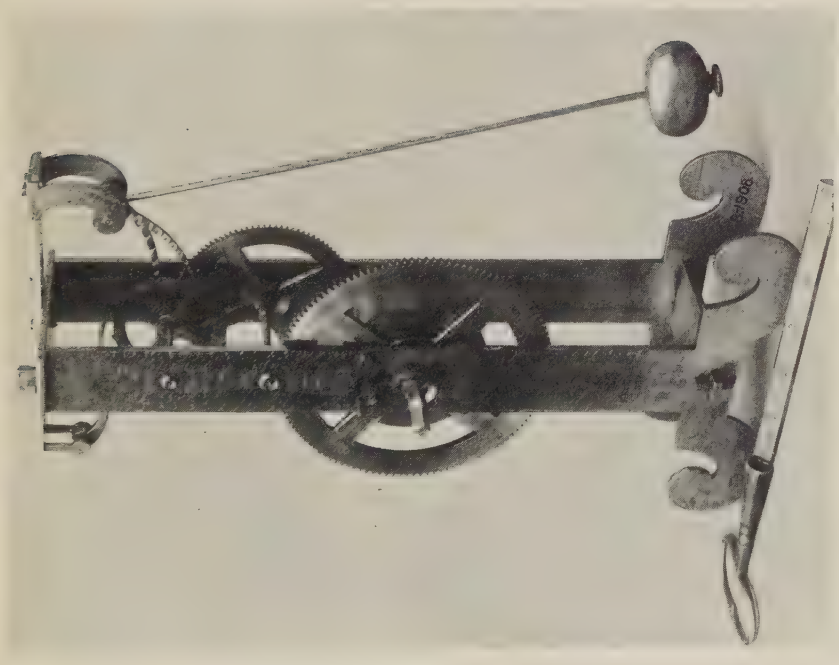
Before the invention of the pendulum, the accuracy of time measurement was very low, and clocks could not be relied on to keep time more closely than to about a quarter of an hour a day at the best, while an error of an hour a day would not be unusual. Up to the middle of the seventeenth century, therefore, clocks had only one hand indicating the hours, and the dial was divided only into hours and quarters, but after the introduction of the pendulum about 1670 the timekeeping was so much improved that a minute hand was added ; second hands were not generally introduced until about half a century later.

The pendulum clock.—Accurate time measurement was first made possible by applying a swinging pendulum to control the rate of rotation of the wheels of a clock. As with so many great inventions, the application of the pendulum to clockwork cannot be attributed to one man alone. Galileo had noticed in 1590 that the time of swing of a pendulum was almost independent of the amplitude of its swing and, following him, astronomers soon came to use a pendulum for timing their observations. The pendulum was, however, started by hand and kept in motion by occasional impulses given by hand, while the number of swings had to be counted by eye. The next great step forward occurred when clock mechanism was applied to keep the pendulum swinging and to count its swings. Galileo and his son Vicenzio were engaged upon this problem, but it is still a matter of controversy whether they actually succeeded in constructing a working clock ; they left, however, drawings of a pendulum clock with an entirely original form of escapement (*see* Plate VIII). There are various somewhat unsatisfactory records of the invention and construction of pendulum clocks between 1600 and 1650 or even before, but it was Huygens who, in 1657, first patented and fully described a pendulum clock which he had designed.

Huygens had calculated in detail the theoretical motion of a pendulum and showed that the period of its swing was not quite independent of the arc, but that it could be made so by suspending the pendulum by means of a pair of cords slung between two " cheeks " of metal shaped in the form of a cycloid. Huygens' clock (*see* Plate VIII) embodied this construction ; it possessed a verge escapement similar to that of the earlier pre-pendulum clocks, but the foliot itself was replaced by a thin metal bar passing through a slot in the pendulum rod or made to engage with a fork or " crutch " which embraced the pendulum rod.

Huygens' method of applying a pendulum to clockwork gave a great improvement in timekeeping and was widely employed, especially

PLATE VIII

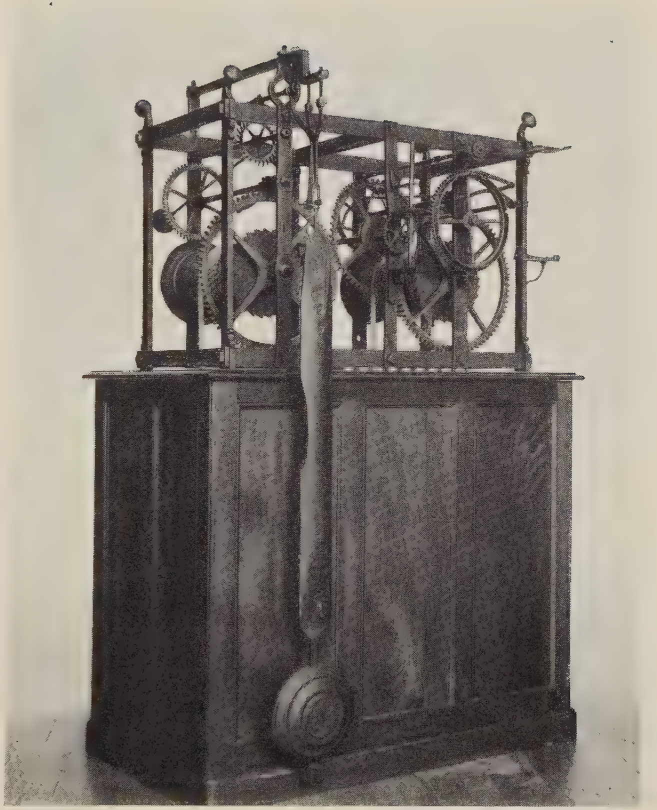


Reconstruction of Galileo's Escapement.
(In the original design the movement is driven by a weight.)

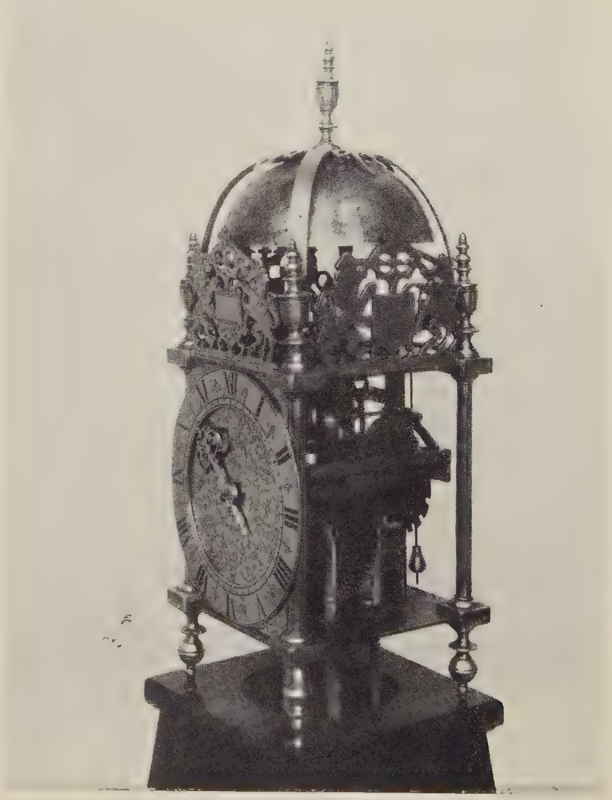
Reconstruction of Huygens' Pendulum Clock.

To face p. 27.]

PLATE IX



Clement's Turret Clock with Anchor Escapement (1671).



English Lantern Clock (1688).

in Holland in the so-called " Zaandam " clocks. The use of cycloidal cheeks was, however, soon discontinued, as in practice they were found to give a good deal of trouble which more than offset their theoretical advantages, and the pendulum was then usually suspended by a thin strip of steel spring.

A still further improvement in timekeeping was obtained by the invention in England a few years later of the " anchor " escapement, now almost universally adopted for domestic pendulum clocks, which gives much less interference with the free swing of the pendulum than the verge escapement. It is probable that the anchor escapement was the invention of Hooke, but it has also been attributed to William Clement, who in 1671 employed it in a turret clock which is now in the Science Museum (*see* Plate IX).

The timekeeping of clocks was so much improved by the invention of the pendulum that from this time onwards nearly all new clocks were made with a pendulum, while many older clocks were adapted to employ one.

Pendulum clocks may be driven either by a weight or by a spring. The earliest weight-driven pendulum clocks were modified foliot clocks with a verge escapement and fitted with a short pendulum (*see* example on Plate IX). The invention of the anchor escapement, however, which requires a much smaller arc of swing than the verge, enabled a longer pendulum, swinging in a smaller arc and giving better control of the timekeeping, to be used. The lantern type of clock therefore gave way to the " grandfather " clock, in which pendulum and weights were enclosed in a long wooden case resting upon the floor. This type of clock was introduced about 1700 and in England quickly became the standard form of weight-driven domestic clock. It proved so well adapted to its purpose that little change has since taken place either in its mechanism or in its external form.

Spring-driven clocks were first introduced towards the end of the fifteenth century, but as these have many features in common with watches an account of their development is deferred to the next chapter.

Precision clocks.—Although the grandfather clock was sufficiently accurate for all normal domestic purposes and hence has undergone relatively little change since its introduction, its accuracy was not sufficient for scientific purposes and much progress has been made in the construction of more and more accurate pendulum clocks. The effects of changes of temperature and of barometric pressure on the rate of the clock have been almost entirely eliminated, and better escapements have been invented which leave the swinging pendulum as free as possible from external interference. A small but important invention is the provision of some source of power to keep the clock going while it is being wound up.

Temperature compensation.—A rise of temperature causes the pendulum rod to expand and lengthen, the pendulum then beats more slowly and the clock loses.

A pendulum with a steel rod loses 2½ seconds per day for a rise of temperature of 10° F. The first method for compensating for this expansion with heat was invented by Graham in 1721. He employed as a pendulum bob a glass or steel vessel containing mercury, which has a much greater expansion co-efficient than steel. By correctly choosing the amount of mercury, its upward expansion could be made to compensate the downward expansion of the steel pendulum rod. A pendulum of Graham type is shown on Plate X.

A second method of compensation was invented about 1726 by Harrison, who made use of the different expansion co-efficients of brass and steel. For practical convenience the brass and steel rods were arranged in the form of a " grid-iron " of brass rods and steel rods, to which the pendulum bob was attached (*see* Plate X). This type of pendulum does not in practice give quite such good compensation as Graham's, but is much cheaper to make, as no expensive mercury is required. About 1800 various types of compensation pendulum employing zinc and steel were devised : on account of the greater expansibility of zinc, fewer rods are required than in a brass-and-steel pendulum. The well-known sidereal standard clock made for Greenwich Observatory in 1872 by Dent employed a zinc and steel compensation. Its advantage over Graham's mercury-and-steel compensation is that the compensation takes place throughout the whole length of the pendulum instead of at the bottom only, so that compensation will still be effected if the temperature varies from point to point of the pendulum. The same advantage is obtained by Riefler's mercury-in-steel pendulum, patented in 1891, in which the pendulum consists of a steel tube containing mercury throughout most of its length.

In 1895 Guillaume in Paris succeeded in producing an alloy of nickel and steel, which he termed invar, whose expansion co-efficient was practically zero, and since this time it has been customary to make the pendulum rods of the highest grade clocks of this alloy, the temperature error being thus almost completely eliminated.

Barometric compensation.—The effect of change of barometric pressure on the rate of a pendulum clock is very complex, components due to change of air friction and to change of buoyancy both being present. Early attempts were made, notably by Robinson of Armagh Observatory in 1831, to compensate the effect by attaching a small mercury barometer to the pendulum itself. The Greenwich sidereal standard clock of 1872, mentioned above, was fitted with a more elaborate form of compensation in which the rise or fall of a fixed mercury barometer was made to lower or raise a permanent magnet and so to vary its pull upon a pair of bar magnets mounted upon the pendulum.

The modern practice, made possible by the advent of clocks electrically wound or maintained and therefore not requiring access by hand, is to allow the pendulum to swing in a hermetically sealed vessel inside which the pressure of the air is kept strictly constant and independent of any barometric fluctuations outside.

