PROCEEDINGS OF THE SOCIETY.

EIGHTEENTH ORDINARY MEETING.

WEDNESDAY, APRIL 9TH, 1924.

SIR FRANK DYSON, LL.D., F.R.S., Astronomer Royal, in the Chair.

THE SECRETARY said that Professor Vernon Boys, who was to have taken the Chair that night, was, unfortunately, unwell. The Society, however, had succeeded in securing the attendance of the Astronomer Royal, who had undertaken to fill the Chair at very short notice.

THE CHAIRMAN, in introducing the lecturer, said he was sure everybody would be extremely sorry at Professor Boys's absence. Professor Boys was the prince of experimenters. No one in the world was more capable of making beautiful and delicate experiments, and the audience, no doubt, would have liked to have his appreciation of Mr. Hope-Jones's clock. What Professor Boys would have had to say about it would have been of the greatest value and interest.

Personally, he was very pleased to take the Chair that night, although he might as well confess at once that his knowledge of the intricacies of clocks was very small. As an astronomer, however, he was much interested in the making of clocks, but he was afraid that he simply trusted to others to supply him with a clock, and then saw how it went. Astronomers had used clocks for 250 years. Up to that period they had got the time by observations of the altitudes of stars. Just before coming to the meeting he had looked up the record of Bradley's clock, and he had been very surprised to find how well it had gone. Its date was about 1755. It had gone between June 1st and August 31st with its rate changing only from a second to a second-and-a-half a day, and its rate changed from one day to another by about a tenth of a second. In recent times, a very great improvement in clocks had been made years ago by Riefler, but from what he had seen of the author's clock at Edinburgh, it seemed to be far ahead of Riefler's clock, and without more ado he would ask Mr. Hope-Jones to state how it had been done.

The paper read was :—

THE FREE PENDULUM.

By F. HOPE-JONES, M.I.E.E.

Exact measurement is the basis of scientific advance. The new Journal of Scientific Instruments recently established by various London Societies, has adopted this axiom as its watchword, and it is a truth which the Royal Society of Arts has always recognised. Last year's series of Cantor Lectures was devoted to precise measurements of length, and, whilst I can make no pretensions to such an exhaustive and brilliant treatise as that of Mr. Sears, the subject I am dealing with this evening is very closely akin to it, being the precise measurement of time.

Just 100 years ago Parliament made provision for restoring the standard yard, should it be lost or damaged, enacting that in this event a new standard should be made, bearing the same proportion to a pendulum beating seconds of Mean Time, in a vacuum at London and at sea level as 36 inches bears to 39.14 inches. Within ten years thereafter the Houses of Parliament were burnt down and the British standard destroyed, but the reference to the pendulum was found to be impracticable.

Thanks to the refinements of modern methods of measurement, we are able to satisfy ourselves that our national standards of length, when compared with one another from time to time, agree to within one part in two million, but that is no proof of their stability, as they may both be changing equally and imperceptibly. It is therefore highly desirable to find some "natural" or external standard as a basis of reference. Mr. Sears has put forward a proposal to refer his standards of length to the length of an Elinvar rod, which, when caused to vibrate longitudinally makes a definite number of vibrations per day. The success or failure of this method depends upon the continued constancy of the *modulus of elasticity* of the rod, its mass and its length.

If we look upon Mr. Sear's vibrating rod as a clock, it may be said that *ultimately* the constancy of its rate depends on the constancy of its *elasticity*, whereas the constancy of the rate of the ordinary pendulum clock *ultimately* depends on the constancy of the value of *gravity*. Which of the two has the higher order of constancy remains to be proved.

We, at any rate, are chiefly concerned with the type of clock which depends on gravity, and our efforts have been directed to eliminate the effect of the various subsidiary influences, and to make the timekeeping of our clock, as Professor Sampson, the Astronomer Royal of Scotland, has put it, "as steady as the length of a rod," and dependent only on gravity. As we have succeeded in measuring time for considerable periods to within 100th of a second per day, or one part in 8 million of the time measured, representing a change of length of one part in 4 million of a pendulum rod beating seconds, it would appear that we have reached the limit of accuracy *if so defined*, and if we can maintain such a constant rate indefinitely—a very different thing to doing it for a month or two.

It may be asked, how do we know that we have achieved this rate? There is no standard in existence with which you can compare your clock to such a degree of accuracy from day to day, but there is, of course an ultimate standard of time based upon the rotation of the earth, and ascertained by transit observations of fixed stars. The methods of observing them, however, are comparatively crude. The transit circle observations, with automatic or semi-automatic travelling cross wire, give only a coarse and approximate reading, compared with the way in which we now record the performances of clocks. At the Edinburgh Observatory the recording instruments comprise an oscillograph and a cinematograph film with continuous motion used as a chronograph, which easily enables the clocks in the Observatory to record their beats to an accuracy of 1/1000th of a second, and they are commonly so recorded every day.

You cannot use stellar observations for a day to day test. When two clocks keep together to within 1/100th of a second for considerable periods, and the telescope frequently makes them wrong—sometimes to the extent of $\pm$ 1/10th of a second—one knows it is the transit observations which are at fault and not the clock. Such observations being admittedly 100 times as rough as the clock observations, you rate the clock from a long series of daily transits, of which you may require to take 100 to establish a straight datum line.

But in this matter Astronomers have had valuable assistance from wireless telegraphy, which now enables them to compare with one another the times of distant Observatories as determined by transit observation. This is done by means of the Rhythmic Signals or Time Vernier, first established by General Ferrié at the Eiffel Tower in 1911, and it enables distant clocks to be compared to an accuracy of 1/100th of a second. It has revealed some rather disturbing discrepancies, unaccountable and irregular; differences amounting to as much as $\frac{1}{3}$ of a second being frequently observed. This remarkable service has thus demonstrated the need for improvement in clocks of the highest order, and will doubtless exercise a powerful influence in that direction, just as on a lower plane the broadcasting of time signals is tuning up the watch and clockmaking profession, and improving the punctuality of the community.

I have said enough to remind you of the importance of precise time measurement, and to give you some idea of the degree of accuracy now demanded by the advance of science. It is in the nature of a race; accuracy of means of comparison has outstripped instrumental accuracy of both clocks and telescopes, and an effort is now being made to bring the clock up to scratch. Improvement is long overdue, for there has been no really important advance in horology for nearly 200 years, that is to say, since the days of Graham, Harrison, Mudge and Arnold, with the exception of Riefler, of Munich, of whom more anon.

