The History of the Chronometer

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THE HISTORY OF THE CHRONOMETER

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Read at the Afternoon Meeting of the Society, 13 *December* 1920.

THE history of the marine chronometer, from its early beginnings to its present form, covers a period of about two hundred years, and I cannot hope, in the time at my disposal, to give you more than a rough sketch of the steps by which it was developed, and of the lives and work of the small body of men who were responsible for that development.

The chronometer came into existence as a particular solution—and, up to the present, the best solution—of the problem of finding longitude at sea. This problem is at least as old as the fifteenth century, when navigators began to make long sea voyages and consequently to get out of sight of land. They soon discovered that to find their latitude was a comparatively simple affair, but that their longitude was a matter of guesswork, and it was over two hundred and fifty years before a general method of finding it, by any other means than "dead reckoning," was discovered. Several theoretically correct methods were proposed, but the practical difficulties in the way of executing them proved, for a long while, insuperable.

The method of combining astronomical observations with a standard of time carried by the observer is, of course, that employed to-day. The local time of the ship's position is found by observation, and the Greenwich time obtained from the chronometer, allowance being made for its rate of gain or loss. The difference gives the ship's longitude.

Although proposed by Gemma Frisius in 1530, this method remained dormant for some two hundred and fifty years, since no machine could be made to keep sufficiently accurate time at sea. As a matter of fact, the accuracy required, which excludes errors of more than a few seconds in twenty-four hours, was not reached, even in astronomical clocks on shore, for nearly two centuries. Consequently sailors continued to depend for their longitude upon "dead reckoning," which simply means keeping as accurate an account as possible of the ship's courses steered and distances logged, and so calculating her change of longitude from her last observed position. This method, at the best of times, was subject to errors of all kinds—unknown compass errors, errors in logging, clerical errors, currents, allowance for leeway, etc., and it is not surprising that ships were often hopelessly out in their longitudes, and that in consequence shipwrecks were frequent. Two good examples of the defect of longitude by dead reckoning are to be found in the narrative of Anson's famous voyage. In 1741 he spent over a month endeavouring to round Cape Horn to the westward, and having, by his reckoning, made good enough westing to place him 10° clear of the most western point of Tierra del Fuego, stood to the north, only to sight land right ahead and to find that owing to an unsuspected easterly set he was still on the eastern side of the cape. Again, after rounding the Horn and parting company with his squadron, scurvy broke out aboard the *Centurion*, and Anson, with his men dying like flies, ran to the northward, hoping to make the island of Juan Fernandez, to re-fit. In the ordinary way the method for making such islands was to get into their latitude and run along it, a plan still practised by many Pacific traders. To save time and lives, and in view of the fact that a few more days of her present death-rate would leave the ship too shorthanded to go about, he sailed straight northward for the island, with the result that he reached its latitude without sighting it, and was uncertain whether it lay to the eastward or the westward of him. He ran westward until (unknown to him) he was within a few hours' sail of the island; then, concluding he was wrong, stood eastward until he made the coast of Chile, and then ran back westward over the same ground until he made the island. This uncertainty as to his longitude lost him the lives of a number of his crew, who would probably have recovered if they could have been got ashore. This is no isolated case.

Many rewards had been on offer for a long time for the discovery of some better method of determining longitude: thus in 1598 Philip II. of Spain, possibly stimulated by memories of the Armada, offered a hundred thousand crowns, and the Dutch Government, soon afterwards, thirty thousand. The Spanish Government, also, for many years paid out small sums to encourage inventors, and cranks of all kinds, competing for their big reward; thus we find Lorenzo Ferrer Maldonado, the reputed discoverer of the Strait of Anian, receiving 200 ducats in 1626 for his discovery of "a compass without variation," which was expected to be of great use in finding the longitude (but why, is not obvious).

But the largest and most famous reward was that offered by the British Government in 1713, and it has the additional distinction of being, I believe, the only one which was ever paid. The main cause of its offer was not, curiously enough, the pressing needs of seamen, but a chimerical scheme brought forward by two gentlemen named Whiston and Ditton, whose names are now only remembered as the subject of a coarse poem by Swift.

They proposed that permanent floating lightships should be established at fixed points on the principal trade routes, firing at intervals star-shell arranged to burst at a height of 6440 feet, thus affording ships an opportunity of determining their distance from the nearest lightship by timing the interval between the flash and the report. They added that this method would be of particular use in the North Atlantic, where, they calmly stated, no depth exceeded 300 fathoms.

Whiston and Ditton, backed by a strong petition from the merchant shipping interest, procured the appointment of a committee to examine both their project and the whole question of finding longitude at sea. The outstanding feature of this committee was the evidence given by Sir

Isaac Newton, one of its members, who gave a short sketch of the "several projects, true in theory, but difficult to execute," proposed up to that time. It is noteworthy that he puts the chronometer method first.

As the result of the committee's report, a bill was passed offering the following rewards: £10,000 to the inventor of any method which, in the course of a voyage from England to any of the West India Islands and back, could determine the vessel's longitude to within 1°; £15,000 if it determined it to within $45'$; and £20,000 if it determined it within half a degree.

At the same time the committee was remodelled as a permanent official body, having the title of the "Royal Commissioners constituting the Board of Longitude." This Board remained in existence for over a century, being finally dissolved in 1828. During its lifetime it had disbursed public money to the extent of £101,000. And here it may be mentioned that the Board of Longitude, like their Spanish predecessors already quoted, found themselves much exposed to the numerous tribe of cranks who are always to the fore when such questions are under discussion. By some obscure process of reasoning it became a widely received notion that the solution of the problem of longitude was inseparably connected with the perpetual motion and the squaring of the circle. And since there has hardly ever been a time when many people have not firmly believed that they possessed the solution of one or both of these problems, it may be imagined that their communications, together with a large number from lunatics and impostors, rendered the work of the Secretary to the Board somewhat harassing. To this day there are people who firmly believe that the British Government has offered an enormous reward for an exact value of π, and this error is entirely due to the £20,000 prize it once really did offer for "the discovery of the longitude."