PLATE X

Three Clock Pendulums : (Left) Uncompensated. (Centre) With Graham's Mercurial Compensation. (Right) With Harrison's Gridiron Compensation.

Maintaining power.—In the simple " grandfather " type of clock the driving force is no longer operative while the weight is being wound up and although the pendulum continues to swing the hands remain stationary. The consequent loss of a few seconds is relatively unimportant in a domestic clock, but cannot be tolerated in an accurate clock. Various devices have therefore been invented for supplying " maintaining power " to a clock while it is being wound. One of the best and earliest of these was invented by Harrison about 1735, and has been widely used for observatory clocks as well as for chronometers. It should be noted that clocks driven by the " endless chain " method invented by Huygens and many modern electrically driven clocks require no maintaining power, as the driving force is unaffected by the winding.

Escapements.—As described in Chapter II, an escapement has two functions—to count the swings of a pendulum and to impart sustaining impulses to the pendulum to make good the energy lost by friction. A good escapement should satisfy Airy's condition of giving an impulse at or near the mid-point of the swing and as little interference as possible elsewhere.

The anchor escapement, though an improvement on the verge, interferes with the pendulum during the whole of its swing and is not therefore suitable for precision clocks. A much improved version of it—the " dead-beat " escapement—was invented by Graham in 1715 : this escapement gives an impulse to the pendulum near its zero position and only a slight frictional drag elsewhere.

Turret clocks.—After the introduction of the pendulum large public clocks (usually termed " turret clocks ") were generally fitted with the anchor or the dead-beat escapement. These escapements, though very suitable for indoor clocks, have certain disadvantages for use in turret clocks, which have their hands exposed to the wind and weather. Since the hands are connected through gearing with the escape wheel, the force driving this wheel is variable. With all ordinary escapements a varying driving force causes variations in the arc of swing of the pendulum and consequently produces small variations in the timekeeping. In order to overcome this difficulty, various types of so-called " gravity " escapement have been invented in which the wheel train, instead of driving the pendulum directly, is made to raise levers which on their subsequent fall give an impulse of constant amount to the pendulum. Its arc of swing should therefore be independent of variations in the driving force, provided that this force is sufficient to raise the gravity arms to their proper height.

Pioneer gravity escapements of simple type were introduced by Mudge and by Cumming between 1760 and 1770, and various modifications of these were made during the following fifty years, but none of these escapements appears to have been wholly successful. A much improved escapement was invented by Bloxam about 1850, but this never came into general use, and the first really successful gravity escapement was that invented by Sir E. Beckett (afterwards Lord

Grimthorpe) about 1852 and fitted to the famous Westminster clock (" Big Ben ") which was constructed in 1854 and set going permanently in 1860. This clock proved to be remarkably accurate and reliable, and its success led to the wide adoption of Grimthorpe's escapement, which became the standard pattern for use in turret clocks.

The further development of precision clocks.—Although the dead-beat escapement remained for so long the standard one for precision clocks, several important clocks were fitted with other experimental escapements. Noteworthy among these was the standard sidereal clock constructed by Dent for Greenwich Observatory in 1872, which was fitted with an escapement due to Sir G. B. Airy, then Astronomer Royal. Although this clock attained a high accuracy, its daily rate varying only by a few hundredths of a second from day to day over a period of several months, Airy's escapement was not generally adopted.

In 1889 Riefler of Munich patented an escapement in which the impulses to the pendulum were transmitted through its suspension spring, the pendulum being otherwise free from interference. This escapement proved very successful in practice, the daily variation of rate of Riefler clocks being only of the order of one-hundredth of a second or even less under the best conditions. Riefler clocks were accordingly adopted as standard clocks in many of the leading observatories of the world.

An experimental clock of great ingenuity and originality was constructed by R. J. Rudd about 1898 ; it consisted of a free pendulum together with a slave clock. Every minute the slave clock gave an impulse to the free pendulum, while the slave clock was automatically regulated by the free pendulum so that it would release the impulse at the correct moment. Rudd's work remained for several years practically unknown, but its importance was realised about 1910, and the same principle of the free pendulum and slave clock was employed in the successful Shortt clock perfected in 1924.

The Shortt clock has surpassed even the Riefler clock in its performance, its daily variations of rate being only a few thousandths of a second under the best conditions. As it is an electric clock, however, further description of it is postponed to Chapter VIII.

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PLATE XI

[*By Courtesy of the Victoria and Albert Museum.*

(Left) German Watch (Late 16th Century). (Right) French Watch (about 1660).

[*By Courtesy of the Victoria and Albert Museum.*

French Spring-driven Clock (Late 16th Century).

V. WATCHES AND SPRING-DRIVEN CLOCKS

The construction of portable clocks and watches was first rendered possible when a spring was employed instead of a suspended weight to supply the driving power of a clock mechanism. It seems probable that the first spring-driven clocks were made towards the end of the fifteenth century, and that the first true watches—spring-driven timekeepers small enough to be carried about on the person—were made by one Peter Hele or Henlein of Nuremberg between 1500 and 1510. None of these pioneer watches is still in existence, but writers of the period have left brief descriptions of them, and there are records of " self-going horologia " being sent from Nuremberg as presents to kings and princes about this period. Watchmaking appears to have started independently in France early in the sixteenth century, but in England no watches appear to have been made until about 1580.

The earliest watches which have survived to the present day are a few German examples of date about 1540 and a French one dated 1551. They are almost spherical in form, but this form did not persist for long, and the typical watch of the late sixteenth and early seventeenth century was in the shape of a circular drum some two inches in diameter and one-half to one inch deep (*see* Plate XI), or an oval drum of roughly similar dimensions ; other forms were, however, occasionally made.

Spring-driven clocks were at first usually in the form of a flat drum some six inches in diameter and a few inches high (*see* Plate XI). The face was on the flat top of the clock, and was often protected by a metal cover, pierced with holes to enable the numbers on the dial to be seen ; the use of glass to cover the dial was not usual until about 1630. Towards the end of the sixteenth century clocks of upright form began to be made. Apart from the spring drive, the mechanism of these early watches and portable clocks was similar in all essentials to that of the weight-driven clocks which preceded them. A wheel or a dumb-bell shaped bar was, however, usually substituted for the foliot balance, but the principle was the same, the wheel or bar being pushed first one way and then the other by means of a crown wheel and verge escapement. As already described in Chapter IV, the rate of a timekeeper employing this mechanism varies greatly with variations of the driving force, and for this reason the early watches were even poorer timekeepers than the early weight-driven clocks. For whereas the pull of a weight is constant whether fully wound up or near the end of its fall, the pull given by a spring varies, being much stronger when it is fully wound than when nearly run down. Various means were therefore sought for making the pull of a spring more constant. The earliest German watches were fitted with a device known as a "stackfreed." This consists of an auxiliary spring which by pressing upon a suitably shaped cam is made to oppose by its friction the action of the mainspring when the latter is fully wound, and to offer less opposition or even slight assistance to it when nearly run down.

French and English watches were from the first fitted with an immensely superior device—the so-called "fusee" (*see* fig. 2), which furnishes an almost perfect solution of the problem of obtaining a uniform torque from a spring whose force varies as it uncoils. The fusee is first met with in sketches made by Leonardo da Vinci in 1490, while the earliest known clock which possesses a fusee is one made by Jacob Zech (Jacob the Czech) in 1525.

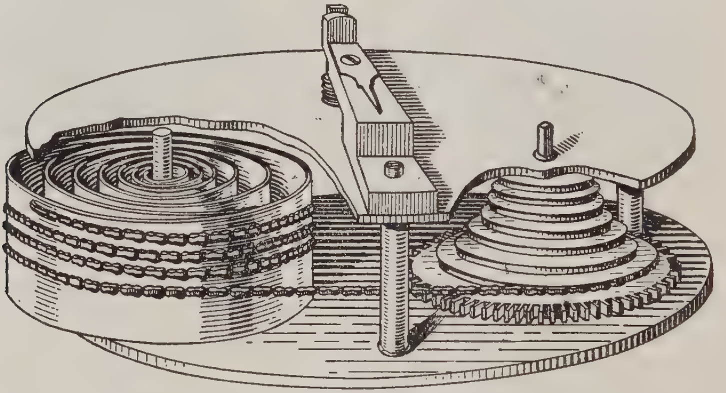

Fig. 2.—The fusee driving mechanism of a chronometer, comprising mainspring, barrel, chain and fusee. The inner end of the mainspring is secured to a fixed axle.

The fusee itself consists of a conical drum with a spiral groove cut in it, and the pull of the mainspring is exerted through a light cord or chain which is unwound from this groove on to the outside of the barrel containing the spring. When the spring is fully wound and exerting its greatest pull the chain is unwinding from the smaller end of the fusee, where it has only a small leverage, while when the spring is nearly run down the chain pulls at the wider end of the fusee, with a greater leverage. By suitably shaping the fusee the torque on its axis can be made quite uniform for all states of the spring. The toothed wheel mounted on the fusee engages with a pinion and so drives the watch mechanism.

The movement of the early German watches was made entirely of iron or steel, probably because their makers were originally locksmiths, but brass was gradually introduced about 1560 and its use soon became general. A similar change from iron to brass took place with portable clocks.

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PLATE XII

English Spring-driven Bracket Clock (about 1700).

Throughout the sixteenth century watches must have been great rarities, and were possessed only by the very wealthy. Their timekeeping was very poor and they were valued as curiosities and for their decoration rather than as timekeepers.

Just as the invention of the pendulum shortly after 1650 produced a very great improvement in the timekeeping of clocks, so the invention of the balance-spring at about the same period produced a corresponding improvement in that of watches. In both cases the reason for the improvement was the same. The foliot or balance-wheel had no regular motion and therefore no timekeeping property of its own, its rate of vibration depending entirely on the driving force, but the time of swing of a pendulum swinging freely under gravity or of a balance-wheel oscillating under the control of a balance-spring is a very definite quantity, and varies only little with the arc of swing.

Until the middle of the seventeenth century the mechanisms of all spring-driven timekeepers were essentially similar at any given period, but the twin inventions of the pendulum and of the balance-spring produced two distinct and separate lines of development.

The mechanism of spring-driven pendulum clocks developed generally along the same lines as that of weight-driven pendulum clocks. They were at first fitted with the verge escapement, but this later gave way to the anchor escapement, while the dead-beat escapement was occasionally employed. The spring-driven pendulum clock (*see* example on Plate XII) is essentially a compact and convenient domestic clock rather than a precision clock, and is consequently rarely fitted with refinements such as temperature compensation. The best-class clocks may be fitted with a fusee, but this is uncommon and, for the accuracy ordinarily required of such clocks, unnecessary.

Spring-driven clocks fitted with balance-springs resemble watches in all essential features of their mechanism and have followed a similar course of development. On account of the fact that the mechanism is compact and can be placed in any position the external form of these clocks is of immense variety and especially in France clocks of fantastic forms were made during the eighteenth century.

Hooke was probably the first to attempt to control the motion of the balance-wheel by means of a spring, but it was Huygens who, in 1675, designed the spiral balance-spring and had successful watches made embodying this invention, though Hooke and the Abbé de Hautefeuille both claimed priority.

By 1700 the inclusion of a balance-spring had become a regular feature of watch mechanism. The next important step was Graham's invention, in 1725, of the cylinder escapement, which was a great improvement on the verge escapement and gave much less interference with the free motion of the balance. The time of swing of the balance was much less dependent upon the driving force than with the verge escapement, and consequently the use of the fusee was abandoned by French and Swiss makers, enabling the watch to be made considerably thinner. In English watches, however, the fusee was retained long after the introduction of the cylinder escapement, the English makers preferring accuracy to convenience.

About 1755 Mudge invented the detached lever escapement, which leaves the balance entirely free for the greater part of its swing and is now almost universally employed in pocket watches. In spite of its excellence it was adopted only slowly by watchmakers. Although it was employed in high-grade watches about 1825, the escapement used in ordinary watches was still the cylinder or even the verge, and it was not until the latter part of the nineteenth century that the lever escapement really came into its own.