Since 1895, when I read my first Paper in London at the British Horological Institute, I have approached this subject from a very definite point of view. My aim throughout has been to relieve the clock, or its pendulum,

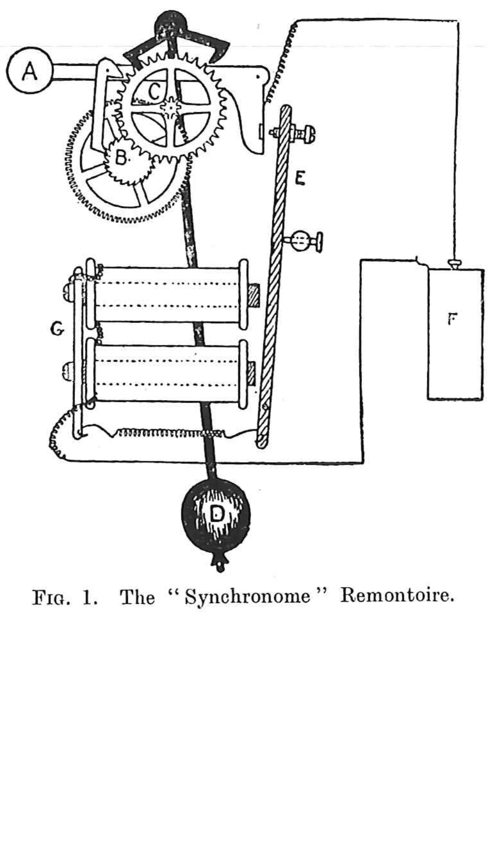

FIG. 1. The "Synchronome" Remontoire.

of interference. The first objects of attack were those innumerable contact applications intended to make clocks self-winding. In so far as energy was robbed from the clock, and was obtained at the expense of the time-keeping function, they were vicious, and had made electric clocks a byword for unreliability. That matter was successfully disposed of by using a cranked lever to drive the clock, lifting or resetting it by the armature of an electro-magnet in the manner shown in Fig. 1.

The weighted lever A as it falls turns the wheels B and C and keeps the pendulum D swinging. When it reaches the armature E the circuit of the battery F is closed, and the electro magnet G replaces the weight by throwing it up on to the next tooth of the ratchet B. The feature of this arrangement was that no energy was taken from the clock, yet inasmuch as the whole of the driving force was transmitted through the surfaces of the contact, its reliability was assured.

That brought us, at the beginning of the century, to the point of being able to say that clocks were no worse for being electrically re-wound, in fact, as the re-winding was frequent and the drive constant, they were perhaps a little better. Incidentally the remontoire action constituted an excellent switch for the operation of circuits of electrical impulse dials, but that has nothing to do with us now, excepting only this, that it exercised its influence towards breaking away from the stereotyped forms of escapement. The vision of the clock-maker had been bounded for a century or more by escapements. Pin wheel, anchor, half dead-beat, dead-beat and gravity, all had been analysed and tried out to the very end. The Graham dead-beat emerged as the best for precision timekeeping.

The limit of accuracy had apparently been attained; an impasse had been reached, and there was no room for further theorising or experimenting.

It appears to have been taken for granted from the earliest days of clockmaking, that it was desirable, or perhaps necessary, for the impulse to be imparted to the pendulum at every swing. In explaining how it has been found possible to free the pendulum altogether, I shall show you that it is neither desirable nor necessary to give frequent impulses, and that electrical time circuits of half-minute periodicity have contributed materially to the breaking away from a hide-bound custom.

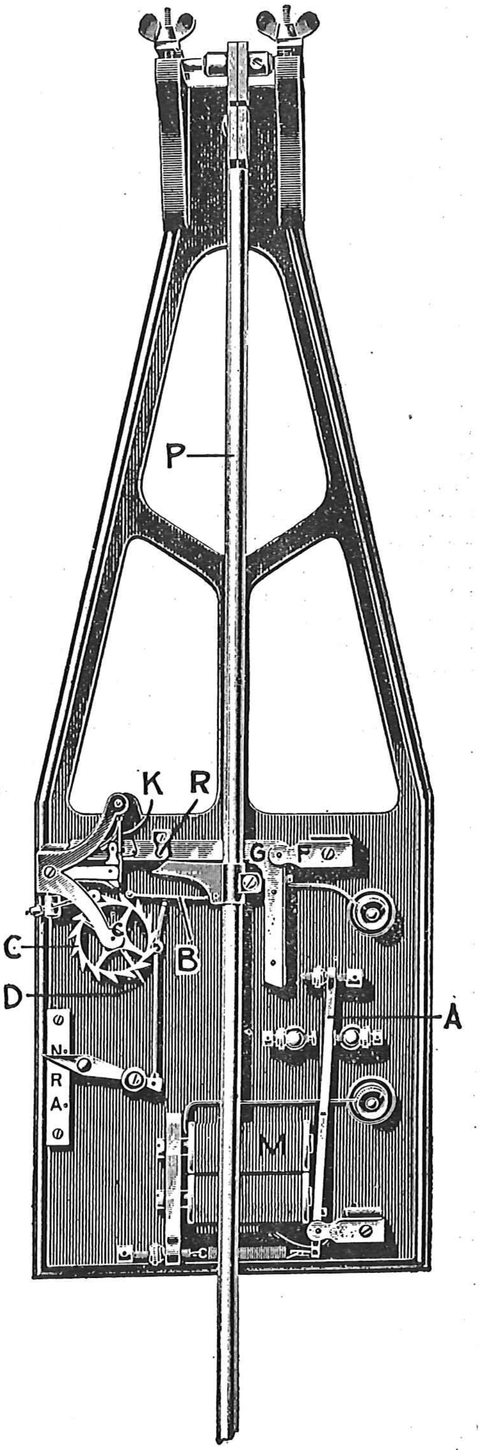

Fig. 2. The "Synchronome" Switch.

There are, of course, two sources of interference with the natural swing of a pendulum; firstly—the very word "escapement" implies it—the releasing of stored power in small instalments; the energy expended by the pendulum in that act of release may be variable; secondly, the impulse itself when given must necessarily interfere to some extent with its free swing.

The first can be dispensed with altogether; the second may be rendered innocuous by imparting it to the pendulum when the latter is passing through its zero position.

To understand how this is done, it is necessary in the first place to master thoroughly the action of this simple electro-mechanical device known as the Synchronome switch, illustrated in Fig. 2. It is a combination of a pendulum and a switch. The pendulum tells the switch when to work (usually every half-minute), and the switch imparts an impulse to the pendulum when it falls.

The switch consists of two moving parts; the right-angled lever G and the magnet armature A resting against stop E. The right-angled lever G is centred at F and normally supported on the spring catch K. Once every half-minute the lever is released, and, after giving impulse to the pendulum, makes contact with the armature, with the result that an electric current passes through magnet M, which accordingly attracts armature A, and throws the lever G up on to its catch again. A number of electrical impulse dials are usually included in this circuit.

If the current is insufficient the armature does not move, and the circuit remains closed until the pendulum on its return swing comes to the assistance of the magnet. This abnormal increase in the time of contact is utilised to give a visible or audible warning of the impending failure of the battery, by lighting a lamp or ringing a bell. The pendulum will usually continue to operate under battery warning conditions for some days, and only ceases to do so when the current has got so low that magnet plays practically no part in the lifting of the lever.

The pendulum releases the switch by means of the 15T wheel C and the vane D, which engages with the catch K at each revolution. The hook B, pivoted upon the pendulum P, rotates this wheel one tooth at a time once every thirty seconds. L is a backstop.