The reward remained on offer for fifty years, and was then won by a chronometer, which thus asserted, for the first time, its definite superiority over all other methods of finding longitude at sea. Such machines had been tried before, but all had been failures.

The first attempt at constructing a marine timekeeper was made by the celebrated Christian Huyghens. About 1662 he constructed two clocks driven by springs, and fitted with short pendulums beating half-seconds. They were tried at sea by a Scottish officer named Major Holmes with moderate success, but it became evident that as a controller the pendulum was unsuitable for use at sea. Huyghens subsequently re-designed his clocks to be controlled by a balance, but although he worked on them for a long time he was unable to get satisfactory results, and concealed his failure in a cryptogram. At the same time Leibnitz, the great German mathematician, published an account of a marine timekeeper which he had invented. From his description it is obvious that it could never have worked, and it only affords confirmation of the fact that

Leibnitz, once he got outside the subject of pure mathematics, was prone to write on sciences whose principles he had not thoroughly mastered.

The next attempt was made by Henry Sully, an Englishman who spent his life in France and devoted it to horology. Sully was born about 1685, and died, prematurely and very poor, in 1728. He produced a watch, for use at sea, with two balances geared together, and in 1724 he presented to the Academy of Sciences a machine by which he believed he had solved the problem. Its controlling mechanism was a weighted lever, pivoted on friction rollers, and connected with a balance by means of a fine wire or silk thread playing between cycloidal cheeks. This design is, I believe, unique.

Sully made a number of these machines, which, when tested on shore, went fairly well at first, but soon became inaccurate. He abandoned this design, but while working on a new one died of inflammation of the lungs, brought on by overwork. One of his curious machines is preserved in the Museum of the Clockmakers' Company at the Guildhall, amongst a magnificent collection of old chronometers and pocket-chronometers, which any one who is interested in the subject should not fail to visit.

After Sully came the "father of the chronometer," John Harrison, winner of the £20,000 reward, and producer of the first reliable marine timekeeper. Harrison was a Yorkshireman, born at Foulby in 1693. He was brought up as a carpenter, but soon acquired a passion for clockmaking. At the age of twenty-five he had invented two very considerable improvements in the pendulum clocks of his day. One was the "gridiron" pendulum, in which the effects of heat and cold in lengthening or shortening it, and consequently making it swing slower or faster, are neutralized by a combination of brass and steel rods, which have, of course, different ratios of expansion. The other was a peculiar and delicate escapement called, from its appearance, the "grasshopper" escapement, which needed no oiling and had hardly any friction.

Harrison next turned his attention to winning the great reward, and designed a marine timekeeper. In 1728 he journeyed to London with his drawings, his pendulum, and his escapement, hoping to get assistance from the Board of Longitude. It is very doubtful whether he would have done so, but Fortune directed him instead to George Graham, a famous London clockmaker. Graham very wisely advised Harrison to make his machine before approaching the Board. He also helped him by lending him money, for which he refused to accept either interest or security.

From 1728 to 1735 Harrison was occupied in building his first timekeeper. Through the great kindness of the Astronomer Royal, I have the honour of being able to exhibit this identical machine to you this afternoon. It has been recently cleaned, but is not in going order. As you see, it has two enormous balances, which were connected together by wires in a practically frictionless manner. The balance springs, which are missing, were four in number—helical springs in tension, acting on the ends of the balance-arms. Harrison made a clever use of his gridiron compensation to neutralize the effects of heat and cold on them. The escapement was a "grasshopper" in two parts, half being fitted on each balance staff, and both acting on the same escape wheel. Finally, he provided the machine with a small spring to keep it going while the mainspring was being wound up (which was done by pulling a cord coiled on a drum).

Crude though it may be, it is hard to praise this machine too highly. In my opinion, it is one of the most wonderful pieces of mechanism ever made. In constructing it Harrison, working single-handed and self-taught, grappled successfully with problems which had defied all previous efforts at solution. If the word means anything, he was a mechanical genius, and certainly he had "an infinite capacity for taking pains." For instance, all the wheels, except the escape-wheel, are of wood, turned out of solid oak, with the teeth, also of oak, let in in groups of four. These teeth, in turn, engage with pinions fitted with lignum-vitæ rollers to avoid friction. It is curious that Harrison, although he gave up the use of wood in his later machines, returned to it eventually. After his death an unfinished chronometer was found among his effects, made of several different alloys, such as bell metal and tutenag, while the arms of the balance were formed of hard wood.

Harrison completed the machine in 1735, and tried it successfully in a barge on the Humber, having made for it a wooden box slung in gimbals. He then applied to the Board of Longitude for a trial at sea, and was sent with it to Lisbon in H.M.S. *Centurion*, the ship which, some years later, took the Acapulco galleon and brought Anson home with nearly half a million sterling. Harrison and his timekeeper returned in H.M.S. *Orford* a month later. I have examined the logs of these two ships, but they do not say much about him. The machine, however, undoubtedly performed very well, and the captain of the *Orford* gave Harrison a certificate in which he stated, "When we made the land, the said land, according to my reckoning (and others) ought to have been the Start; but before we knew what land it was, John Harrison declared to me and the rest of the ship's company that, according to his observations with his machine, it ought to be the Lizard—the which, indeed, it was found to be, his observations showing the ship to be more west than my reckoning, above one degree and twenty-six miles."

Harrison exhibited his machine to the Board of Longitude soon after his return, and they advanced him £500 and desired him to make another, if possible a smaller one. As a matter of fact, he made three others, but none was tried at sea until 1761, and in the mean time he had a hard struggle to live, although the Board gave him several sums of £500 at intervals to assist him. These were subsequently deducted from the reward he received.