About 1650 the typical oval drum-shaped form of watch began to be replaced by a thick lens-shaped form (*see* Plate XI), and this remained characteristic for over 100 years. The introduction of the cylinder escapement and the abolition of the fusee enabled the French and Swiss makers to produce a considerably thinner watch, and a further advance in thinness was obtained by the introduction, about 1765, of the " Lepine calibre." The exceptionally fine watches made by A. L. Breguet of Paris between 1780 and 1820 showed that relative thinness was compatible with accuracy.

The earliest watches possessed only a single hour-hand, but about 1700, after the introduction of the balance-spring, hands indicating minutes came into use. During the next twenty-five years various methods of indicating hours and minutes on the same dial were tried, until the present-day method of employing concentric hour and minute hands became standardised. Seconds-hands did not come into general use until after the invention of the cylinder escapement had improved the accuracy of watches sufficiently to make their indications of value. Some watches were also fitted with indicators showing the day of the week and month, the moon's age and phase, while others were fitted with repeating mechanism, which is briefly described in the last chapter of this Handbook.

In sixteenth and seventeenth-century watches the pivots of the wheel train ran in plain holes in the iron or brass frame. About the middle of the eighteenth century, however, attention was devoted to the oiling of the bearings, and the holes were opened out a little at one side to provide a small reservoir or " sink " for oil. In 1704 a patent was taken out by Debaufre and Facio for the use of pierced rubies as bearings, and jewelled bearings were subsequently used by various makers during the eighteenth century, but they did not come into general use until the nineteenth century.

The construction of Harrison's fourth marine timekeeper in 1759 marked a very important stage in the evolution of portable timekeepers. Harrison's instrument was essentially a large watch with many refinements, designed for use on board ship for determining longitude. It proved so accurate and successful for this purpose that many of the leading horologists of the day turned their attention to the design and construction of marine chronometers. From this time onwards, in fact, most of the improvements in portable timekeepers were applied in the first place to chronometers, though they were also embodied to a certain extent in high-class watches; they were usually too expensive for use in ordinary watches. The more important of these improvements are described in the next chapter.

While the eighteenth century saw the introduction of a great number of inventions improving the timekeeping of watches, many of these inventions lay almost dormant for many years, and it was left to the nineteenth century to see their general adoption. The greatest advance in watchmaking in the nineteenth century was, however, the cheapening of watches and their production in really large numbers; this was rendered possible by the use of machine tools in their manufacture. The supersession of hand by machine work was a gradual process, lasting over practically the whole century, the progress being made mainly in Switzerland, which rapidly attained a leading position in the watchmaking industry, while English watchmaking, which had been supreme in the eighteenth century, gradually declined.

The first really cheap watch was produced by Roskopf in Switzerland in 1865; it was quite a fair timekeeper and sold well. The famous Waterbury watch was designed by Buck in the U.S.A. and put on the market in 1880. By 1888 the output of the Waterbury factory had reached half a million watches per year, while so rapid has been the subsequent rise in watch manufacture that in recent years the number of watches exported annually from Switzerland has averaged nearly ten million, and some five million watches are sold each year in Great Britain alone.

VI. CHRONOMETERS

The position of a ship at sea is known when its latitude and longitude have been determined. The navigator can find his latitude by making measurements on the sun or stars, but in order to find his longitude he must, besides making a measurement of this kind, know the standard time at which the observation was made, *i.e.* the time at some fixed point on the earth's surface whose longitude is known. His astronomical observations give his local time, and his longitude east or west of the given fixed point is given simply by the difference between this local time and standard time, 15° of longitude corresponding to one hour of time.

The early coastwise navigators were able to make their way from landmark to landmark and it was not until long ocean voyages began to be made in the fifteenth and sixteenth centuries that the need for a method of finding the longitude was felt. Various astronomical methods of finding standard time were suggested, but none of these proved of sufficient accuracy. The employment of a timekeeper to be carried on board ship was proposed by Gemma Frisius in 1530, but as the only timekeepers of that period were foliot clocks and watches they were incapable of any approach to the accuracy necessary.

The first timekeepers made specifically for use at sea were designed by Huygens about 1659. They were pendulum clocks embodying a half-minute " remontoire" (*i.e.* driven by a small weight which was wound up every half minute by a mainspring), and were mounted in gimbals in order to keep them upright as far as possible. When tested at sea they behaved reasonably well in calm weather, but in rough weather their timekeeping became very erratic and they frequently stopped altogether. They had no form of compensation for the effect of varying temperature, and their rate varied, of course, with the varying attraction of gravity at different places on the earth. Huygens himself was evidently convinced of their failure, as he turned next to the design of timekeepers controlled by a balance-wheel and spring, but these were not, apparently, sufficiently accurate to be of use in determining longitude, probably owing to the effect of change of temperature on the rate. This effect is much greater for a timekeeper with a balance-spring than for a pendulum clock.

In 1714 Thacker of Beverley proposed a marine timekeeper to which a " maintaining power " was fitted. This is a device to keep the instrument going while it is being wound, and was the first of its kind. Thacker's machine contained no device for temperature compensation, but he proposed to ascertain its rate at various temperatures and then in use to record carefully the prevailing temperature and apply a suitable correction. There is, however, no record of the instrument ever being tested at sea. A further ingenious but unsuccessful marine timekeeper was constructed by Sully and tested in 1726.

As time progressed and long sea voyages became more common, the problem became more pressing, and large rewards were offered by various governments for a method of finding a ship's longitude with sufficient accuracy. As early as 1598 a large sum had been offered by Philip III of Spain, and in 1714 the British Government offered an award of £10,000 for a method of determining a vessel's longitude at sea to within an accuracy of 1°, at the end of a voyage to the West Indies, £15,000 if the accuracy was to within 40′, and £20,000 if within 30′. Since one degree of longitude corresponds to four minutes in time, an error of 30′, or half a degree, corresponds to an error of two minutes in time, so that in order to win the full award it was necessary for a timekeeper to err by less than this amount in the six weeks' voyage. A timekeeper which even exceeded this performance was, however, constructed by John Harrison, a Yorkshire carpenter, who devoted practically his whole life to the work. Between 1728 and 1759 Harrison designed and constructed four marine timekeepers, all of entirely original design, and with the fourth of these he eventually succeeded in winning the award.

Harrison's first timekeeper (*see* Plate XIII) was completed in 1735; it was essentially a large spring-driven clock, controlled by two balances, which were connected together by a system of wires (effectively a frictionless gearing) which caused them to oscillate always in opposite directions, so that any effect of the ship's motion was eliminated. It was fitted with Harrison's own " maintaining power." The effect of temperature was compensated by varying the effective length of the balance-springs, the instrument being the first balance-wheel timekeeper to employ any compensation for temperature changes. The instrument was tested first in a barge on the Humber and then sent on a voyage to Lisbon and back, on which its performance was very encouraging. On his return from Lisbon, Harrison at once started to construct a second timekeeper, which was in general similar to the first, but which embodied several improvements, including a remontoire which enabled the force driving the escape wheel to be kept remarkably uniform, the escape wheel itself being driven by a pair of helical springs re-wound every 3¾ minutes by the mainspring. This instrument was completed in 1739, but was not at once tested at sea, as Britain was then at war with Spain, and it was feared that the instrument might be captured. As a result of tests made on land, however, Harrison began in 1741 to construct a third timekeeper, which he expected to be still better. Owing to some cause not yet known this timekeeper was not completed until 1757. It resembled the two earlier timekeepers but had wheel instead of bar balances, a spiral balance-spring, and a bi-metallic " compensation curb " operating upon the balance-spring and altering its effective length according to the temperature. The third timekeeper was never actually tested at sea, for it was superseded by the fourth, which Harrison had intended to be a mere auxiliary to it, but which proved to be equally accurate. The fourth timekeeper (*see* Plate XIII), completed in 1759, was much smaller than its three predecessors, and was essentially a large watch about five inches in diameter, but it embodied all Harrison's experience gained with the larger instruments. It had only a single balance-wheel, and the escapement employed was a much improved modification of the verge, while as in the third timekeeper compensation for the effect of changes of temperature was obtained by varying the effective length of the balance-spring by means of a compensation curb and a remontoire was fitted in order to supply a constant driving force to the escapement.

In 1761 the fourth timekeeper was taken to Jamaica and back in H.M.S. "Deptford," being tended on the way by Harrison's son William. On this voyage it more than fulfilled all expectations, as on arrival at Jamaica it was found to have erred by no more than five seconds, corresponding to an error in longitude of only $1\frac{1}{4}'$, or approximately $1\frac{1}{2}$ miles in the latitude of Jamaica. Harrison had evidently succeeded in solving the problem of determining longitude at sea. The reward of £20,000 was not at once paid to him, however, as the Board of Longitude suspected that the good going of the chronometer might be accidental. A second test was therefore made in 1764, and William Harrison again accompanied the instrument, this time to Barbados and back. Its performance was as good as on the first test, its total error in five months being only fifty-four seconds, while after certain corrections had been applied for its declared change of rate at different temperatures this error was reduced to fifteen seconds. The Board were agreed that this striking performance was sufficient to win the award, and after much delay and friction between the Board and Harrison the final instalment of the award was paid over in 1773, after Harrison had made public the full details of the instrument.

Harrison had shown that it was possible to construct a timekeeper which would keep sufficiently accurate time at sea, but his timekeeper was complicated and difficult to construct, and it was left to his successors to design instruments which could be produced in large numbers so as to be available for all sea-going ships. The progress made was remarkably rapid, and by 1820 chronometers of the form in use at the present day were being made in large numbers and chronometer-making had become an important branch of the watch trade.

Thomas Mudge, the inventor of the detached lever escapement for watches, was the first to follow Harrison in designing marine timekeepers. He constructed an instrument which was similar in general respects to Harrison's fourth timekeeper, but embodied a "constant force" escapement of his own invention which was theoretically very perfect, but, like several of Harrison's mechanisms, too complicated for general use. Mudge constructed two further timekeepers which were tested at Greenwich, but their going was not entirely satisfactory, and as Mudge died shortly afterwards his work was left unfinished.

Meanwhile other horologists in France were at work on the longitude problem. In 1748 Pierre Le Roy had invented a "detached" escapement, the first of its kind, in which the balance-wheel was free from any interference during the major part of its swing. In 1763 he constructed a large marine clock, and in 1766 he produced his remarkable " montre marine." This machine was entirely original, and its design was quite independent of that of Harrison's fourth timekeeper, particulars of which had not been made public at that date. Besides the detached escapement Le Roy's instrument embodied another entirely novel feature—the first compensation balance, in which compensation for changes of temperature was effected by varying the effective size of the balance and not, as in Harrison's instruments, by varying the effective length of the balance-spring. Le Roy's instrument was tested at sea and found to be as good as Harrison's.