Impulse is given to the pendulum by the little roller R, attached to the gravity arm, running down the curved end of the pallet J fixed to the pendulum. At the moment of release the sloped face of the pallet has just *not* passed under the roller, and the pendulum has just not reached its mid position. Thus the impulse is given while the pendulum is passing through its mid or central position, and the pendulum is quite free at the ends of its swing. The escapement is, therefore, not only detached, but operates at zero, and thus fulfils the horologist's ideal.

The shape of the impulse face of the pallet J has been determined mathematically, so that the impulse commences very gradually, increases to its maximum at zero and then decreases in an identical manner.

When the switch is used to operate circuits of electrical impulse dials it is called a master clock, and is designed so that its minimum operating current is more than that required by any dial or other instrument in the circuit, and, as all the operating magnets are in series, it follows that the circuit has considerable self-induction, and that the current takes some hundredths of a second to attain its full value. Consequently, it is impossible for the switch to operate without supplying sufficient energy to the various dials to propel them.

I demonstrated this by oscillographs in my 1910 Paper, before the Institution of Electrical Engineers, one of which is reproduced here. It may be described as a photograph of one of the Synchronome half-minute impulses. The small depression

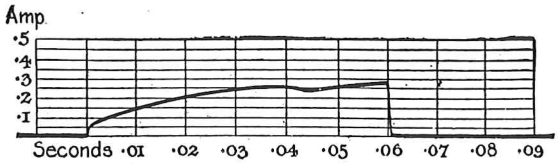

FIG. 3. Oscillograph of Synchronome impulse.

between .04 and .05 seconds represents the operation of the dials, and the area enclosed between the curve and the base line represents the quantity of electricity consumed per impulse, which in this case is .012 coulombs, and, since the impulses are repeated every half-minute, this equals about $3\frac{1}{2}$ amp. hours per annum. As each dial requires about $1\frac{1}{2}$ volts across its terminals, the annual consumption of energy per dial is about $5\frac{1}{4}$ watt hours.

As the voltage of the battery drops, the duration of the contact increases, the energy consumed remaining practically unaltered; consequently a very considerable drop must take place before the switch commences to indicate failing battery.

The oscillograph test, which will infallibly reveal the slightest intermittency or raggedness of impulse, demonstrates the perfect cleanliness and precision of the make and break, cardinal virtues not easily obtained.

It will be observed that the energy devoted to making a good and reliable contact is considerable, but it is not taken from the pendulum. It comes from the electro magnet, being, in fact, the whole of the energy developed by that magnet, and it is all mechanically transmitted through the surfaces of the contact.

All that the pendulum has to do is to count out the half-minutes (by pulling round an idle wheel), and to release the catch supporting the gravity arm.

If only these two duties could be done for it, then we could truthfully call it a free pendulum, subject to no interference whatever, excepting only that which is inevitable and inherent in the act of impelling it. Is this possible? For long enough it seemed so impossible that no one even asked for it. After all, we can hardly blame clockmakers for not inventing an escapement which does not escape.

The idea is to employ a subsidiary instrument—some extraneous mechanism—charged with the duty of releasing the gravity arm, and that this instrument should be dominated or controlled in some way, so far as time-keeping goes, by the free pendulum. Thus, if perfect phase synchronisation could be maintained between two pendulums, one could be employed to perform the duty for the other.

At first view it is not easy for a person of average intelligence, even though he may have the mechanical instinct and be well versed in clock escapements, to understand how it is possible for a free pendulum, which is not allowed to touch anything, or to do any work whatever, to communicate synchronising impulses to another. In saying "Not allowed to touch anything" I was not quite correct, for it is touched by something, viz., a falling gravity lever, which imparts an impulse to it. Advantage is taken of the fact that the exact point of time at which the impulse terminates is determined by the pendulum, and, the impulse being over, the gravity arm in its further fall is employed to give the synchronising signal. It is with a view to simplifying this explanation that I have had to tax your patience to acquire a thorough understanding of the Synchronome switch.

Refer to Fig. 2, and consider for a moment what determines the precise instant at which contact between G and A occurs. It is, and always must be, dictated by the pendulum in its passage from left to right, after receiving the impulse. Assume for a moment that we have found some means of releasing the gravity arm G without the aid of hook B, wheel C and vane D, then let us establish our free pendulum and apply such a gravity arm catch and magnet to it. The gravity arm being released by some means, delivers its impulse to the pendulum, and the resetting of it (in other words, the remontoire or switching operation) will take place, as we have seen at a point of time dictated by the free pendulum itself.

Obviously, therefore, we have in this switching operation a synchronising signal of absolute precision, obtained from the free pendulum without affecting it in any way, and with regard to the impulse which is the immediate preceding cause of the operation, it only affects the free pendulum in so far as any impulse not absolutely concentrated as a blow delivered upon it when passing through its zero point, may rank as a possible disturbance to its natural period of vibration.

The diagram, Fig. 4, in which the same reference letters are used as in Fig. 2, shews the arrangement and inter-connection of the two clocks. It will, of course, be understood that in the free pendulum the catch K, which holds up the impulse lever, is released by an electro magnet at the moment the impulse pallet reaches precisely the right position. This magnet (which substitutes the count wheel and releasing mechanism of the standard switch movement)

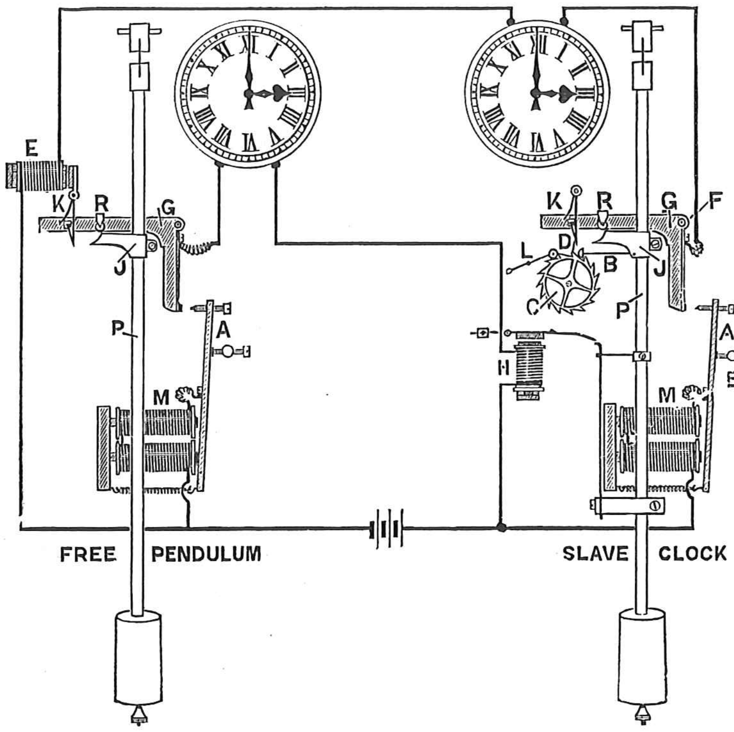

Fig. 4. Circuit diagram of Free Pendulum and Slave Clock.

is connected in the remontoire circuit of the slave, while the slave is synchronised through the agency of another electro magnet connected in the remontoire circuit of the Free Pendulum.