In 1749 the Royal Society awarded him the Copley medal, and long afterwards they offered to make him a Fellow, but he declined the honour in favour of his son, William Harrison, who had grown up to be his father's right-hand man.

Harrison's second and third machines may be passed over, since they exhibit only detailed improvements over No. 1, but in his No. 4 machine, which was a large watch about five inches in diameter, he produced a most wonderful piece of mechanism.

He abandoned in it the huge balances and complicated anti-friction devices of his earlier efforts. No. 4 is, in many ways, an enlarged version of the common pocket-watches of Harrison's day, with the addition of a number of contrivances which removed practically all the causes of their defective time-keeping.

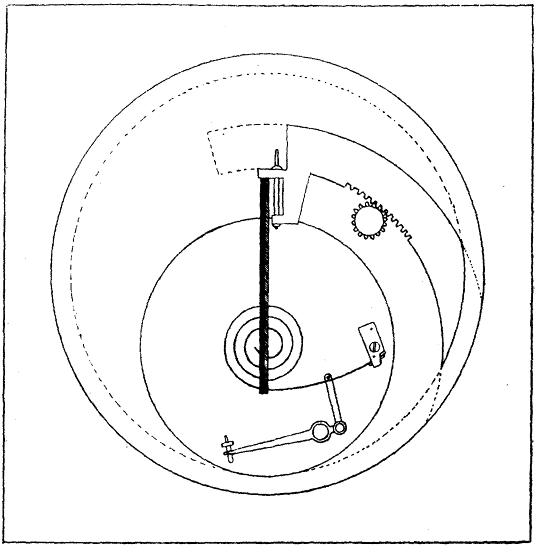
First of all, he contrived a secondary spring to keep the watch going while the mainspring was being wound—a device which, as we have seen, he had fitted to his first machine many years earlier. There is no question that this "maintaining spring" was Harrison's invention, and it is still fitted in chronometers. This is the only one of Harrison's inventions which has not yet been superseded.

Secondly, he eliminated the errors caused by friction in the train of wheels by fitting a small spring which drove the escape-wheel direct, and which was wound up eight times a minute by the mainspring, the latter, of course, being wound once a day by hand. In this way he arranged that the force driving the escape wheel was practically constant, since the small spring had ten turns and never uncoiled more than a sixth of a turn before being rewound. This device, which is known to clockmakers by the name of a "remontoire," had been used by both Huyghens and Sully, but Harrison's application of it was novel and effective, and although the "remontoire" is no longer used in any form in chronometers, the detached escapement having rendered it superfluous, it was a powerful factor in Harrison's success.

It is worthy of note that the modern Riefler clock, the most accurate timekeeper yet made, employs this principle, and is wound every forty seconds.

Thirdly, although Harrison, not having room to fit his "grasshopper" escapement, retained the clumsy one of the watches of his day, called the "verge" escapement, he had shorn it of most of its errors by his remontoire, and he proceeded to improve it still further by making the pallets—the parts of the balance acted on by the escape wheel—of diamond, and curving them so that they were less effective when the balance vibrated through a long arc than when it described a short one. For the same purpose, that of isochronizing the arcs, he added a small pin, which he named the "cycloid pin," which was touched by the balance spring when the balance vibrated a long arc, and so, by reducing the spring's effective length, increased its strength. As a matter of fact he rather over-corrected the defects of his escapement, and his balance described long arcs in slightly less time than it did short ones.

Finally, he provided his watch with a compensation for the effects of heat and cold. A rise of temperature makes a balance spring weaker, and also increases the moment of inertia of the balance, so that its beats are slower, and the watch loses. Cold has the reverse effect. When an ordinary watch is regulated by moving its indicator to "fast" or "slow," what happens is that one alters the position of two little pins, which hold the outside coil of the balance spring between them. By so doing you alter the effective length of the spring, and thus make it stronger or weaker. Harrison arranged an automatic way of doing this, and he used the same difference between the ratios of expansion of brass and steel which, as we have already seen, he employed in his earlier machines. Here is a view of his mechanism for effecting it. He took two thin strips of brass and steel and riveted them together, so that they formed a single compound strip, and he provided that two pins situated at one end of it should embrace the balance spring, while the other end was rigidly fixed. Now if, at a certain temperature, this strip were absolutely straight, it can easily be seen that on a rise of temperature the brass, expanding more than the steel, would cause the strip to become convex on the brass side, and concave on the steel side, and that if one end were rigidly held, the other would move the curb pins along the balance spring and so shorten it, thus increasing its strength to compensate for the weakening caused in it by the increased temperature. *Mutatis mutandis*, similar effects would occur for a fall of temperature. Harrison also provided that the position of this compound strip, which he called his "thermometer curb," could be shifted bodily so as to adjust the watch for mean time, but he found that this adjustment did not answer, and abandoned it. As we shall see later, this method of compensation is imperfect, and has been abandoned, but in its day it represented an enormous advance. Harrison himself was aware of its defects, and suggested, in a pamphlet I shall notice presently, that the compensation ought to be in the balance itself—as it now is.