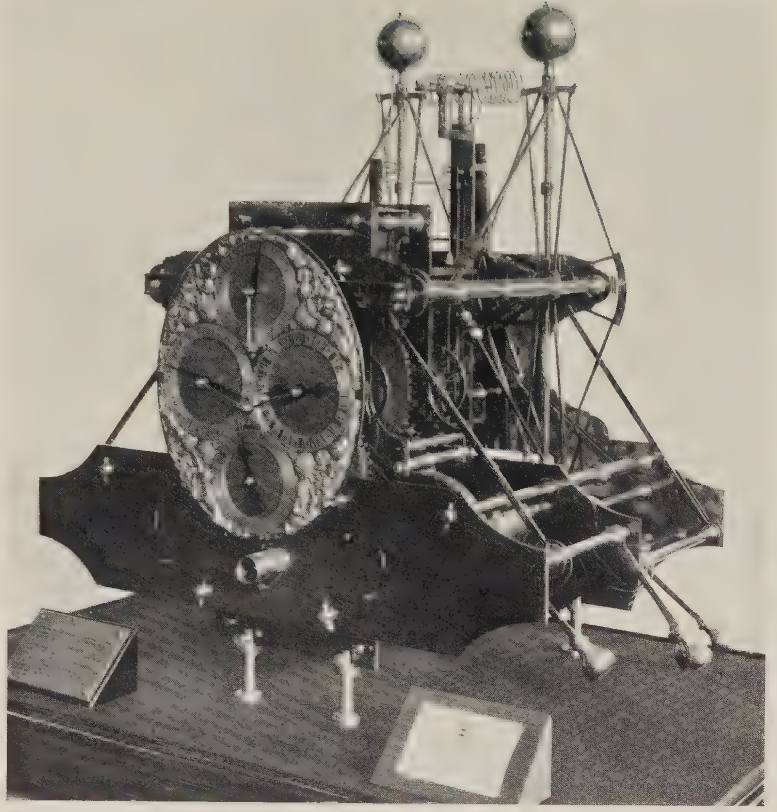
Berthoud, also in France, constructed some seventy marine timekeepers, and has some claim to be considered as the inventor of the " spring detent " form of chronometer escapement, now almost universally employed in chronometers, though both Arnold and Earnshaw, who were at work in England, claimed the invention as their own. To these two men, however, must be given the credit for converting the making of chronometers from a highly skilled individual operation into a commercial proposition. Arnold was the first to employ the helical form of balance-spring which is now a standard in chronometers, while Earnshaw introduced the method now very widely employed for making compensation balance-wheels.

After the deaths of Arnold and Earnshaw chronometer-making had become well established and relatively little change has since taken place in the essential mechanisms of chronometers. Further progress has, however, been made towards making the time of swing of the balance independent of variations of the driving force and of the friction in the train of wheels, and in obtaining more and more perfect compensation for the effect of changes of temperature.

Isochronism.—In an ideal simple harmonic motion the period of an oscillation is entirely independent of the amplitude of swing, and swings of different amplitudes are said to be isochronous. The motion of a chronometer balance-wheel controlled by its spring approaches closely to this ideal, but does not quite attain to it. Arnold, who introduced the helical form of balance-spring, had found by experiment that the swings of the balance could be made almost perfectly isochronous if the two ends of the balance-spring were bent into the form of certain curves. No explanation of this result was forthcoming until 1861, when Phillips published a detailed memoir in which the same result was obtained theoretically. He gave curves showing the necessary forms for both helical springs as used in chronometers and spiral springs as employed in watches. Phillips' predictions were found to be fully borne out in practice, and the balance-springs of chronometers and of high-class watches are now generally shaped to his curves.

Temperature compensation of chronometers.—In watches and chronometers time is measured by counting the oscillations of a balance-wheel controlled by a balance-spring. The time of a single oscillation depends on the moment of inertia of the balance-wheel and on the stiffness of the balance-spring, and both of these quantities vary with temperature. The balance expands with rise of temperature, and this expansion increases its moment of inertia and causes the time of oscillation to be greater ; if the balance is made of brass the resulting loss is about five seconds per day for a rise of temperature of 10° F. The stiffness of the balance-spring decreases with rise of temperature, and with a steel spring this decrease causes a loss of about one minute per day for a rise of 10° F. The effect of the change of stiffness of the spring is thus over ten times as important as that of the expansion of the balance.

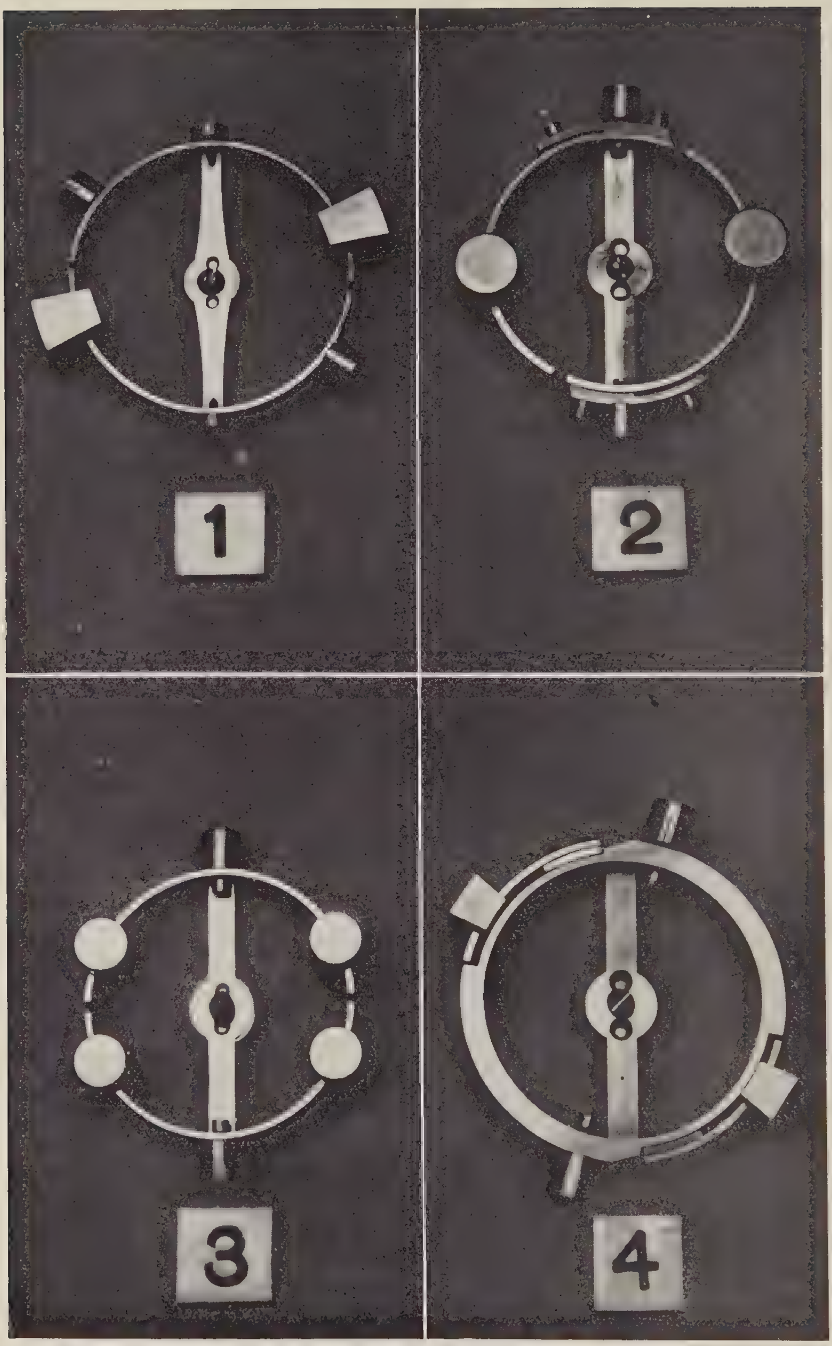
Harrison and the earlier chronometer makers tried to eliminate this effect by making the effective length of the balance-spring vary with temperature. The spring passed between two pins mounted at one end of an arm, and the position of the pins was made to vary with change of temperature. This device was in many ways satisfactory, but it interfered with the isochronism of the spring. As previously stated, Le Roy was the first to effect the compensation by varying the moment of inertia of the balance, the method now universally adopted. He mounted two small thermometers on his balance, and arranged these so that a rise of temperature caused mercury to be transferred from the circumference towards the centre of the balance, so that its moment of inertia was reduced. He was able to obtain good compensation in this way, but the plan has not come into general favour. The method also invented by Le Roy and used by Berthoud, Arnold and Earnshaw and succeeding makers was to form the rims of the balance of bi-metallic strips of brass and steel, carrying weights at their ends. A rise of temperature causes these strips to bend and carry the weights inwards, thus reducing the moment of inertia of the balance. By suitably proportioning the strips and weights it is possible to make the reduced moment of inertia of the balance compensate for the reduced stiffness of the spring. Good compensation can be obtained by this method, but there still remains a small residual error, known as " middle temperature error." A chronometer fitted with a steel balance-spring and with the usual brass-and-steel compensation balance may be adjusted to keep accurate time at, say, 40° and 80° F., but it will gain some $1\frac{1}{2}$ seconds per day at a temperature of 60°, mid-way between the two, and it will lose at temperatures above 80° and below 40°. This error is due to a variety of causes, the most important being that the stiffness of the balance-spring does not vary quite uniformly with temperature ; there is, for instance, a slightly greater loss of stiffness between 60° and 80° than between 40° and 60°. To obtain perfect compensation it is evidently necessary to design a compensation balance whose moment of inertia varies with temperature according to a law similar to that of the variation of stiffness of the balance-spring, that is to say, the weights must be made to move inwards slightly more for a rise of temperature than they move outwards for an equal fall. Throughout the nineteenth century a great deal of ingenuity was displayed in designing " auxiliary " compensations to achieve this end. Most of them were " discontinuous," coming



Harrison's First Marine Timekeeper (1735).
(*See* text, p. 37.)

Harrison's Fourth Marine Timekeeper (1759).
(*See* text, pp. 37–38.)

PLATE XIV



Four Compensation Balances for Marine Chronometers.

(1) Modified Earnshaw Type. (2) With Poole's Auxiliary Compensation.

(3) Guillaume or "Integral" Balance. (4) Invar Balance with bi-metallic blades.

into action at a certain fixed temperature, and though fairly successful in practice, they were often complicated and difficult to construct.

Two simpler solutions have since been found as a result of the researches of Dr. Guillaume of Paris on the properties of the nickel-steel alloys. One of the early results of these researches was the discovery of the alloy termed " invar," whose expansion with change of temperature is practically negligible. In 1899 Guillaume prepared a special alloy to replace steel in the bi-metallic arms of a compensation balance, and chronometers employing this alloy were shown at the Paris exhibition in 1900. The alloy possessed an expansion coefficient which varied with temperature and its properties were such that, combined with brass, it caused the weights of the balance to move inwards more for a rise of temperature than they move outwards for an equal fall, which is the effect desired. A balance employing this alloy (*see* Plate XIV) is termed a " Guillaume " or " integral " balance, and is able to compensate almost perfectly for the change in stiffness of a steel balance-spring with changing temperature.

A balance of this type has, however, a few remaining disadvantages. Firstly, since each of the arms of the balance is fixed at one end only, as the balance rotates the free end tends to swing outwards under the influence of " centrifugal force " and so to increase the moment of inertia of the balance. This effect is more marked the greater the arc of swing of the balance, as its peripheral velocity is then greater. The isochronism of the balance is therefore upset, larger arcs of swing occupying a longer period than short ones. Secondly, the steel balance-spring is liable to disturbance from magnetic effects. Both of these troubles are eliminated by a second method due to Guillaume. About 1920 he was able to produce an alloy whose elasticity was practically independent of change of temperature, and which was, in addition, non-magnetic. This alloy was composed mainly of nickel and steel, with the addition of chromium and other elements and was termed " elinvar." By making the balance-spring of elinvar magnetic disturbances are entirely eliminated, and the disturbing effect of temperature changes is removed at its source, so that a plain uncut brass balance-wheel can be employed. Chronometers with elinvar balance-springs were introduced by the Swiss maker Ditisheim in 1920, while in a modified type (*see* Plate XIV), introduced by Ditisheim about 1923, the balance was fitted with a small pair of bi-metallic blades in order to compensate for small residual effects, but these blades were so short and therefore stiff that the effect of centrifugal force on them was negligible. The compensation attained in this way was so good that the very small disturbing effect due to change of barometric pressure now became just noticeable, and in order to reduce this effect the blades were countersunk in the wheel so as to reduce air resistance as far as possible.

The various methods of temperature compensation described above are of course applicable to high-grade watches as well as to chronometers, but are usually too expensive to be employed in cheaper watches. The use of elinvar balance-springs is now, however, becoming very widespread, especially in Swiss watches.