Just as the remontoire of the free pendulum operates the synchronising magnet on the slave every half-minute, so the remontoire

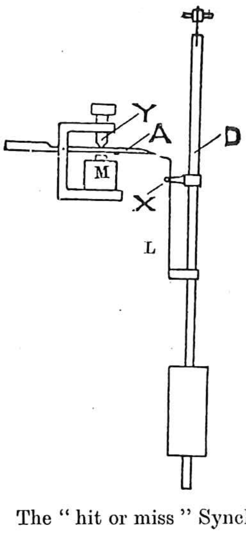

Fig. 5. The "hit or miss" Synchronizer.

of the slave operates the releasing magnet of the free pendulum's gravity arm every half-minute, and the effect is that one pendulum measures time and does no work, whilst the slave does all the work and has its precise timing done for it, a very satisfactory mutual arrangement.

The synchronisation of the slave pendulum is achieved by means of the device illustrated in Fig. 5.

The synchronising electro magnet M is fixed adjacent to the slave pendulum D, so that its armature A is horizontal, and will, when attracted, just engage with the upper end of the springing vertical lever L attached to the slave pendulum, as the latter passes through its mid position, the engagement only being possible when the pendulum is swinging from right to left.

When this engagement takes place the continued movement of the pendulum bends the springing lever L and calls into play a force which assists gravity, and consequently accelerates that particular half swing by a small fraction of the period of vibration. X and Y are stops against which L and A normally rest.

The slave is given a small losing rate of about 6 seconds a day compared to the master, and is started up so that when swinging from right to left the operation of magnet M by the remontoire contact of the master pendulum movement is just too late for A and L to engage. Then, as a result of the losing rate, the phase difference of the two pendulums will gradually decrease until engagement finally takes place, with a consequent advancement of the phase of the slave corresponding to the quickening action of the spring. As this quickening action is arranged to be about twice as great as the amount lost by the slave during the interval in which it is undisturbed, it follows that at the next impulse the slave will not have dropped back quite enough to permit engagement by the electro magnet and a miss will occur; by the end of the next half-minute, however, the phase difference will be approximately the same as when the initial engagement took place, and a second engagement will ensue with a corresponding quickening.

This cycle of operations will obviously continue indefinitely, and the phase difference between the master and slave will not be allowed to vary by more than plus or minus the advancement produced by one operation of the spring. A losing rate of 6 seconds per day equals 1/480th of a second per half-minute, so that the quickening action of the spring need not exceed 1/240th of a second, and the phase difference of the two pendulums will never exceed plus or minus this amount. As long as the losing rate of the slave relative to the master does not increase to more than 12 seconds per day, nor decrease to less than zero, it will be held in phase with the master, and it will be agreed that the above limits of rate are amply sufficient to warrant the statement that the control of the slave by the master is complete.

It should be mentioned that the impulse roller and pallet are arranged in the master, or free pendulum, somewhat differently from that shown by the diagram Fig. 4, and the drawing Fig. 2, in order that the termination of the impulse may be independent of the drop of the lever, and dependent only on gravity and the arc of the pendulum.

Having thus relieved the pendulum of the last vestige of its duty, let us now consider the extent to which the impulses we impart to it are likely to interfere with its natural period of vibration. They are, of course, constant in value—uniform weight falling uniform distance. They are concentrated as far as possible at the centre of its path where its velocity is greatest. If this concentration were complete, the interference would not affect its natural period of vibration at all. If the duration of each impulse is about the 1/10th part of a second, and occurs only once in each half-minute, it represents 1/300th part of the time measured. Compare this with existing clock escapements, where the duration of the disturbance is either continuous or of the order of 50 per cent., or one second out of every two.

Nevertheless, "impulsing" is the one source of possible disturbance, and must be reduced to the absolute minimum. With that object and also with a view to cutting out the whole set of complex considerations involved in variation of air density, we proceed to exhaust the case from the normal of 760 mm. to about 30 mm. of mercury, by enclosing the whole free pendulum in an airtight case and pumping it out.

This reduction in pressure reduces the pendulum friction practically to that of the flexing of the suspension spring, and enables the normal arc to be maintained with an impulse lever of about 1/5th of the weight that would be required had the air been left in the case at atmospheric pressure. An arc of 100 minutes is maintained by a weight of .43 grammes falling 2.0 millimetres once every half-minute, the equivalent of about 1/8th foot-lb. per week. One seldom puts less than 50 foot-lbs. into the grandfather clock on Saturday night.

Of the stagnation of clock invention for nearly 200 years I have already spoken. The only other developments in that period which occur to me as worthy of mention are the Grimthorpe gravity escapement and Riefler's clock. The former has been a conspicuous success on turret clocks, for which it was designed, but it has not otherwise contributed to the science of accurate time measurement. The latter, on the other hand, has been adopted to an increasing extent in the world's observatories for the last thirty years, and held all the records until beaten at the Edinburgh Observatory last year. Briefly described, the top chops and trunnion are rocked on knife-edges coincident with the axis of suspension. By this means the impulse, derived from an escape wheel, is transmitted to the pendulum through the suspension spring. For a short distance beyond zero the spring is straight, the pendulum and trunnion swinging together on knife-edges, then the scape wheel delivers its impulse to the pallet and rocks the trunnion back a little, locking it there, and thus imparting its impulse through the spring.

Of course, it is not a free pendulum, though at first sight it appears to be, but the evils of interference are greatly reduced by avoiding all mechanical contact with the pendulum below the point of suspension.

The credit for the general idea of this division of labour by the employment of another clock must be accorded in the first place to Mr. R. J. Rudd, of Croydon, who accomplished it in the year 1898, but he hid his light under a bushel, and though he published a short description of it, it was never discovered by anyone competent to express the theory, and to turn his application of it to practical use.

A year or two later, in ignorance of Rudd's work, the late Sir David Gill attempted it in a clock for the Cape Town Observatory. He failed, but he was the first to speak of a "slave" clock. Mr. C. O. Bartrum, of Hampstead, in ignorance of both, patented a method of free pendulum and slave in 1913, and Father O'Leary, S.J., of Dublin, patented one in 1918. But I have not heard of any attempt to develop these inventions or to test their possibilities.

The principles involved appear to me to have been very inadequately dealt with by these inventors, and it is doubtful whether any of them appreciated fully the advantages inherent in this division of labour. Also, their electro-magnetic and/or mechanical apparatus usually transgresses one or other of what may now be laid down as two fundamental precepts, that just as the right time to impart impulse to a pendulum, with a view to minimum interference with its natural rate, is when it is passing through the centre or zero position at its maximum velocity, so the right time to synchronise it, i.e., to apply maximum interference to its natural rate, is when it is at the end of its swing and its velocity is at its lowest.

When once stated, these principles are perfectly obvious, but they have neither been realised nor expressed before, and I think there has been a tendency in our horological schools to adhere too closely to the text books on clock escapements, instead of looking beyond them with a wider vision and using them to illustrate great truths and natural laws.