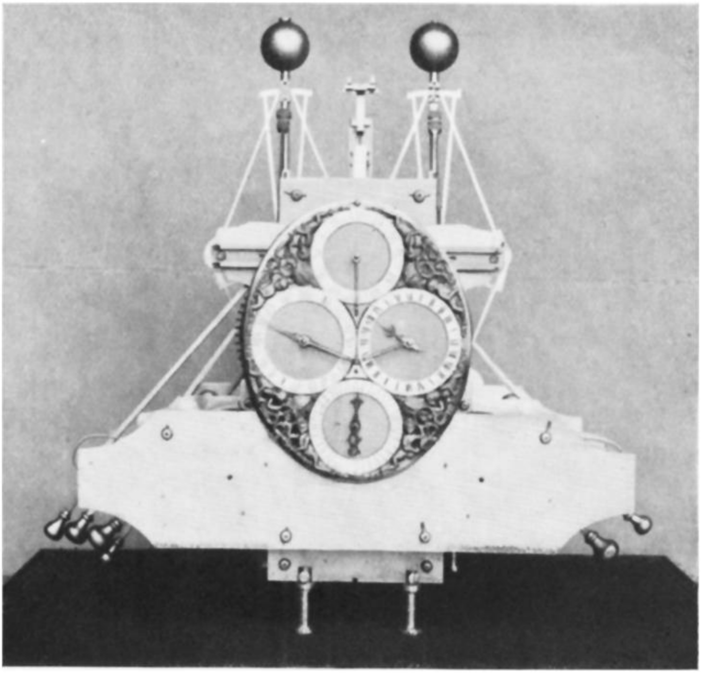
Harrison's compensation

The watch embodying these inventions of Harrison's is a beautiful piece of work, and very costly. It was jewelled wherever possible, to reduce friction, and the top plate and balance cock are a mass of the most elaborate chasing. How much of it is Harrison's own work is uncertain, but his master mind dominates its construction. It is marked "John Harrison and Son, 1759." The mainspring, remontoire spring, and maintaining spring were made by Maberly, a famous London spring-maker, and I think the chasing was the work of a jeweller; but all the elaborate mechanism, including the balance-spring, is undoubtedly Harrison's own work, assisted, of course, by his son. What Harrison himself thought of it can be seen from an unpublished description of it which he wrote, and of which I possess a copy. He concludes his account of the watch by saying, "And I heartily thank Almighty God that I have lived so long, as in some measure to compleat it . . . , and I think I may make bold to say, that there is neither any other Mechanical or Mathematical thing in the World that is more beautiful or curious in texture than this my watch or Time-keeper for the Longitude."

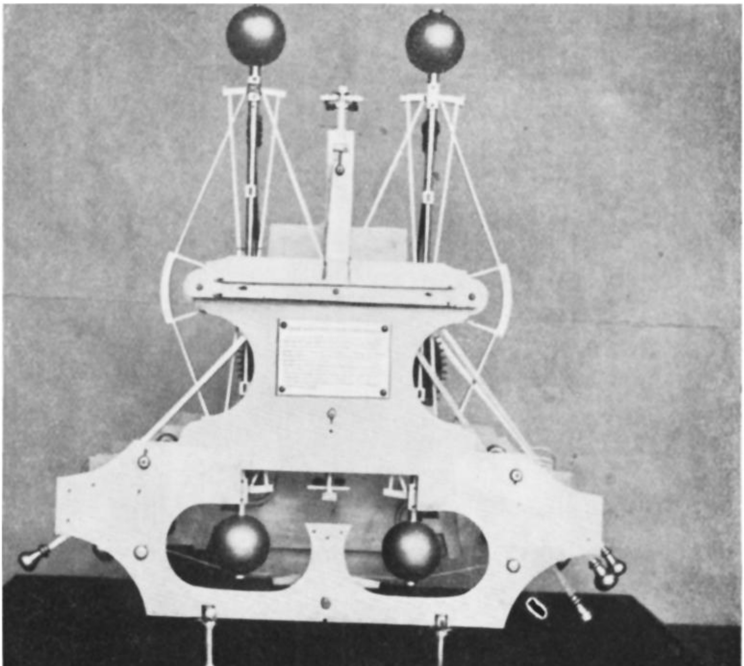
The Astronomer Royal very kindly offered me the loan of this watch in order that I might exhibit it to you, but, with his permission, I chose instead the duplicate of it made ten years later by Larcum Kendall, since the latter is an exact copy of No. 4, and has an added interest by reason of its magnificent performances when tested for several years at sea by one of the greatest of all navigators—Captain James Cook. Here is Kendall's duplicate, and you will observe that it is simply an enlarged watch, and is not slung in gimbals. Although he had used them with his first machine, Harrison subsequently took an aversion to gimbals, and alleged that they caused more errors than they avoided. It is certain, though, that had he employed them for No. 4 he would have annulled one of the few remaining defects of his masterpiece—its varying rate of going in different positions.

Harrison had applied in 1757 for a trial of his third machine, under the Act of Queen Anne, but the granting of this was delayed for various reasons until 1761, by which time No. 4 was finished. As Harrison was now sixty-eight, his son, William Harrison, was allowed to sail in his stead, and he left Portsmouth with No. 4, aboard H.M.S. *Deptford*, on 18 November 1761. After eighteen days at sea the dead reckoning gave the ship's longitude as 13° 50′ W., but by the chronometer it was 15° 19′ W., and William Harrison asseverated so strongly that the latter was correct that the ship, which was bound for Madeira, altered course accordingly, and the island, as he had predicted, was sighted next day. This, as a contemporary account put it, was a matter of relief to the ship's company, who were then in great want of beer.

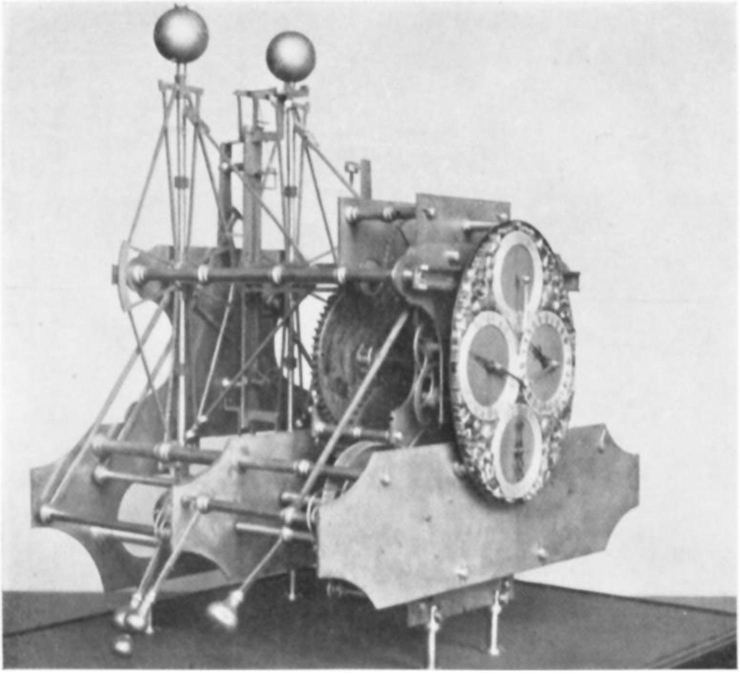
When the *Deptford* reached Port Royal, sixty-one days out from Portsmouth, the watch was found to be nine seconds slow, and on its return to Portsmouth, in very stormy weather, its total error after an absence of