VII. JAPANESE CLOCKS

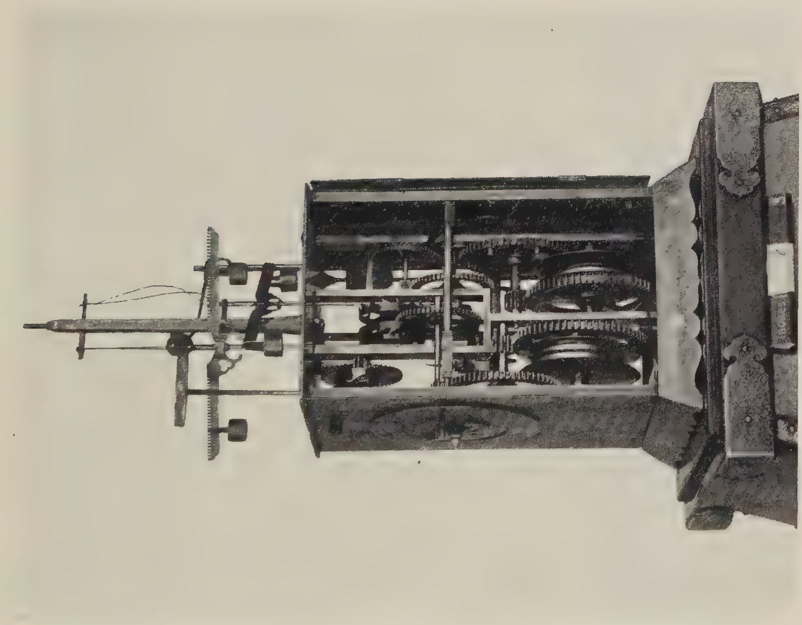
The clocks of Japan are of special interest and require separate description, since their development has followed a trend entirely different from that of the clocks of Western Europe. Japan had been discovered by the Portuguese navigators about 1550, and from 1600 onwards Dutch traders were in regular contact with the Japanese. It is very probable that clocks were first taken to Japan by the Dutch; they were " lantern " clocks controlled by a verge and foliot, and the first clocks made in Japan were probably copied very closely from them. Japanese clocks subsequently failed entirely to keep pace with the improvements in European clocks. The balance-spring was introduced and widely used, and so was the small " bob " pendulum, but the verge escapement remained in universal use. It was not until Japan began to throw herself open to Western influences and civilization in 1866 that clocks of modern type began to be made in Japan.

Whereas in Europe time reckoning by equal hours was introduced shortly after the introduction of mechanical clocks, in Japan " temporal " hours continued in use until as late as 1873, and so it was necessary to adapt mechanical clocks to indicate temporal hours. It appears to have been customary to count a considerable period of twilight at each end of the day as belonging to the day, so that in midwinter in the latitude of Japan (35° N.) " day " and " night " were, on this reckoning, of equal length, while at midsummer the day was some $2\frac{1}{3}$ times as long as the night; day and night " hours " were therefore of equal length in midwinter, but in midsummer a day hour was $2\frac{1}{3}$ times as long as a night hour. " Day " and " Night " were divided each into six hour-intervals.

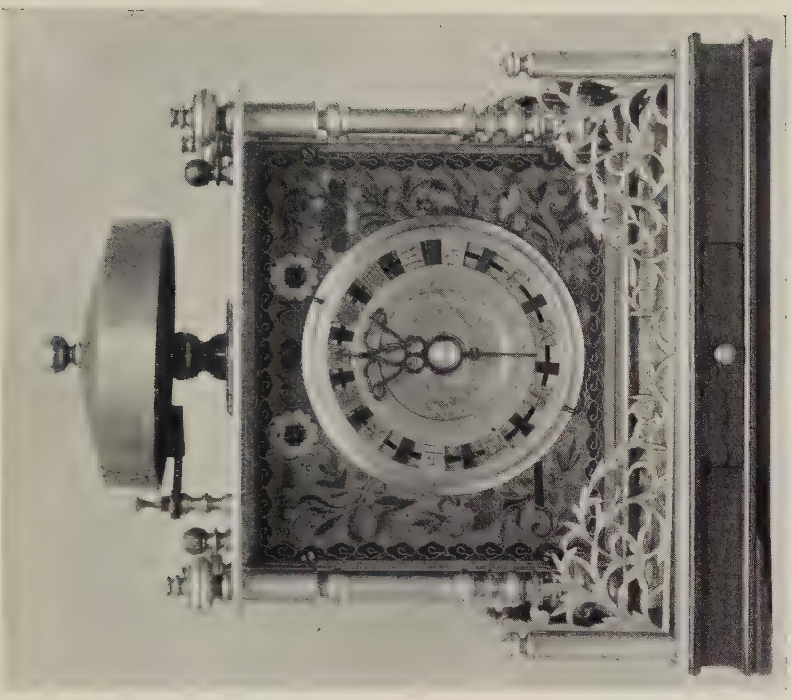
Adopting the late Mr. J. Drummond Robertson's classification, Japanese clocks can be divided into three main types which he terms " lantern," " bracket " and " pillar " clocks. The first two types bear a general resemblance to their European prototypes, but the third is peculiar to Japan.

Lantern clocks, the oldest type (*see* Plate XV), were usually weight-driven and mounted on a stand one to two feet high. Their rate was controlled by a verge and foliot balance, and time was indicated by a hand moving over a twelve-hours dial. With this type of clock it must have been necessary to adjust the weights of the foliot each morning and evening, to allow for the different lengths of day and night hours, but in order to overcome this difficulty many of the later clocks of this type were made with two escapements, each complete with crown-wheel, verge and foliot, and mounted side by side. One escapement was in use during the day and the other, vibrating more rapidly, during the night, the change-over being automatic and effected by the striking mechanism. The only adjustments then necessary

PLATE XV

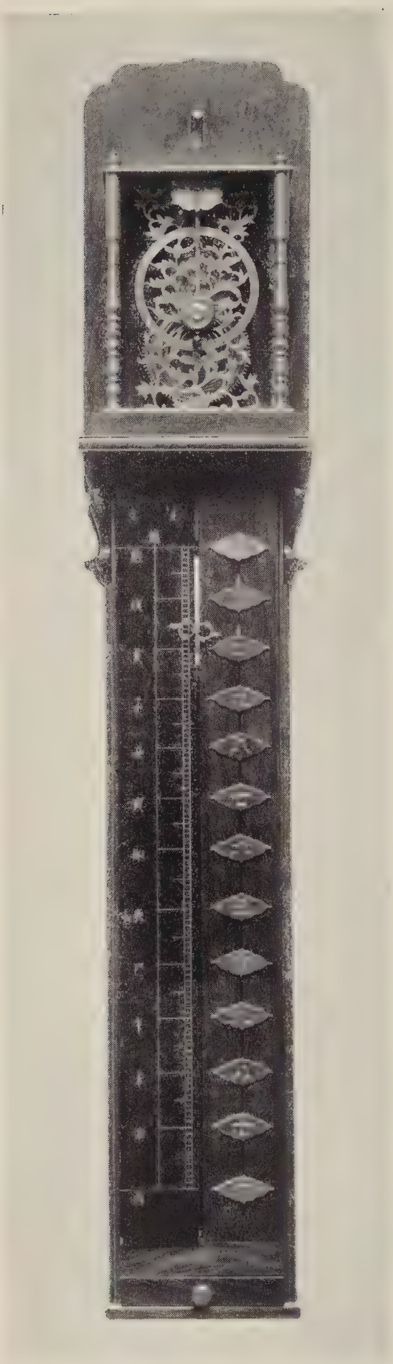


Japanese Lantern Clock.
Of the two foliot balances, one is in use during the day, the other during the night.



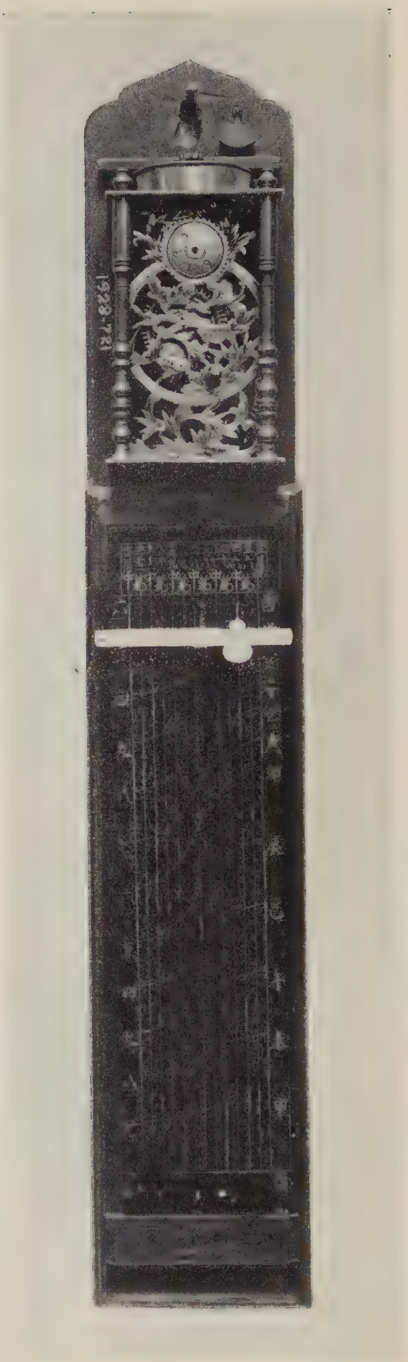
Japanese Bracket Clock, Spring-driven, with "bob" Pendulum.
The "hour" marks are adjustable.

PLATE XVI



Japanese Pillar Clock, Weight-driven, with " bob " Pendulum.

The " hour " marks are adjustable, and a separate graduated scale is provided for each pair of months.



Japanese Pillar Clock, Weight-driven, with Balance and Spring.

The time-scales for all the months are combined on a single plate, and the hour indicator is adjustable horizontally to bring it over the correct scale.

were to move the weights of each foliot as the seasons changed ; this operation would be carried out, probably by a clockmaker, about once a fortnight.

In the spring-driven "bracket" type of clock (*see* Plate XV) which Mr. Drummond Robertson considered to have been a later development, introduced about 1830, the rate is usually controlled by a balance-wheel and spring. With this mechanism there was no possibility of varying the rate by day and by night, and so the variation had to be introduced in the method of indicating the time. Instead of the usual rotating hand a fixed pointer and a rotating dial were employed, and each hour mark was mounted on a small plate sliding in a grooved ring in the dial. These plates could then be adjusted according to the season ; they would be equally spaced round the dial in midwinter, but in midsummer they would be in two groups—a close group of six for the short night hours and a widely spaced group of six for the longer day hours.

In the third or "pillar" type of clock (*see* Plate XVI) the hours were indicated by a pointer attached to the driving weight and moving over a vertical scale as the weight slowly descended. A set of scales was supplied for a single clock, each scale being suitable for use in one particular month of the year. In a variant of this type the scales for all the months were marked upon a single plate and the pointer was adjustable so as to move over the appropriate scale at any given season.

Many Japanese clocks are fitted with striking mechanism of the count-wheel type, but the count-wheel is cut in a different way from that employed in Europe, in consequence of the different Japanese method of counting the hours. Their hours, from midday to midnight, were numbered 9, 8, 7, 6, 5, 4 respectively and again the same from midnight to midday. At the half-hours following odd hours a single stroke was sounded, and at the alternate ones two strokes. The count-wheel of a Japanese striking clock was therefore normally cut to give successively 9, 1, 8, 2, 7, 1, etc., strokes.

Japanese clocks appear to have been individual productions, and can never have been very widely used, as their price must have been high, and the earlier types may have required the services of a skilled clockmaker to adjust them every fortnight. With the introduction of European time-reckoning in 1873 clocks of modern type began to be made, and the first factory was set up in 1875.

VIII. ELECTRIC CLOCKS

One of the most valuable properties of electricity is the ease with which it can be used to transmit effects to a distance. It is possible, for instance, to operate a telegraph receiver, to heat a room, or to drive an electric train, by means of electric power generated in a power station situated many miles away, and in the same way it is possible to control the hands of a clock from a so-called " master " clock which may also be at a considerable distance away. A single accurate clock can thus be made to contol and synchronise a large number of distant clocks so that all can be made to keep time together. Synchronised systems such as these are of great value as they enable a uniform time system, controlled from a single accurate clock, to be distributed over a whole building or factory or even over a whole railway system.