These principles have not been easy to realise. The first, the delivery of impulse at zero, was achieved by Arnold and Earnshaw in the chronometer detent escapement 140 years ago. Many attempts have been made to apply the same method to a pendulum by those who appreciated the fact that none of the recognised clock escapements leave the pendulum free at the ends of its swing. Several people did it, but success being measured by adoption rather than by grace, the one to be mentioned is that of Sir Henry Cunynghame, who accomplished it with a mechanical escapement in 1906, which he assisted me to incorporate into the Synchronome System.

The second, however, the theory of synchronisation, is comparatively young as a problem, as it involves the use of electrical impulses, and this subject has been greatly neglected and misunderstood. A chronicle of attempts would reveal many blunders. One veritable stumbling block has been the confusion of indicated error and error of rate, two very different things. The synchroniser above described and the method of using it in combination with the Synchronome system to produce the free pendulum, is the invention of Mr. W. H. Shortt, M.Inst.C.E., who has been carrying out research work on high grade time-keeping since 1910. We had both been seeking a solution of this particular problem since I saw Rudd's clock at Croydon, and many methods were patiently tried out and discarded. I want to bear testimony to Mr. Shortt's ability in the conduct of patient and systematic research which has won for him the blue riband of our Turf, that is to say, a record of a higher degree of time measurement than any that has yet been achieved by man.

Synchronization involves two things, first a comparison, and then a correction. In Mr. Shortt's synchronizer the comparison is made when both pendula are at zero. It is then, immediately after impulse has been delivered, that the free pendulum transmits the comparing signal and it is when the slave clock is also at zero that it receives the signal and makes the decision as to whether or not acceleration is required. The correction, if it is made, takes place when the pendulum is on its half swing to the left, out and home, the action thus completely embracing the extremity of the swing which is where interference disturbs the pendulum most.

Before discussing the performance of the clock as recorded on the rate chart, let me sum up briefly those features to which I attribute the success achieved :—

There is NO INTERFERENCE with the pendulum's natural period of vibration, that is to say, it has nothing to do but to swing.

The IMPULSE is

(1) Uniform in value ;

(2) Delivered at or about zero ;

(3) Small in quantity ;

(4) Imparted occasionally, *i.e.*, at wide but regular intervals.

It is in a VACUUM which makes (3) and (4) possible, and eliminates all barometric considerations.

It is erected in a room kept at CONSTANT TEMPERATURE, because although the pendulum itself is compensated with the greatest thoroughness and care, the compensation can never be sufficient of itself.

It has only been possible to realise the

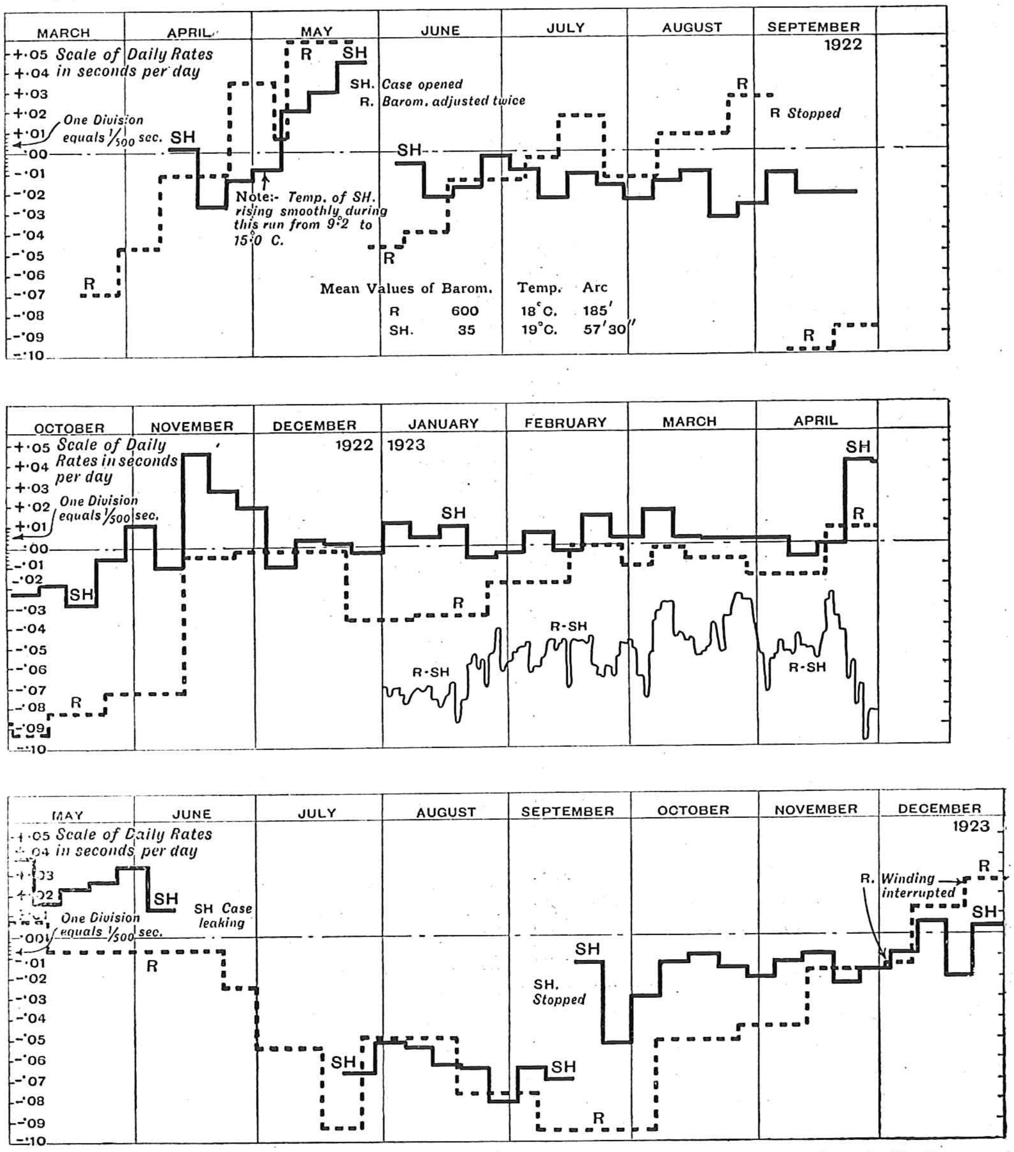

FIG. 6. Rates of Clocks Shortt (Synchronome) and Riefler, plotted from figures given in Professor Sampsons' Paper, R.Soc. Edin. January 14th, 1924.

above conditions by means of the Synchronome system, which had already met most of them and what is more important had proved its reliability up to the hilt. Not until a system has "worked out its salvation in fear and trembling" by public use in competition can it be trusted for the responsible work of an observatory. Astronomers cannot afford to waste time and money in experimenting and they would be particularly disinclined to do so in the case of electric clocks in whose name so many crimes have been committed.

The experience we have had of this clock since 1921, added to the obvious moral to be drawn from the success of Riefler's, has led me to the firm conviction that, for precision timekeeping, escapements are dead.

For this experience of the running of the clock we have had to thank Professor Sampson, the Astronomer Royal of Scotland.