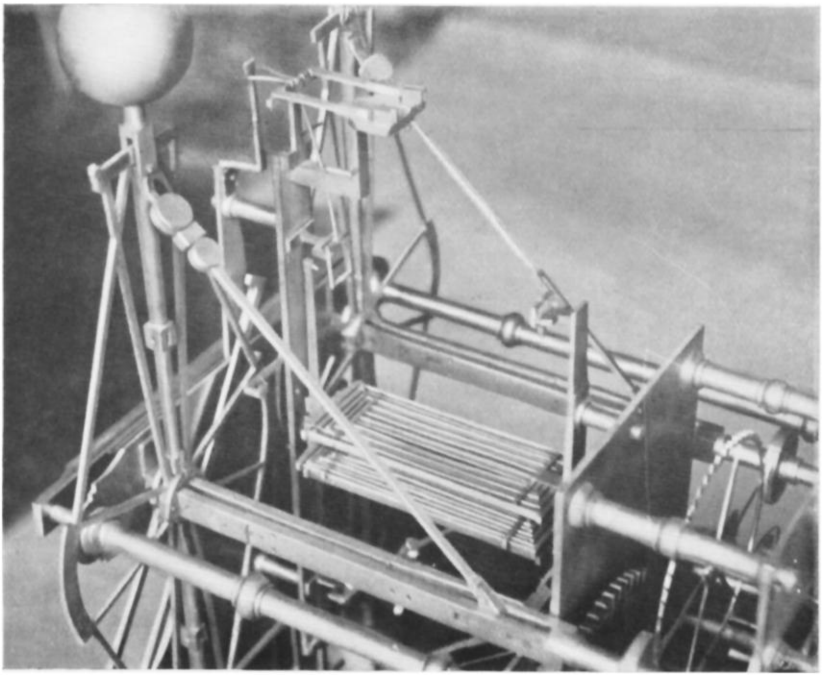
HARRISON'S FIRST CHRONOMETER: FRONT VIEW: DIALS AND HEADS OF BALANCES



BACK VIEW: THE COUPLED BALANCES



HARRISON'S FIRST CHRONOMETER: SIDE VIEW: TRAIN AND BALANCE



THE BALANCES AND GRIDIRON FROM ABOVE

five months was 1 min. $53\frac{1}{2}$ sec., corresponding to an error in longitude of $28\frac{1}{2}'$. Harrison's pride in his masterpiece was not unjustified.

The longitude of Jamaica, however, was then regarded as rather uncertain, and although the Board of Longitude advanced £5000 to Harrison on account of the reward, they demanded a fresh trial of the watch, and accordingly, in 1764, William Harrison and No. 4 were sent in H.M.S. *Tartar* to Barbados, accompanied by Dr. Maskelyne as representative of the Board. Harrison declared the rate of his watch, before sailing, as one second a day gaining. No. 4's error at Barbados was forty-three seconds, and after returning to England its total error, allowing for rate, was fifty-four seconds in a period of 156 days, corresponding to an error in longitude of about 14′—a far finer performance even than its voyage to Jamaica.

Then began a long and bitter struggle between Harrison and the Board of Longitude. Harrison contended that he had complied with the terms of the Act, and demanded the £20,000. The Board pointed out that the winning method, whatever it was, had to be shown "generally practicable and useful," and they demanded that he should first explain, and give drawings of, the mechanism of his timekeeper, also that a copy of it should be made by some other person. After much wrangling and paper warfare, Harrison complied with these conditions, and took his timekeeper to pieces before a committee of scientists and watchmakers nominated by the Board. Even then there was much delay; but in 1765 Harrison was paid another £5000, and finally in 1773, after the personal intervention of H.M. King George III., he received a further £8750, which completed the amount of the reward. The Board, however, entered a silent but effective protest against the finality of his work by immediately procuring the passage of an Act of Parliament offering a further reward of £10,000 for any means of finding the longitude within half a degree. They stipulated that, if this were competed for by a timekeeper, such machine's total error should not exceed four minutes in six months.

The copy of Harrison's watch demanded by the Board was made by Larcum Kendall in 1766–1769. Kendall only contracted to make an exact part-for-part copy, without guaranteeing its performance, and charged £450 for it. This is the watch I have here, and its going, when tried at sea, reflected the greatest credit on both Harrison and Kendall. Captain Cook had it with him in the *Resolution* on his Antarctic voyage, 1772–1775, which, with its alternations of dead calm and furious gales, tropical heat and extreme cold, was as severe a test as could well be imagined, yet so well did the watch perform that Cook remarks in his Journal, "I must here take note that our longitudes can *never* be erroneous while we have so good a guide as Mr. Kendall's watch." He made a special point, also, of asking for this watch when he sailed again in the *Resolution* on his third voyage in 1776. It is curious to note that the accuracy of its going put the Board in the anomalous position of continuing to offer a reward of

£10,000 for a feat which this chronometer in their possession had already shown itself fully capable of performing.