Various methods of distant control have been used. In some of the earliest ones currents were sent out from a master clock every second, and the pendulums of the subsidiary clocks were kept swinging in unison with that of the master clock. In a method which has been much more widely adopted the master clock sends out a pulse of current every minute or half-minute, which energises the electro-magnet of each distant " impulse dial " and so moves its hands through the space of one minute or half a minute. In other systems the subsidiary clocks are independent mechanical clocks whose hands are automatically set right every hour by a current pulse transmitted from the master clock. In a still further method of synchronisation, which is now developing rapidly, the subsidiary clocks are driven by alternating current from the mains, the frequency of which is carefully controlled so that the clocks keep correct time.

It is also possible to employ the forces due to electric currents to supply the power necessary to drive a clock. The electro-magnetic forces may be applied direct to the pendulum, or they may be used to restore the gravity arm of a gravity escapement after the arm has given its impulse to the pendulum, or the driving weight or spring of an ordinary escapement clock may be re-wound at intervals by some form of electric motor.

The development of electric clocks.—During the second half of the eighteenth century various inventors had tried to make use of electricity for signalling at a distance by making use of electro-static effects, but the results achieved were of little practical value. Volta's invention of the voltaic cell in 1800 and Oersted's discovery in 1820 of the magnetic effect of an electric current, however, opened up a vast new field, and progress in the knowledge of electro-magnetic phenomena and in their practical applications became rapid. The first commercial electric telegraph in Great Britain was introduced by Wheatstone and Cooke in 1838–9 and it was soon realised by Wheatstone and others that by means of electric currents a " master " clock could be made to transmit synchronising signals to a number of distant clocks.

In 1840 Alexander Bain patented a number of methods of controlling distant clocks from a central " master " clock by means of currents sent out every second, every minute or every hour, and also methods of maintaining a pendulum in vibration by means of electromagnetic forces. He proposed to make the necessary electric contacts by means of an arm mounted on the pendulum or by means of a commutator mounted on the same spindle as the escape wheel.

Though Bain was the pioneer in pointing out the various ways in which electricity could be employed in horology, his systems did not achieve commercial success, the principal cause of failure being the inefficiency of the electric contact.

Wheatstone, also in 1840, described and exhibited at the Royal Society an electric clock in which a commutator was mounted on the same spindle as the escape wheel ; a brush on this commutator made a contact every second and transmitted a current to the secondary clocks. This system was not successful, again principally on account of the precarious nature of the contact. The great difficulty encountered in all systems in which the contact is made in this general manner, or directly from the pendulum, is that if the electrical contact is to be a certain and reliable one, the pressure to be applied to it must be so great as to be liable to stop the clock and in any case to interfere seriously with its timekeeping. Wheatstone tried to overcome this difficulty by employing an electrical circuit which was always closed. He took an ordinary mechanical clock but used as a pendulum bob a magnetised steel bar vibrating within a coil. The moving magnet induced in the coil a current which was transmitted to the impulse dials. The pendulum thus behaved as a dynamo yielding alternating-current of frequency one * per second, and the impulse dials were effectively synchronous motors driven by this current. This system, though it eliminated the trouble due to faulty contacts, was bad from the timekeeping point of view, as the interference with the free motion of the pendulum was very great. It was tried for a time in London University and in the Royal Institution about 1870, but was soon abandoned.

In 1842 an ingenious way of driving a pendulum by an electromagnet was invented by Hipp of Neuchâtel. His method was to allow the pendulum to make an electrical contact and so help itself to an impulse whenever the arc of swing fell below a given definite value. The advantages of this arrangement are that the impulses can be given sharply at the mid-point of the pendulum's swing, the pendulum swings freely in between impulses, and its arc of swing is kept very nearly constant and independent of the voltage of the driving battery. When the battery is new the impulses will be strong and therefore infrequent, while with a failing battery the impulses will be weaker and more frequent.

Between 1850 and 1885 various systems of distant control were tried. In 1857 R. L. Jones, the stationmaster at Chester, adopted a

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* In the case of a pendulum beating half-seconds.

system in which the pendulums of a number of ordinary mechanical clocks were made to swing in unison with that of a master clock by means of currents sent out every second. The system was further developed by Messrs. Ritchie of Edinburgh, who dispensed with the independent drive of the subsidiary clocks, making the seconds impulses perform the propulsion as well as the synchronisation.

A method of forcibly correcting the hands of a clock every hour by means of an electrical signal was proposed by Bain in 1840. Systems of this type were put into practical use by the Standard Time Company of London in 1874 and by Messrs. Ritchie of Edinburgh in 1876, while a method patented by Lund in 1876 was employed on the Victorian railways in 1892. Some of the Underground Railways of London have for many years employed a similar system, the individual clocks being electrically wound and being corrected every hour by a time-signal transmitted from a central master clock, while, as described later in this chapter, the International Time Recording Company transmit an hourly set of " supervising " signals to their minute impulse dials.

A synchronised system which has been very widely used is that in which a master clock makes an electrical contact every minute or every half-minute and closes a circuit containing the electro-magnets of all the subsidiary " impulse dials." These electro-magnets then operate and move the hands of their respective dials through the space of one minute or of half a minute. This system is particularly suitable for use in factories and institutions, where a dial movement can be installed in each room without great expense.

A system of this type must be thoroughly reliable if it is to be of value and many of the earlier systems failed on account of unreliability. The chief difficulty encountered is that of securing a reliable electrical contact from the master clock without interfering with its accurate timekeeping. If the contact is not reliable, then either on occasions it may fail altogether, so that the impulse dials will miss an " impulse " and so be late, or the contact surfaces may " chatter " and each impulse may consist of several small bursts of current, each of which is recorded by the dials as a separate impulse, so that the dials will be fast.

In 1860 Hipp introduced a system in which the effects of uncertain contacts were to some extent eliminated. His master clock transmitted a current each minute, successive currents being in opposite directions, and the permanently magnetised armature of the dial movement was made to swing alternately from one pole to the other of an electro-magnet. With this design, an impulse consisting of several small bursts of current will be recorded as only a single impulse, since all are in the same direction. Following Hipp, polarised movements of this general type came into considerable use on the Continent.

In 1895 a form of master clock giving reliable uni-directional half-minute impulses was patented by Hope-Jones and Bowell. In this pioneer " Synchronome " clock the force which pressed the contacts together was not derived from the pendulum or wheelwork, as in the majority of earlier master clocks, but was supplied by an electro-magnet in the act of restoring a gravity arm which drove the clock mechanism. The power necessary to maintain the vibrations of the pendulum was thus mechanically transmitted through the surfaces of the electric contact. The method ensures a decisive "make" of contact, a firm pressure throughout its duration, and a sharp "break," so that a single well-defined current impulse is sent out to the dials. The timekeeping of the pendulum is not affected by the contact-making process, and the contact itself is of brief duration, thus ensuring long life to the dry battery used as a source of electric power. The same method of contact-making is still employed with success in the modern "Synchronome" and "Pulsynetic" systems, though in these, as described later in this chapter, the gravity arm gives its impulse directly to the pendulum and the escapement and clock mechanism are abolished.

In the system of the International Time Recording Company a contact is made every minute by means of levers falling off cams which rotate with the escape wheel of a mechanical clock, while in addition the clock sends out every hour an extra series of impulses which check or "supervise" the accuracy of the secondary instruments, stepping up any which may have missed an impulse, while those which for any reason may have got ahead are held back. It is not anticipated that this "supervising" action will often be necessary, but it serves as an additional hourly check on the accuracy of the controlled instruments. The contacts on the master clock do not deal with the current required for the whole system, but are connected with the coil of a relay, the full current for operating the secondary instruments being dealt with by the relay contacts. The system is intended to be operated from the electric mains supply.

Among other modern systems in use in Britain are those of the Silent Electric Company, in which a master clock of Hipp type actuates rotary dial movements, and the "Magneta" system in which a small generator is mechanically released every minute and transmits a small pulse of current to the dials, the electrical circuit remaining permanently closed.

In the foregoing part of this chapter emphasis has been laid chiefly upon the usefulness of electricity for the synchronisation of clocks, since this is its most characteristic contribution to horology. The use of electricity for propulsion has, however, an importance of its own. As described at the beginning of the chapter, the electro-magnetic forces may be applied to the pendulum, to restore the gravity arm of a gravity escapement or to re-wind the driving weight or spring of an escapement clock.

Independent clocks in which the electrical maintenance is applied directly to the pendulum have found no special sphere of usefulness, though they are in use to a certain extent as domestic clocks.

The application of electro-magnets to gravity escapements has, however, been of great value, as it has removed many of the difficulties inherent in a purely mechanical gravity escapement.

Pioneer electric gravity escapements were designed by Shepherd in England in 1849 and by Froment in France in 1854, but these were little, if at all, better than their mechanical contemporaries and were not therefore widely used. More recently, however, electric gravity escapements have been introduced in which the impulses to the pendulum are made invariable in amount and are given at such relatively rare intervals and in such a manner as to interfere very little with the motion of the pendulum, which is thus nearly free. In the " Pulsynetic " and the modified " Synchronome " master clocks, both developed between 1904 and 1907, a light hook attached to the pendulum engages with the teeth of a light " count-wheel," turning it through the space of one tooth every two seconds and through a complete revolution every thirty seconds. Each revolution a gravity arm is released, imparts an impulse to the pendulum, and afterwards makes a firm electrical contact and is restored to its original position by an electro-magnet, the same current which energises this electro-magnet being transmitted to all the impulse dials, which are connected in series. Apart from the slight friction involved in turning the count-wheel, the pendulum swings freely in between impulses, and so the timekeeping is of a high order.

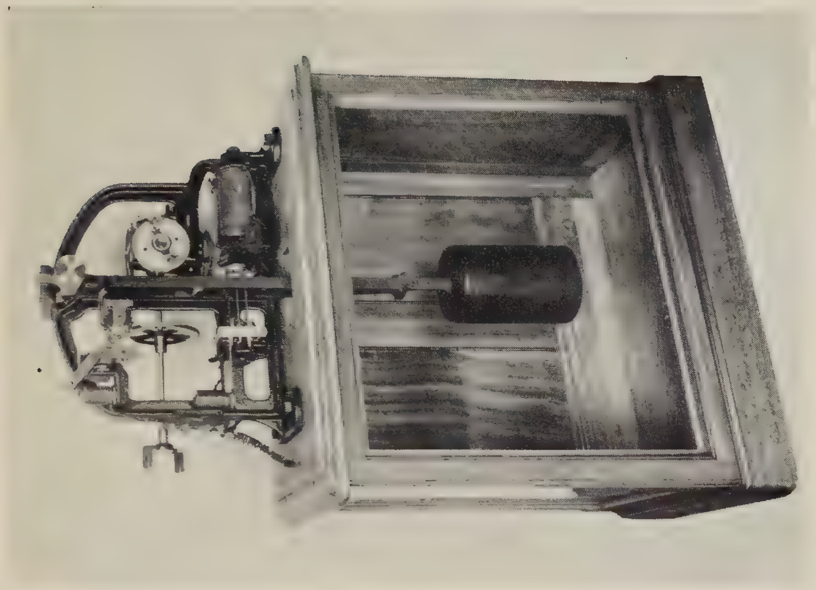
The Shortt clock (*see* Plate XVII), perfected in 1924 by W. H. Shortt, working in conjunction with F. Hope-Jones and the Synchronome Company, is a clock of similar type in which the free pendulum does not even have to turn the count-wheel, the operation being carried out by a subsidiary or " slave " clock. Every half minute the slave clock releases a light arm carrying a jewel which is allowed to fall upon a small wheel mounted on the free pendulum ; in rolling off this wheel it imparts a light impulse to the free pendulum and afterwards transmits a synchronising signal to the slave clock by means of Shortt's " hit-and-miss " synchroniser. The free pendulum therefore swings entirely freely except for the fraction of a second every half-minute during which it is receiving its impulse, while the impulse given is constant in amount and is given symmetrically about the mid-point of the swing. As described in Chapter IV, the daily variation of rate of a Shortt clock under the best conditions is only a few thousandths of a second—a variation of less than one part in ten million.