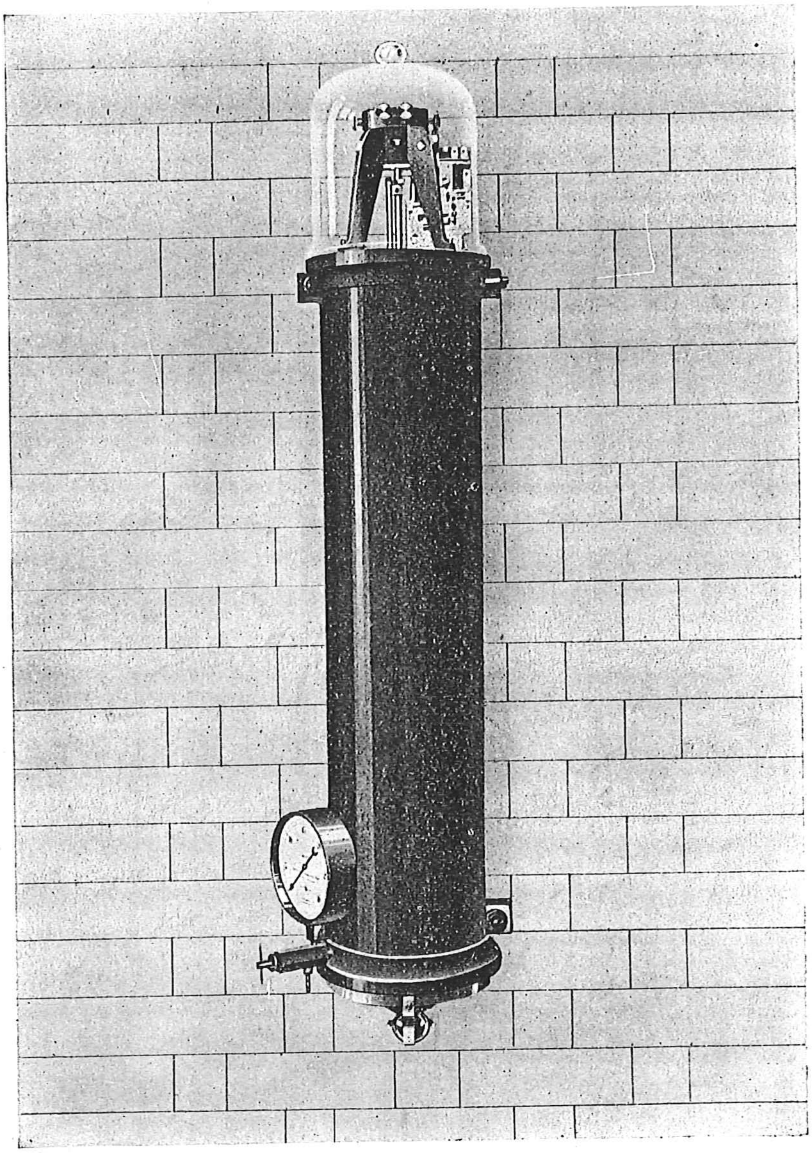

Fig. 7. Free Pendulum in Vacuo.

Since 1918 he has been contributing a series of papers to the Royal Society of Edinburgh on timekeeping. These and other contributions to the Proceedings of the Royal Astronomical Society in description of his special apparatus installed at the Edinburgh Observatory, have placed him in the forefront among the astronomers of the world as having specialized on accurate time measurement. His instruments at Edinburgh comprise an oscillograph and a cinematograph film with continuous motion used as a chronograph having the 10th parts of a second automatically recorded on the strip by means of a vibratory tongue over a window slit obscured and revealed at each vibration. With the use of a reading microscope the record is measured to the thousandth of a second. All the clock records appear on this strip.

I exhibit on the wall a chart (Fig. 6) produced with his permission from his last Royal Society of Edinburgh Paper. On it are plotted the rates of the Free Pendulum in red (black line) and of Riefler No. 258 in blue (dotted line). This particular Riefler has acquired some fame as probably the best ever produced by that firm. It is, of course, far superior to the best Graham dead beat escapement clock. I must here emphasise the unusual scale upon which the rate chart is drawn. If the horizontal divisions had been made to represent seconds as is customary, the curve would be so flat as to lose all interest—as flat as ditch water. It is doubtful if you could see any deviation from the zero line. And even if we multiplied the vertical scale by 10, so that each division represented a 10th of a second, it would still be too small a scale to express the facts clearly; the curve would lie entirely within one division. So we multiply by 10 again, using widely spaced horizontal lines, each space between them representing 1,000th of a second.

Owing to imperfections of transit observations, the problem of clock comparison on this high plane of precision is an exceedingly difficult one. Professor Sampson expresses the problem as follows:—"Given a number of clocks, A, B, C, . . . compared regularly, frequently, and accurately with one another, and compared also at irregular intervals, sometimes entailing long gaps, with the much rougher final stellar standard, to ascertain precisely what is happening in any interval." Professor Sampson treats the problem in this way: "The simplest plan, and that which I have taken, is to adopt one clock as director. The errors which are indicated by stellar observation for the director are charted just as they are observed, on every practicable night, without any smoothing whatever. Against these are also set the relative going of the director and each of the other clocks as shown by the microchronograph. The former chart may often run as a set of improbable zigzags. The latter will indicate reliably all sharp changes of relative rate that actually occur."

This method is open to the objection that if one of the other clocks was actually going better than the director, it does not get justice done to it, but is debited with the director's faults. Professor Sampson gives several instances of this, and I need hardly say that I believe our rate to be steady, that our line, to be truthful, should be a straight one and that the variations are the other fellow's; further, that it will so be proved when the free pendulum is elevated to the position of the director in the Edinburgh Observatory.

Now a few words with regard to nomenclature. New inventions require new names; the inventor coins them and their currency depends upon their utility. I have coined one, the Synchronome Switch, because it seemed to me to be a fundamental device possessing a number of distinctive qualities—a device which is likely to be used in different ways for different purposes; therefore, a single word to express it and its inherent virtues will be a convenience.

The word Slave, first used in this connection by the late Sir David Gill, is obviously appropriate as applied to the pendulum synchronously coupled to the Free Pendulum to perform the releasing function for it. This might lead one to speak of the Free Pendulum as the Master, but it must not be forgotten that what we now use as a Slave has been customarily regarded as a Master Clock, and will still remain so in so far as it is a transmitter of electrical impulses for the purpose of operating circuits of electrical impulse dials. When it is so used perhaps the term "Transmitting Slave" will be more appropriate than Master Clock.

Any number of transmitters can be controlled by a Free Pendulum and there is absolutely no limit to the contact making and switching operations which a Slave may perform without affecting the Free Pendulum even indirectly. A slave clock will operate

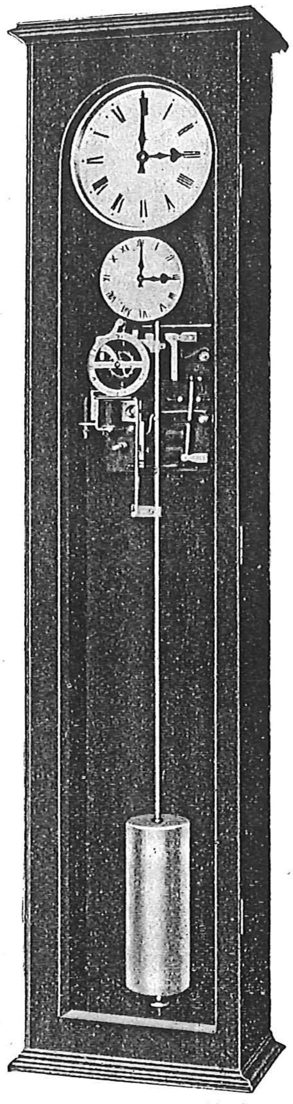

FIG. 8. Slave Clock.