Harrison, while waiting to receive his reward, made a fifth watch, an improved No. 4, which is now in the Guildhall Museum, and in 1775 he published an extraordinary pamphlet called "A description concerning such mechanism as will afford a nice or true mensuration of time." This work, which, unlike previous pamphlets published in his name, was his own unaided production, affords proof of the statement, often made in his lifetime, that it was exceedingly difficult for him to express his ideas, either verbally or in writing. The manuscript of it is in my possession, and, although the handwriting is quite clear, the meaning is often unintelligible.

Harrison, who thus ended his long and laborious life in the enjoyment of well-deserved success and reward, died in 1776, aged eighty-three, and was buried at Hampstead.

Although he had "blazed the trail," his chronometer was superseded almost immediately by others of simpler design. Only two men followed in his footsteps, Larcum Kendall and Thomas Mudge. Kendall, as we have seen, made the copy of No. 4 which performed so well, and he then tried his hand at simplifying Harrison's construction. He made two attempts at this, one of which was the famous chronometer stolen with the *Bounty*, and recovered fifty years later in Chile, but neither was so good a timekeeper as his copy of No. 4. The *Bounty's* chronometer, which, by courtesy of the Secretary of the Royal United Service Institution, I examined a short time ago, is simply a large ordinary watch, with a compensation curb, but no remontoire. It is still in going order. Kendall's second attempt, now at Greenwich, is a watch with a peculiar escapement of his own designing, and he afterwards made a beautiful little pocket-chronometer, now in the Guildhall Museum, in which he reverted to the principles of No. 4 and fitted a remontoire.

Far more important, in the history of the chronometer, is Thomas Mudge, a London maker who devoted the last twenty years of his life to improving marine timekeepers. He was a gifted horologist and a most amiable man, but his chronometer, beautiful piece of mechanism though it was, proved far too complicated. It may be described as an over-developed No. 4. Harrison's watch went for a day, Mudge's for eight days: No. 4 had a single balance spring and compensation curb, Mudge fitted two of each: Harrison's remontoire was wound eight times a minute, Mudge's machine had two remontoires, each wound up three hundred times a minute: lastly, Harrison's workmanship was good, but Mudge's was exquisite.

His movement embodies two balance springs, one for regulating and one for compensation. Two small spiral springs form the remontoires, and they are alternately wound by the escape wheel and unlocked by the balance. The upper and lower ends of the balance staff run between friction wheels. Adjusting this escapement was no simple matter, but the weak spot of Mudge's chronometers was not so much that as the defective, although ingenious, compensation.

It is due to Mudge's memory to say that he planned his chronometer before becoming acquainted with the details of Harrison's. He built three of them, but, although repeatedly tried at the Royal Observatory, they did not satisfy the new conditions imposed by the Board of Longitude. He finally petitioned Parliament for a reward, and, in spite of the Board, was awarded £3000. He died in 1794. Mudge's best title to fame is that he was the inventor of the detached lever escapement, now almost universally employed in watches.

But Mudge was passed in the race by other competitors. Foremost amongst them, and second only to Harrison himself, is Pierre Le Roy, a Frenchman, and the true father of the modern chronometer. In 1766 Le Roy presented to King Louis XVI. a marine chronometer of his invention, embodying all the main features of a present-day one. It was suspended in gimbals, which removed all errors of position, and had a single dial showing hours, minutes, and seconds, the hour-hand turning to the left.

The machine really consisted of an enormous balance, weighing about 5 ozs., with a comparatively small watch-movement to keep it swinging. It was suspended by a thin piece of harpsichord wire, and kept in position by friction-rollers. This suspension is very delicate, but fragile, as is shown by the fact that while Le Roy was posting down to Havre with two of these chronometers for trial at sea, the wire of one balance was broken by the motion of the carriage. Nothing daunted, however, he fitted a new wire at his inn that night, and reached Havre with both of his chronometers going.

Le Roy was the discoverer of the fact that any balance spring can be made practically isochronous—that is, able to make the balance describe long and short arcs in equal times—if it be of one particular length, which can be found by experiment. Accordingly he abandoned the use of a compensation curb, which acts by altering the length of the balance spring. Also, having obtained an isochronous spring (or springs, for he used two), it was unnecessary to employ either a remontoire or a fusee, since variations in the driving force might alter the arc described by the balance, but could not affect its time of describing them. Consequently he fitted his chronometer with what is called a "going barrel," now used in almost all watches, in which the mainspring acts on the train of wheels with a force varying directly as its tension.

His escapement, too, was a tremendous improvement on Harrison's. It was "detached": that is to say, it left the balance free to swing, except for the moment when it was unlocking the escapement and receiving impulse. Lastly, he put his compensation in the place where, as Harrison pointed out, it ought to be—in the balance. He invented a balance composed of brass and steel strips, which we shall afterwards find Arnold and Earnshaw using, but he finally devised and adopted a very ingenious one which had two thermometer tubes filled with mercury and alcohol, and so arranged that a rise of temperature diminished the inertia of the balance in such a proportion as to compensate for the weakening of the spring, and *vice versâ*. A similar balance was successfully used, long afterwards, by an English maker named Loseby.

Le Roy's chronometer, which is preserved in the *Musée des Arts et Métiers* at Paris, was tried at sea, with another like it, in 1767 and 1768, and their performances in both cases were extremely good. Le Roy, however, never received such public recognition or reward as had been granted to Harrison. As M. Gros, in his excellent treatise on 'Escapements,' has indignantly remarked (I translate), "Harrison, for the invention of a mechanism which was abandoned almost immediately, received £20,000: the Frenchman of genius, who has added one more to the glories of France, received—a medal."

Since Le Roy's chronometer was completed before any particulars of Harrison's work had been published, its design was entirely original, and reflects the very greatest credit upon its inventor.