Mechanical clocks electrically wound at relatively long intervals (generally termed " self-wound clocks ") have a certain sphere of utility of their own, particularly for use with time-switches for street-lighting and for the control of industrial processes. Many different methods of winding have been invented, and it is impossible to give any adequate description of them here ; they are, however, well represented in the Museum collection. As already mentioned in Chapter IV, electrical winding is valuable for precision clocks, as it enables the pendulum to be mounted in an air-tight case, and so to be unaffected by variations of barometric pressure.

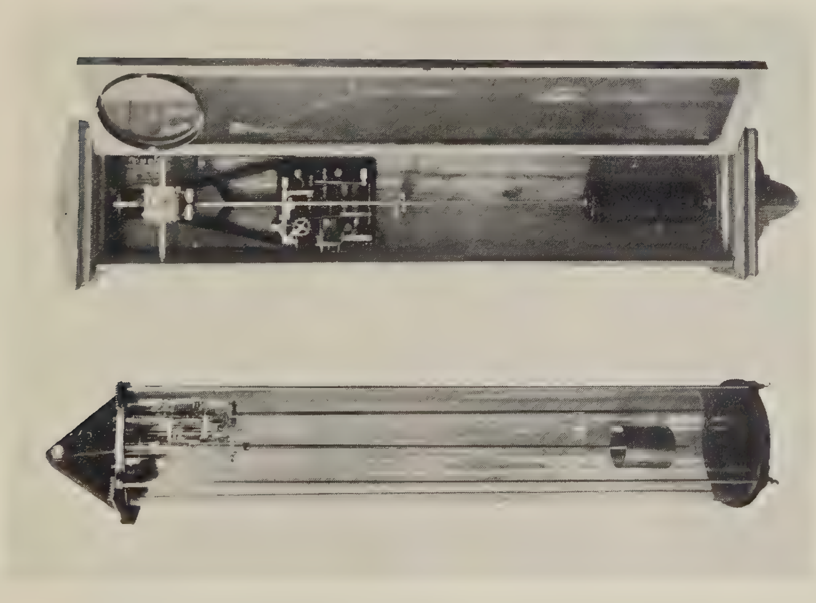
Turret clocks.—Electric drive and control can be applied with advantage to turret clocks. Perhaps the simplest application is the

[To face p. 48.

PLATE XVII



Gent " Waiting Train " Electric Turret Clock.
(*See* text, p. 49.)



Shortt-Synchronome Free Pendulum Clock (left) with Slave Clock (right). (The free pendulum is mounted in a special case for exhibition purposes).

PLATE XVIII

[By Courtesy of Messrs. T. & F. Mercer.

Mercer Marine Transmitter Control Unit and Panel for S.S. *Queen Mary*, controlling over 600 Clocks.

Everett Edgcumbe " Synclock " Synchronous Electric Timepiece.
(*See* text, p. 50.)

fitting of an electric motor to wind up the driving weight of a mechanical clock and thus to save the manual labour of winding, which in the case of a large clock is considerable. There are several ways of placing a mechanical turret clock under the control of an accurate electrical master clock. A synchronising device can be fitted to the pendulum, thus keeping it swinging always in unison with that of the master clock, or the pendulum and escapement can be removed and replaced by an electrical escapement, released every half minute by a signal from the master clock. Turret clocks are also constructed (*see* Plate XVII) in which both drive and control are electrical, while even the striking and chiming mechanism can be electrically operated. Synchronous motor turret clocks are also made, similar in principle to the synchronous domestic clocks described later in this chapter.

Marine clock systems.—Systems of electric clocks under unified control are particularly useful on ocean-going liners, in which " ship's time " has to be changed daily to allow for the ship's change of longitude. If the ship is equipped with a number of independent mechanical clocks each one of these must be altered individually, but with a unified electric system the alteration can be carried out by means of a single operation at a central control cabinet. Marine electric clock systems are therefore fitted with special arrangements by means of which all the dials of the system can readily be advanced or retarded together (*see* Plate XVIII).

Synchronous motor clocks.—Of recent years an entirely new method of electrical control of distant clocks has come into general use. This method is to drive the clock hands through suitable reduction gearing by a synchronous motor connected to an alternating-current electric supply. All clocks of this type connected to the same supply will, if initially set right and fed with uninterrupted current, show the *same* time, and if the frequency of the supply is kept carefully constant at a predetermined value, the clocks will all show *accurate* time. The system can then be regarded as a synchronised one in which the synchronising impulses arrive at twice the frequency of the alternating-current supply, *i.e.* 100 times per second with a 50-cycle supply. The system has become a practical proposition only in recent years, with the spread of the " grid " system of distributing electric power. With this system of interlinked power-stations it is necessary for each individual station to keep the frequency of its supply closely constant, and it thus becomes worth while to utilise this constancy for time-keeping purposes.

The use of alternating-current mains in this way for distributing time was suggested by Hope-Jones in 1895, but until 1916 there was no commercial system in which the speed of the generators was regulated with sufficient accuracy. In that year, however, Warren in the United States brought out a small synchronous motor of very low power consumption suitable for driving a timekeeping mechanism and also produced a frequency meter which could be installed in power-stations to enable them to control the frequency of the supply with sufficient accuracy. Meters of this type were installed in several power stations in the United States in 1916; these stations forthwith began to keep a careful control of their frequency, and synchronous electric clocks were put on the market. The subsequent development was rapid and by 1932 it was estimated that over 90 per cent. of electricity consumers in the United States were supplied with time-controlled current, while more than a million synchronous motor clocks were sold in the single year 1930.

In Great Britain the North Metropolitan Electric Power Company installed a frequency meter at their Willesden power station in 1922 and began to control the frequency of their supply for timekeeping purposes, Kettering followed suit in 1927, while in 1929 the London Power Company began to control their very large system. Very few synchronous clocks were used in this country, however, until 1927, when the " Synclock," operating under Warren patents, was placed on the market by Everett, Edgcumbe & Co. (*see* Plate XVIII). A few years afterwards several other firms began to manufacture synchronous clocks in this country, and by June, 1932, half the power stations in the country were time-controlled, while in February, 1935, it was estimated that over three million households in Great Britain were supplied with time-controlled A.C., and the number was stated to be increasing at the rate of half a million per year.

Synchronous motor clocks are well suited for ordinary domestic use, as they are almost silent, they require no winding or other attention, they are robust, and their consumption of current is almost negligibly small. Time-controlled power stations now control their frequency so carefully that synchronous clocks connected to the supply are kept within a few seconds of Greenwich time.

Synchronous clocks are of two main types—self-starting and hand-starting. Any short interruption of the supply of current will cause a self-starting clock to be slow subsequently by an amount equal to the duration of the stoppage. In order to prevent the possibility of mistakes due to false indications of this sort, self-starting clocks are fitted with a small indicator which shows if there has been any interruption of current since the indicator was last set: clocks of the hand-starting type require no such indicator, since any interruption of the supply stops them altogether.

In a normal district current stoppages are extremely rare, but for use in districts in which the supply is peculiarly liable to interruption special clocks are made. These are of various types, but usually consist of some combination of an escapement clock and a synchronous motor in which the escapement is brought into action upon a failure of current, or in which the escapement clock is continuously in action, being corrected at intervals by the synchronous motor.

IX. CHRONOGRAPHS

Chronographs are instruments intended for measuring short intervals of time of the order of a few minutes, a few seconds or even a fraction of a second. They are used for timing races, for measuring the velocity of projectiles at different points of their path, for sound-ranging and echo-sounding, in which distances are measured by the time taken by sound to traverse them, in the measurement of human "reaction times" in physiological and psychological research, for finding the exact times of transit of stars across the meridian, and in a great variety of physical experiments.

It is of course possible to measure a relatively long interval of time with an ordinary clock or watch by reading off from the dial the times of the beginning and end of the interval and subtracting one from the other. Intervals measured in this way are, however, liable to be in error by a second or more, as it is not possible to observe the event and the clock dial simultaneously. If accuracy to within a fraction of a second is required some means must therefore be found for recording the beginning and end of the interval by hand, so that the observer's eyes can concentrate on the event, as in timing an athletic race with a stop-watch. If still higher accuracy is required the personal element with its associated uncertainty can be eliminated by carrying out the recording entirely automatically by means of electric signals, as in timing a motor-race, where the wheels of the car operate an electric contact, or as in sound-ranging, where the sound is picked up by a microphone and converted into an electric current which operates the recording apparatus.

Stop-watches and pocket chronographs.—The earliest method employed for the measurement of short intervals of time was to start and stop by hand all or part of an ordinary train of clockwork. The earliest stop-watches of the eighteenth century were ordinary watches which could be stopped at will by means of a device which pressed a small arm against one of the more rapidly moving wheels or against the balance itself or its roller. A considerable error is introduced in starting and stopping the watch in this way and later stop-watches were fitted with an independent centre-seconds hand which could be started and stopped without interfering with the main train of wheels and the balance. Still later, mechanism was fitted by means of which successive pressures on a button caused the hand to start, stop and fly back to zero. A watch fitted with this type of mechanism is often termed a "pocket chronograph." With a balance-wheel vibrating at the normal rate of 5 times per second, it is capable of measuring intervals of time to an accuracy of about one-fifth of a second, while special pocket chronographs are made in which the balance vibrates 30 times per second, and with which the accuracy attainable is approximately one-tenth of a second, being limited mainly by the human factor.

Chronoscopes.—The uncertainty due to the human element could be removed if the button of a stop-watch could be operated by means of an electro-magnet, controlled by an electrical signal transmitted from the event to be recorded, and this is effectively what is achieved in chronoscopes, in which a train of clockwork is kept in continuous motion while an indicating hand can be thrown into or out of gear with it by means of an electro-magnetic clutch. The first instrument of this type was designed by Wheatstone in 1840, and in 1842, in conjunction with South and Purday, he carried out some actual experiments at Campden Hill Observatory with a modified form of the instrument. The velocity of a ball fired from a pistol and the rate of a fall of a ball under gravity were measured, and Wheatstone suggested that the instrument could be used for measuring the velocity of sound in air, water or rock masses. He considered his chronoscope to be accurate to one-sixtieth of a second.

Some years later an improved form of chronoscope was invented by Matthäus Hipp of Neuchâtel. As in Wheatstone's instrument, the clockwork was kept continuously in motion, the indicating mechanism being thrown into or out of gear with it by means of a clutch operated by a pair of electro-magnets, but the rate of rotation of the escape wheel was controlled by a metal reed vibrating 1,000 times per second, equivalent to a balance-wheel oscillating 1,000 times per second. The rate of rotation of the clockwork was thus extremely uniform, and Hipp claimed that his instrument was accurate to $\frac{1}{1000}$ second.

A more modern form of chronoscope was introduced by Wood and Ford in 1919, in which the rate of rotation of the hand was electrically controlled by a tuning-fork. The fork was electrically maintained, and the electrical impulses derived from it were fed into a " phonic motor " the armature of which rotated in exact synchronism with the impulses. Careful tests showed that the error in an individual measurement made with this instrument was less than $\frac{1}{1000}$ second, while if a series of measurements could be made, the probable error was reduced to about $\frac{1}{10000}$ second. The instrument was much quieter in action than Hipp's chronoscope, and was capable of running continuously for a practically unlimited period, whereas Hipp's weight-driven instrument required re-winding every five minutes.

Recording chronographs.—In these instruments the fixed dial and moving pointer of the chronoscope are replaced by a moving recording surface and a fixed recording pen, operated by hand or by an electro-magnet, which records a mark upon the surface at the beginning and end of the interval to be measured, while a second series of marks, giving a time-scale, are made, usually by a second pen operated by a standard timekeeper. The recording surface is usually a sheet of paper wound round a drum which rotates uniformly or a strip of paper unwound from a spool and drawn past the recording pens at a uniform speed by means of a pair of rollers, but in special types of chronograph the record may be made on light-sensitive bromide paper by means of a spot of light focused upon it. The pen which marks the time-scale is usually operated once a second by means of electrical signals transmitted from a clock, but sometimes a recording stylus is fixed to one prong of a tuning-fork vibrating, say, 50 times per second and thus giving a time-scale graduated in fiftieths of a second; with optical recording the light may be wholly or partially interrupted every second or more frequently.