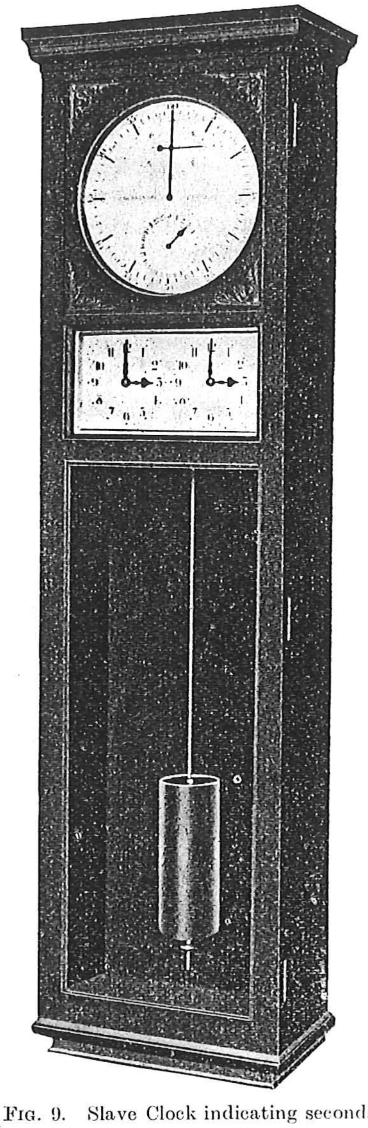

FIG. 9. Slave Clock indicating seconds.

circuits of electrical impulse dials, including turret clocks, just as well as chronograph pen magnets and seismograph recorders, and if the Free Pendulum is a Sidereal, it may control the motion of telescopes used for stellar photography.

It is also a great convenience to be able to set the clock to time. Hitherto it has not been possible to set to time clocks sealed up for constant barometric pressure without breaking the seal. A feature of the Free Pendulum which will be highly appreciated by astronomers is that the slave clock (its only time indicator) can be readily set either forwards or backward, the only limitation is that it cannot be set less than two seconds either way, that being the period of vibration of the Free Pendulum which, of course, is never touched.

Time has not permitted me to deal adequately with other methods of maintaining and counting the vibrations of a Free Pendulum. I had to choose between an historical and a practical lecture, and I chose the latter, but I must remind you that it can be and has been done by radically different methods, such as by means of a selenium cell, and also by means of the Triode valve. I have, however, found these proposals to be deficient in the counting and switching functions, which are of the utmost importance, and for this and many other reasons I prefer my own methods.

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DISCUSSION.

THE CHAIRMAN, in opening the discussion, said Mr. Hope-Jones had given an extremely lucid account of what he himself, at any rate, found rather a difficult subject. One thing about which he felt very strongly was that the author's clock, and the rates which were shown to have been got at Edinburgh, certainly met—and very much more than met—all the requirements of astronomers at the present time. The difficulty of the astronomer was with his instrument; there were questions of stability of his mounting, possibility of flexure in the axis, and so forth, and under those conditions, with such instruments, astronomers did not get anything like as much precision as they did with clocks.

MR. C. O. BARTRUM said that he had recently spent an afternoon at the Edinburgh Observatory, when he had been very much impressed by Mr. Shortt's clock. To see the dream of his youth actually realised before him was quite moving. He had been greatly flattered to find that the humble effort which he had made in 1917, to which the author had made reference in his paper, had been proved by Mr. Shortt's results to have been on the right lines in so very many ways. Unfortunately, his clock had been left in a rough model, and it had never been realised as a properly made instrument. It was rather curious that so many investigators had been working on the same idea without knowing of each other's efforts. For instance, he had never heard of Rudd's clock. When he designed his clock he thought that the slave principle was absolutely new, but he had found that it was quite an old idea. He was pleased to find that Mr. Shortt had dropped his inertia escapement; he had always felt it was wrong. What Mr. Shortt had done was to remove the symptom of a complaint without remedying the disease itself. On one occasion he had ventured to correspond on the subject, and he had to confess that Mr. Shortt had given him a very clever and charming reply which had made him feel rather uneasy.

He considered that Mr. Shortt's clock marked an epoch in time-keeping, and he thought the lecturer had convinced the audience of that fact. Genius was here shown as a combination of simplicity and efficiency, but genius had also been defined as an infinite capacity for taking pains. Mr. Shortt had shown this too by the way he had studied every detail with such care. After all, the carrying out of details and the way in which an idea was developed, was almost as important as the actual idea itself. That was exemplified by the reference which Mr. Hope-Jones had made to the Leroy clock at Edinburgh. Mr. Hope-Jones had described the escapement—a very commonplace idea; it was based on the principle of the old Mudge gravity, but it was so beautifully carried out and made, that the clock was only second to Shortt's, and better than the old Riefler.

He believed it would be agreed that Mr. Shortt's great advances were two in number, firstly, the simple mode in which he synchronised his slave pendulum, and, secondly, the hanging of the master pendulum in a low pressure.

He took exception to what Mr. Hope-Jones had said about inventors not understanding the principle of the slave. Personally he ventured to think he did understand it. When he read his paper before the Physical Society, Professor Boys was in the Chair, and after the paper had been read Professor Boys had made some very interesting remarks, one of which was that his (Mr. Bartrum's) method of synchronising could have been greatly simplified if he had merely arranged that the error of the slave should be wiped out by a definite chunk, either positive or negative. Mr. Shortt had gone one better than that. By keeping his slave with a losing rate he just wiped out a chunk of error and reversed it in one direction only. That was a wonderfully clever idea.

With regard to the low pressure, however, it had been a great surprise to him to find that the resistance to the pendulum had shown such a decrease as the pressure was lowered. He believed the ordinary orthodox physicist would state that the logarithmic decrement of a pendulum, or the dissipation of energy, depended on the viscosity and that the viscosity was independent of pressure. In fact, a learned Professor had given him the figures which Professor Crookes had found as the result of his experiment of swinging a pendulum in different pressures. If the dissipation at atmospheric pressure was taken at 100, when the pressure was reduced to one ten-thousandth of an atmosphere it only fell to 78, and at one-millionth it was still 14. Mr. Shortt had experimented and had found that when he reduced it merely to one-twentieth he had brought down the dissipation of the energy to something like one-fifth. He hoped that Mr. Shortt would publish those results as they would be most interesting. He noticed that the American Geodetic Survey used pendulums hanging in a low pressure—he presumed in order to keep up the swing for a long time.