Contemporary with Le Roy was his great rival, Ferdinand Berthoud, who also devoted many years to the improvement of chronometers. He is chiefly remarkable for the extraordinary variety of his conceptions. Some of his chronometers were controlled by a balance; some by two balances geared together; one by a pendulum. Some were driven by weights, and some by springs. Some had compensation curbs, some compensation balances; at least one had both. Some had cylinder escapements, some detent escapements, and some were fitted with modifications of various other patterns. Some were fixed, some slung in gimbals; some had their dials vertical, some horizontal, and the dials themselves exhibited many differences of arrangement. Berthoud's industry and inventiveness were amazing (he was also, in his spare time, one of the most voluminous writers on horology who ever lived), but his work does not exhibit quite the scientific thoroughness or the perfect adaptation of means to ends which characterize that of Le Roy.

I regret very much that I am unable to show you portraits of either Le Roy or Berthoud, but I have here a little chronometer by Berthoud. It is an early one, No. 37, made about 1785. It is still a good timekeeper, and in one or two points I prefer it to a modern chronometer, since you can wind it without turning it upside down, as you have to do nowadays; you can lock the balance in a moment without doing it any injury, and you can set the hands to any hour, minute, and second you like while the chronometer is going. It has a compensation curb *and* a compensation balance. The escapement is a detached one—a pivoted detent.

But at the same time that Berthoud was making machines such as this, the mechanism of the chronometer was undergoing its last important development at the hands of two Englishmen, John Arnold and Thomas Earnshaw. These two were contemporaries, and hated each other cordially.

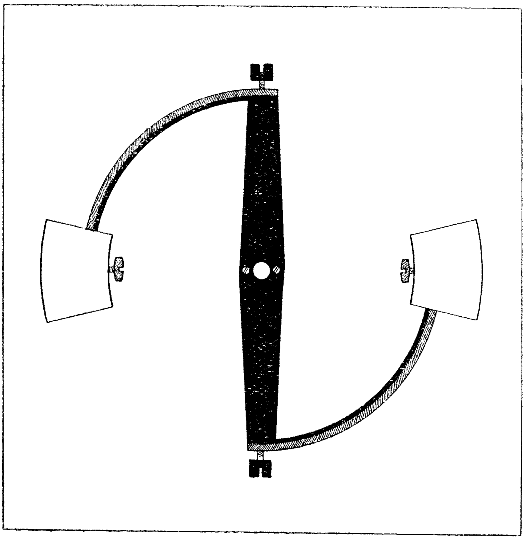
John Arnold was for some time a gunsmith, and first made his mark in London as a clockmaker in 1765, when he presented to H.M. King George III. an extraordinarily small watch, which was the size of a silver two-penny piece, and weighed 127 grains. In spite of its absurdly small size it was a half-quarter repeater. He turned his attention to chronometers, and three of his early efforts were sent aboard the *Resolution* and *Adventure*, on their Antarctic voyage, for comparison with Kendall's copy of Harrison's No. 4. Two of these are in possession of the Royal Society, who have kindly permitted me to exhibit them. They have compensation curbs, like No. 4, and most peculiar escapements, which are quite unique, and impossible to describe briefly. They were not good timekeepers, and Arnold set about making better ones.

And here it becomes difficult to distinguish between his work and that of Earnshaw. Both men brought out forms of compensating balance, and of detached escapement, substantially resembling each other. Arnold patented a compensation balance, which he subsequently abandoned, in 1775, and took out a patent for his final form of escapement in 1782. Earnshaw never patented his balance, but took out a patent for his escapement, or, rather, got a maker named Wright to patent it for him, in 1783. So that in point of priority Arnold's patent was a year ahead of Earnshaw's. On the other hand, Earnshaw repeatedly asserted, once in Arnold's presence and that of the Lord Mayor, that Arnold had learnt of his invention from a maker named Brockbank, and filed his specification a week later; and to this challenge Arnold never made any public reply.

Nowadays it is possible to admit the merits of both men without further probing this vexed question, which is essentially this—either the inventions were independent or Arnold borrowed from Earnshaw. As the improvements made by both men had much in common, and those of Earnshaw became the standard, I will not confuse you by illustrating or describing Arnold's. He never entered any chronometers for public trial at Greenwich, but—and this is the important point—he established a manufactory of them at Chigwell in Essex, and so for the first time made them available to seamen generally. This was a service the importance of which is hard to over-rate. No longer were chronometers to be the jealously prized possession of a few chosen navigators. In 1799, when Arnold died, he and his men had made over one thousand good chronometers, and Earnshaw upwards of five hundred, and never again was there to be any need for ships to run the risks they had done even twenty years before.

The Board of Longitude paid Arnold, at various dates, £1322 in recognition of his valuable work, and in 1806 they made it up to £3000, paying the balance to his son, John Roger Arnold, who succeeded him.

Thomas Earnshaw, Arnold's rival, was born in 1749. From all accounts, he was an independent and straightforward man, somewhat abrupt and unpolished in his manner, but a consummate horologist. He worked his way up from the position of a watch-jobber to that of a chronometer manufacturer. In 1783, as we have seen, he introduced his new escapement and balance. The escapement's action is very simple, yet in the hundred and forty years since he invented it no better one has been devised, nor is it easy to see how it could be simplified or bettered. A tooth of the escape wheel is locked by a detent mounted on a spring, which carries a second small spring on its tip. As the balance swings, a projection on a roller mounted on the balance-staff engages with the small spring, which presses on the detent-spring and bends it slightly, thus releasing the tooth. The escape-wheel promptly turns, and in so doing another tooth falls on a stone fixed in the roller and gives the balance an impulse. The detent-spring resumes its position, and the next tooth locks on it. As the balance swings back, the projection again hits the small spring, but this now merely gives way to it, and the tooth remains locked. This escapement is the best known for use in chronometers. It only gives impulse in one direction, and is not self-starting.