The use of a rotating drum for measuring short intervals of time appears to have been first suggested by Thomas Young in 1807. He proposed to drive the drum by means of a suspended weight, the rate of revolution being controlled by a form of centrifugal governor. The drum was to be covered with paper or wax upon which a pencil or strip of metal was gently pressed and could be deflected by hand at the required instant. Young proposed to mark out a time-scale upon the record by means of a style fitted to a vibrating body.

The next step in the development of the recording chronograph was to actuate the recording pen by means of a small electro-magnet instead of by hand as in Young's instrument. The credit for the invention of the electro-magnetic chronograph was claimed both by Wheatstone in England and by L. F. C. Breguet (grandson of the famous A. L. Breguet) in France. In 1845 Breguet published an account of an instrument which he had constructed a year previously, whereupon Wheatstone claimed that he had previously designed an instrument of this type, similar in many respects to Young's apparatus, but recording by means of an electro-magnet instead of by hand.

Both Wheatstone's and Breguet's instruments were intended mainly for use in investigating the motion of projectiles in flight. In investigations of this kind the projectile is usually caused to make or break a series of electrical contacts at various points of its path, and to record these electrical changes on the chronograph. By thus measuring the intervals of time taken by the projectile to pass from one point to the next, the way in which its velocity varies with its distance from the gun can be ascertained. The intervals to be measured are only fractions of a second, and hence in order to obtain accurate results for the velocity the chronograph must be able to measure the intervals to an accuracy of $\frac{1}{100}$ or preferably $\frac{1}{1000}$ second.

Siemens was at work on this problem in Germany, and after a long series of experiments with chronoscopes he constructed in 1845 a drum chronograph in which the recording was carried out by an electric spark. The ball from the gun was made to close a circuit and discharge a Leyden jar, the spark passing from a fine metal point to the polished steel drum of the chronograph, where it produced a faint discoloration. All mechanical moving pens with their possibilities of friction and lag were thus eliminated. A disadvantage of the method was, however, that measurements could be carried out only close to the gun, as it was impossible to use long electrical leads owing to insulation difficulties. The rotation of the drum in Siemens' instrument was controlled by a conical pendulum.

The first chronograph which appears to have fulfilled adequately the requirements of artillerymen was one constructed by the Rev. F. Bashforth in 1865. He departed from previous practice by making no attempt to drive the drum at a uniform rate ; instead of this he fitted it with a heavy flywheel and allowed it to rotate freely while the measurements were being recorded.

Chronographs were first used by astronomers for recording the transits of stars at Washington Observatory in 1849. The records were made either upon a moving strip or "tape" of paper, as in a Morse telegraph, or upon a rotating drum, and marks were made every second by means of an electrical contact system on an accurate clock. The recording method was introduced at Greenwich a few years afterwards by Airy, who in 1856 installed a large chronograph employing a conical pendulum to drive the drum uniformly. Astronomers had previously timed their transits by listening to the beats of a clock and estimating by ear the fractional part of a second.

Drum and tape chronographs similar in essentials to the early ones described above are still used for a great variety of purposes. Considerable development has, however, taken place in instruments for the measurement of very small time-intervals to the highest accuracy. Measurements of this kind are possible only if the events whose durations are to be measured are electrical in nature, or can be translated into variations of electric current or voltage, as, for instance, in sound-ranging, where a microphone is used to receive the sound and convert it into a current change.

The two principal problems to be solved in constructing an accurate chronograph are, firstly, to ensure the accuracy of the time-scale marked upon the record, and secondly, to reduce the lag, or rather any variation in the lag, between the occurrence of the event and the response of the recording pen.

To obtain an accurate time-scale either the motion of the recording surface must be kept very uniform or a fine scale of time must be marked on the record by means of a tuning-fork or other vibrator. Approximately uniform motion can be obtained by the use of a centrifugal governor as in Wheatstone's and Breguet's instruments, by means of a conical pendulum as used by Siemens and by Airy, or by the use of an electrically driven " phonic motor " whose speed is controlled by the vibrations of an electrically maintained tuning-fork.

In all the earlier chronographs described above (with the exception of the Siemens spark chronograph) the recording was carried out by means of some kind of pen attached to the armature of an electromagnet, the record itself being made either in the form of an ink trace upon paper, a fine scratched line upon a smoked surface, or a series of fine holes pricked in the paper. These methods have the disadvantage that friction, variable in amount, occurs at two points—the bearings of the armature and the point of contact of the pen with the paper. The first source of friction can be removed by replacing the electro-magnet and armature by an oscillograph in which pivots are eliminated, while by employing photographic recording the second source of friction is removed and the moment of inertia of the moving system can be greatly reduced, with a corresponding increase in the speed of response.

Kelvin's syphon recorder, introduced in 1867, was a pioneer moving-coil galvanometer intended for recording Morse messages transmitted through the Atlantic telegraph cable, but it has also been used for chronographic purposes.

Oscillographs designed for photographic recording by means of light reflected from a mirror were first constructed by Blondel in France in 1893 and by Duddell in England in 1897, while the string galvanometer—an oscillograph of very rapid response, in which the moving shadow of the fibre or " string " is photographed—was invented by Einthoven in 1903. All these types of oscillograph have since been widely used as chronographs. Telephone receivers and loud-speakers units can also be adapted for use as chronographs by fitting them with a writing style or a small mirror for photographic recording. Oscillographs of the types just described are capable of responding in a time of a few thousandths of a second.

For the measurement of small intervals of time to a higher accuracy than this, as in the determination of the height of the reflecting layers in radio research, recourse must be had to the cathode ray oscillograph, in which there are no mechanical moving parts, the recording being carried out by a beam of electrons deflected electrostatically by means of a pair of plates and afterwards impinging upon a fluorescent screen or photographic plate. The time-scale is supplied electrically by means of a second pair of plates deflecting the electron beam in a direction at right angles to the direction of the deflection to be recorded. The normal type of cathode-ray oscillograph with an accelerating voltage of a few hundred volts can be used for the study of electrical phenomena whose total duration is less than $\frac{1}{10000}$ second, while a high-voltage oscillograph with an accelerating voltage of some 50 kilovolts is capable of recording electrical changes taking place in less than $\frac{1}{100.000.000}$ second, provided that the voltage available is great enough to deflect the electron beam sufficiently.

X. ALARM, STRIKING AND REPEATING MECHANISMS, TIME RECORDERS AND TIME SWITCHES

These are all accessory mechanisms which can be fitted to a timekeeper in order to enable it to perform other functions in addition to or instead of indicating the time of day upon a dial. Alarms, striking mechanisms and time switches are devices which are released by a timekeeper at a pre-set hour, while repeating mechanisms and time-recorders enable the time of day at any instant to be recorded either audibly or by means of a printed record respectively.

Alarm and striking mechanisms are both of considerable antiquity and may even have been fitted to the elaborate water-clocks which preceded mechanical clocks. The first mechanical clocks were, in fact, intended to sound an alarm and to strike rather than to indicate the hour upon a dial. The Milan clock of 1335 is known from contemporary descriptions to have been a striking clock, while the Wells clock of about 1392 possesses a quarter-chiming mechanism in addition to its hour-striking mechanism, though this may possibly be a later addition. The striking mechanism of these early clocks was of the count-wheel type, and proved so well fitted for its purpose that this mechanism with only slight modifications is in use to this day, though in domestic clocks it has been generally supplanted by the rack mechanism invented by the Rev. E. Barlow in 1676. The earliest Nuremberg watches were fitted with alarms, and some of the later ones possessed striking mechanism in addition.

Repeating mechanism enables the time of day to be ascertained by ear instead of eye and so enables the time to be found in the dark. It was first made possible by the invention of rack-striking mechanism, in which the hour struck depends solely upon the position of the hands. Repeating mechanism appears to have been first applied to clocks by Barlow in 1676, but its application to watches appears to have been made independently by Barlow and by Quare, a well-known London watchmaker, about ten years later. The watches employing Barlow's invention were actually made by Tompion. These pioneer repeaters sounded the hours and quarters. During the next hundred years small improvements were continually being made in repeating work; these were mainly devices to prevent any possibility of the wrong hour and quarter being sounded. The sounds were at first struck upon a bell, but this was a somewhat bulky object to incorporate in a watch and was later replaced by a wire gong, an invention due to A. L. Breguet in 1789; some watches were also made in which the blows were struck upon the case of the watch itself.

Clocks with repeating mechanism sounding minutes were constructed early in the eighteenth century, but no watches with minute-repeating work are known earlier than the nineteenth century.

Time switches can be only briefly described here. They are special forms of switches, operated automatically by a timekeeper, and are very widely used nowadays for switching street-lamps on at dusk and off at dawn, for controlling the lights of buoys at sea in a similar manner, for switching on and off shop-window and other display lights at pre-determined times, for ringing factory sirens and school bells, and for the control of a great variety of industrial processes.

The first use of time switches for controlling street-lamps was at Bournemouth in 1897, and they are now very generally employed for both gas and electric lamps. The early models required daily winding, but eight-day movements were soon fitted, and many movements are now electrically wound. The earlier street-lamp switches required setting according to the season of the year, but some of the more modern ones are fitted with special " solar " dials, by means of which the time of switching on and off is automatically varied to follow the varying times of sunset and sunrise throughout the year. The only attention which the modern switches require is therefore an occasional check on the accuracy of the clock, and this can be carried out each time the lamp is cleaned.

Time recorders are instruments which record automatically the time of day at which a certain event takes place. They are most widely used for registering the time of arrival and departure of employees, but they can also be utilised for a variety of purposes, such as to record the times at which trams or omnibuses pass a definite point on their route, to check the rounds of a night-watchman, or to register the times at which a safe, strong-room or shop is locked or unlocked. In general, time recorders embody a clock mechanism which rotates a set of type wheels, together with some device whereby at any given instant the type wheels can be made to print upon a card or sheet of paper, thus recording visibly the time (usually to the nearest minute) at which the printing operation was performed.

The earliest time recorders were the watchmen's " tell-tale " clocks, invented by Whitehurst of Derby about 1750. In these clocks a wheel rotating with the hour hand carried a number of pins, which passed in turn beneath a striker. A blow on the striker caused the pin beneath it at that moment to be driven inwards. A visible record of the times at which the striker had been struck was thus given by the positions of the pins which had been driven inwards.

The first recorder to print a record in actual figures was invented by Bundy in the U.S.A. in 1885. This recorder was intended for checking the times of arrival and departure of employees, and was operated by any one of a series of numbered keys, which, when inserted into the recorder and turned, printed upon a roll of paper the number of the key together with the time of the operation. In the earliest Bundy recorders the time was shown only to the nearest hour, but in later models minutes as well were recorded. A further improvement was to make the type wheels move sharply at the end of each minute and hour respectively : the continuous motion used at first led to some uncertainty in reading records made near the half minute.

In 1888 Dey of Aberdeen invented a " dial " time register in which the employees were recorded in their numerical order instead of in chronological order, while in 1894 Cooper in the U.S.A. developed the first time recorder to print records on cards, each employee having his own card.

The Bundy type of recorder is now almost obsolete, although many examples are still in use, particularly as traffic recorders on tramway and omnibus routes, but the dial and card types of recorders have been very considerably developed, and are now fitted with a great number of ingenious devices to prevent any kind of mistakes or misuse, and to facilitate the examination and analysis of the records.

The earlier time recorders were independent timekeeping units, but since in a large organisation it is essential that all the different recorders in use shall show the same time, many time recorders are now electrically synchronised. Recorders originally constructed as independent units can be synchronised by fitting their pendulums with a synchronising device, or the pendulum and escapement can be removed and an electrical escapement substituted. Many modern time recorders are specially designed for control by a central master clock, while models are also made which are fitted with synchronous motors and designed to operate from alternating-current mains in the same way as synchronous electric clocks.

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