With regard to the amplitude of vibration, he had discussed that question in his paper with reference to his own arrangement, which was precisely similar to Mr. Shortt's from that point of view, and he had made some experiments. He had come to the conclusion that in a case like this, where the escapement error was likely to be quite small as compared with the circular error, a small amplitude was indicated. He had adopted one degree on each side. Mr. Hope-Jones said that he had taken 140 minutes.

MR. HOPE-JONES: One degree, 40 minutes.

MR. BARTRUM asked if that meant semi-amplitude or the whole.

Mr. Hope-Jones replied the whole.

Mr. Bartrum said therefore that would be 70 minutes on each side.

Mr. Hope-Jones: Fifty.

Mr. Bartrum asked if Mr. Hope-Jones could give any idea of the variation of that amplitude.

Mr. Hope-Jones said it appeared in Professor Sampson's paper of January 14th, read before the Royal Society of Edinburgh. There were some figures given there of the amplitude. Professor Sampson watched the amplitude of the arc very closely under the microscope, but they were small variations.

Mr. Bartrum, continuing, said he desired to conclude by making some general remarks. With his three clocks Dr. Sampson was now getting such records of time that there were indications he was not measuring time, but measuring conditions—either changes of gravity or changes of the earth's magnetic field, or some other changing conditions. Personally he began to think from Mr. Shortt's final result that the next step would be possibly a time-keeper, independent of gravity, and non-magnetic. It seemed to him that they were coming to that—that the pendulum clock had come to finality, because after all, Mr. Shortt measured time to one part in 8-millions. That meant he could detect a change in gravity of one part in 4-millions. He did not know whether there was any possibility of such change, but it seemed to him there were interesting possibilities when one got to such accurate time-keeping.

The Chairman said there was one point he would like to put to the author as a possible limit of the pendulum clock, and that was earth tremors. One got earthquake shocks now and again, and one knew that there were small seismic vibrations. If those should, by any fortunate chance, have a period of two or three seconds, they would, he took it, make an ultimate limit on the accuracy obtainable by pendulum clocks; but there was not the slightest evidence so far. One simply had to say that the evidence was against those seismic vibrations being of such amount as to affect the pendulum.

Mr. Bartrum said that Prof. Sampson had showed him that his three clocks—the Riefler, the Leroy and the Shortt—were at times altering their rate together, as if there was some external effect acting on them all.

Father J. P. Rowland said, with regard to seismic disturbances, he doubted very much if the vibrations, which whilst varying somewhat in magnitude, were always very small, would be likely to affect the clock, but he had often wondered whether small tiltings of the ground, which certainly indicated changes of level with changes of temperature, atmospheric conditions, and perhaps other things, influenced the rate of a clock. It would be extremely interesting if investigations were made as to how far earth movements might limit the accuracy which could be obtained by pendulum clocks. If an instrument were set up to indicate more definitely earth tiltings rather than vibrations, some correlation might be found between the levels and the rate of the clock which would show connection.

Major C. E. Prince said the author had referred to the extraordinary accuracy of astronomical clocks. It was rather interesting to try to discover how much of that accuracy was due to physical perfection and how much was due to perfection of the method. For example, it was obvious that, with a pendulum which was non-expansible and working in a perfect vacuum, any errors would be the errors of the method and not of the pendulum itself. He would have been interested to see the two divisions of the subject separated in order to see how much of the accuracy was due to each of them.

It seemed to be laid down by everybody that the smallest possible interference of the pendulum was desirable, but would it not be more scientifically accurate to impulse as often as possible; that was, to supply energy in far more minute quantities more often? It seemed to him from fundamental considerations that was what ought to be done, but there seemed to be some rule against that which apparently had been arrived at by practice, and which he would like to have explained.

With regard to the question of the accuracy obtained from putting the pendulum in a very low pressure, was that because the pressure was low, or simply because in the containing case the variations of atmospheric pressure from outside were not felt?

Mr. R. J. Low said it appeared from the diagram shown on the wall that the rate was always changing. Had any attempts been made to compare it with magnetic charts over a corresponding period, and also with the gravitational effects of the position of the moon, and the sun, and the tide? Also, were the comparisons taken at exactly the same time every day? He asked this because when he was watching the Synchronome slave clock working, he had noticed that the hit-and-miss governor did not work every time. If one looked into it very carefully one saw that it was undergoing what he might call a rhythmical hunt. It might be the same with the master clock—that if one could analyse its motion carefully enough one would find it was alternately running fast and slow, and that if one got a graph of it it might look something like an ordinary sine curve. When those concerned had compared the clock every day for a week they might have chanced to take all the points above the zero line for one week, and in another week they might have chanced to take them all below the zero line. Had that any bearing on the graph shown on the wall?

With regard to magnetic effects, to his mind it seemed entirely wrong to have a magnetic field anywhere near a swinging pendulum, as this field is never constant, owing to the varying battery voltage and resistance, and also the earth's field. These fields were bound to affect even a metallic pendulum of non-magnetic material, and much more so one of invar, which was magnetic.

THE AUTHOR, in reply to Mr. Low, said the period at which the clocks were compared every day at Edinburgh was either uniform, or else an allowance was made for any differences which might occur through known causes, and things were brought to a uniform time datum for observation. That was mentioned in the paper to which he had referred, which had been read before the Royal Society of Edinburgh on January 14th last. He hoped it was perfectly clear to Mr. Low's mind that no variation of battery in the electric self-winding action or Synchronome remontoire, could possibly affect time keeping. In many systems of electric clocks he was sorry to say the impulse imparted to the pendulum varied as the battery varied. There was nothing whatever of that kind here. He gathered that Mr. Low objected to the presence of an occasionally active electro magnet anywhere near the pendulum. That was one of those refinements to which possibly people would turn their attention now. Having got down to a fresh datum of accuracy one looked forward to the slightest possibilities. It had never occurred to him before that such things could possibly be a source of variation.

Mr. Bartrum had ably put forward the possibilities of the achievement of such great accuracy in time-keeping leading investigators into deeper considerations altogether—as to whether it was quite Time which they were measuring.

The chart on the wall actually did show the variation of gravity. The question had been asked as to whether the moon was affecting that rate. It had been pointed out to him that for the period of nine months the variations in the chart exactly corresponded with the adding or subtracting of the moon's weight to the earth and gravity. Such matters certainly did want looking into. Some of them might be quite laughable when they came before an astronomer, but the fact that such questions were asked showed the present trend of thought.

Major Prince spoke of the impulse being given more often. He quite admitted that, on the basis of pure reason, it might be very well asked what was the difference between giving 30 very small power impulses, one every second, and one larger impulse equal to those 30 added together every half minute? Theoretically it was the same thing, but in practice it was not. They just had to take it from a common sense point of view and consider which could be done with the least variation. He might say that to divide up that impulse of .43 grammes falling a distance cf 2 mm. every half minute into 30, the pivot friction might be 50 per cent. of it every time, and that pivot friction would be subject to variation. He thought Major Prince would see his point. It was just a matter of common sense, what one could do best. Prof. Sampson had expiessed to him the opinion that veiy likely it would be better if the impulse was given every minute instead of every half minute.

A vote of thanks to the author for his paper concluded the meeting.