Earnshaw's balance

Arnold's escapement was very like this, except that the escape-wheel turned the other way, and the detent unlocked by moving inwards. J. R. Arnold, however, is known to have admitted, in private conversation, that Earnshaw's escapement was the better, and after the latter's death in 1829 he adopted it. Still, Arnold's was a perfectly adequate escapement. I have a pocket chronometer fitted with it, made about 1815, which is an excellent timekeeper, though subject to the defect of all watches with a chronometer escapement, that any sudden jerk may stop them, and they will not start themselves. The lever escapement, on the other hand, is self-starting, hence its practically universal employment in watches. It would be used in chronometers, too, but for the fact that it needs oiling, and that the ageing of the oil affects its performance. The chronometer escapement needs no oil.

In Earnshaw's balance the curved arms are made, like Harrison's "thermometer curb," of brass and steel strips, not riveted, but fused together, the brass outside. As the temperature rises, the weights are brought slightly nearer the centre and so decrease the inertia of the balance. The two small screws are for mean time adjustment.

Earnshaw was paid £3000 in 1806 as a reward for his improvements. But he was much dissatisfied with this amount, and in 1808 issued a pamphlet called 'Longitude—An Appeal to the Public,' in which he stated his grievances. This work, although perfectly honest and candid, and containing valuable information, is a masterpiece of unconscious humour. For instance, he winds up an impassioned apostrophe to the Hydrographer of the Navy with the delightful peroration, "Do this, and Earnshaw is your friend"!

And at this point the history of the chronometer, as far as the development of its mechanism is concerned, practically terminates. It is, indeed, a conclusive testimony to the finality of Earnshaw's work that one of the greatest mechanicians who ever lived, Abraham Louis Breguet, could find practically nothing in the chronometer, as he left it, which would bear improvement. Breguet devised an exceedingly delicate and beautiful remontoire escapement, which he used in some of his chronometers, but which gave no better results than Earnshaw's; and he showed his extraordinary power of cutting the Gordian knot of a mechanical difficulty by producing a mechanism which entirely did away with the position-errors of pocket chronometers. This he did by a device which he called a "tourbillon," and which provided that the escapement gradually revolved in a circle, and consequently had no fixed position.

But, generally speaking, the transformation of the chronometer, from a possibility to a commercial actuality, took place between the years 1761 and 1785, and later makers have more or less accepted the mechanism of the chronometer as Earnshaw left it, and devoted their energy to improving the compensation. For the simple compensation balance devised by Earnshaw can only be absolutely correct at two particular temperatures. Between these a chronometer with that compensation will gain, and outside them it will lose. Several devices, however, have since been introduced which more or less surmount this defect.

Here I must finish my sketch of the chronometer's history, and, in concluding it, let me express the hope that, in whatever manner the future history of the chronometer and its makers may be affected by the recent developments of wireless time signals and wireless direction finding, it may be many a long year before the chronometer as a means of finding longitude is superseded, and that even when Macaulay's New Zealander, in years to come, visits the ruins of Greenwich Observatory and finds the chronometer-room long deserted and forgotten, there may yet be some living who still remember the little band of men who bequeathed us the chronometer of to-day—Le Roy, Mudge, Berthoud, Arnold, Earnshaw, and, above all, John Harrison.

Before the paper the PRESIDENT said: I have much pleasure in introducing to you Commander Gould, one of the staff of the Hydrographer at the Admiralty, who has for a long time past taken a special interest in chronometer construction.

Commander Gould then read the paper printed above, and a discussion followed.

The PRESIDENT: The Hydrographer of the Navy has honoured us with his presence, and we shall be indebted to him if he will open the discussion.

The HYDROGRAPHER: I think we have all listened with very great interest to this lecture, which is somewhat technical, and perhaps some of those present did not quite understand all the points; but I would like first to say this, that we are extremely fortunate for the permission which has been afforded us for Lieut.-Commander Gould to give his lecture under the auspices of the Royal Geographical Society. It is apparent, I think, that a great deal of research and study has been compressed into a comparatively short lecture in order to cover so much ground going back over two hundred years, and that has only been possible by the assistance of those interested in horology; and I should like to say how very much we are indebted to the Astronomer Royal, for it is only by his extreme courtesy that we are able to see all these very delicate and extremely valuable instruments. The archives of the Royal Observatory have been carefully studied, and much has been included in the interesting form of this paper. It is quite true to say this, that when we go back to such a period as one hundred and fifty years ago—and it can be amply borne out by complete evidence—many longitudes determined by Cook's chronometers stand to this day without material alteration. There were no submarine cables or wireless telegraphy in those days, and voyages occupied generally four years—to this day those longitudes remain practically as they were then determined, and it is due to the workmanship of these chronometers which we have seen, one of which was actually on board the *Resolution*, that such results were possible. Coming to a later period, it is the same on the coast of South America, particularly Chile and Peru. So much for the past. Dealing with the almost immediate past (I refer to the epoch during the war), there is a point which may perhaps not have struck you, and that is the immense number of chronometers then made and the very large number lost by sinkings. Many of the chronometers made in this country were by people not necessarily bearing English names, and our then enemies were responsible for very good chronometers of high workmanship. We reached a position towards the middle of 1917 when they were of extreme value. There were not enough to go round, and the Admiralty had perforce to ask those who possessed chronometers, perhaps of great age and history attaching to them as family heirlooms, to lend or dispose of them to the Admiralty. These were, in most cases, of quite good workmanship and only required cleaning, and they were used and "did their bit" in the war. The response was very cordial, and many owners had already volunteered in this way. The difficulty in obtaining chronometers is not being able to turn them out quickly. The war thus produced a severe strain on British enterprise, but we were able to meet all requirements, largely through the good help afforded by the Astronomer Royal and his able staff, for it is not sufficient to manufacture chronometers—they have to be rated and put in proper working order at Greenwich Observatory before they can be issued. Dealing with the future, I think the lecturer alluded very briefly to wireless