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Paper 6

On the Origin of Clockwork, Perpetual Motion Devices, and the Compass

Derek J. de Solla Price

ON THE ORIGIN OF CLOCKWORK, PERPETUAL MOTION DEVICES AND THE COMPASS

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Ancestor of the mechanical clock has been thought by some to be the sundial. Actually these devices represent two different approaches to the problem of timekeeping. True ancestor of the clock is to be found among the highly complex astronomical machines which man has been building since Hellenic times to illustrate the relative motions of the heavenly bodies.

This study—its findings will be used in preparing the Museum's new hall on the history of timekeeping—traces this ancestry back through 2,000 years of history on three continents.

THE AUTHOR: *Derek J. de Solla Price wrote this paper while serving as consultant to the Museum of History and Technology of the Smithsonian Institution's United States National Museum.*

In each successive age this construction, having become lost, is, by the Sun's favour, again revealed to some one or other at his pleasure. (*Sūrya Siddhanta*, ed. Burgess, xiii, 18–19.)

THE HISTORIES of the mechanical clock and the magnetic compass must be accounted amongst the most tortured of all our efforts to understand the origins of man's important inventions. Ignorance has too often been replaced by conjecture, and conjecture by misquotation and the false authority of "common knowledge" engendered by the repetition of legendary histories from one generation of textbooks to the next. In what follows, I can only hope that the adding of a strong new trail and the eradication of several false and weaker ones will lead us nearer to a balanced and integrated understanding of medieval invention and the intercultural transmission of ideas.

For the mechanical clock, perhaps the greatest hindrance has been its treatment within a self-contained "history of time measurement" in which sundials, water-clocks and similar devices assume the natural role of ancestors to the weight-driven escapement clock in the early 14th century.[1] This view must presume that a generally sophisticated knowledge of gearing antedates the invention of the clock and extends back to the Classical period of Hero and Vitruvius and such authors well-known for their mechanical ingenuities.

Furthermore, even if one admits the use of clocklike gearing before the existence of the clock, it is still

[1] This traditional view is expressed by almost every history of horology. An ultimate source for many of these has been the following two classic treatments: J. Beckmann, *A history of inventions and discoveries*, 4th ed., London, 1846, vol. 1, pp. 340 ff. A. P. Usher, *A history of mechanical inventions*, 2nd ed., Harvard University Press, 1954, pp. 191 ff., 304 ff.

necessary to look for the independent inventions of the weight-drive and of the mechanical escapement. The first of these may seem comparatively trivial; anyone familiar with the raising of heavy loads by means of ropes and pulley could surely recognize the possibility of using such an arrangement in reverse as a source of steady power. Nevertheless, the use of this device is not recorded before its association with hydraulic and perpetual motion machines in the manuscripts of Riḍwan, *ca.* 1200, and its use in a clock using such a perpetual motion wheel (mercury filled) as a clock escapement, in the astronomical codices of Alfonso the Wise, King of Castile, *ca.* 1272.

The second invention, that of the mechanical escapement, has presented one of the most tantalizing of problems. Without doubt, the crown and foliot type of escapement appears to be the first complicated mechanical invention known to the European Middle Ages; it heralds our whole age of machine-making. Yet no trace has been found either of a steady evolution of such escapements or of their invention in Europe, though the astronomical clock powered by a water wheel and governed by an escapement-like device had been elaborated in China for several centuries before the first appearance of our clocks. We must now rehearse a revised story of the origin of the clock as it has been suggested by recent researches on the history of gearing and on Chinese and other astronomical machines. After this we shall for the first time present evidence to show that this story is curiously related to that of the *Perpetuum Mobile*, one of the great chimeras of science, that came from its medieval origin to play an important part in more recent developments of energetics and the foundations of thermodynamics.[2] It is a curious mixture, all the more so because, tangled inextricably in it, we shall find the most important and earliest references to the use of the magnetic compass in the West. It seems that in revising the histories of clockwork and the magnetic compass, these considerations of perpetual motion devices may provide some much needed evidence.

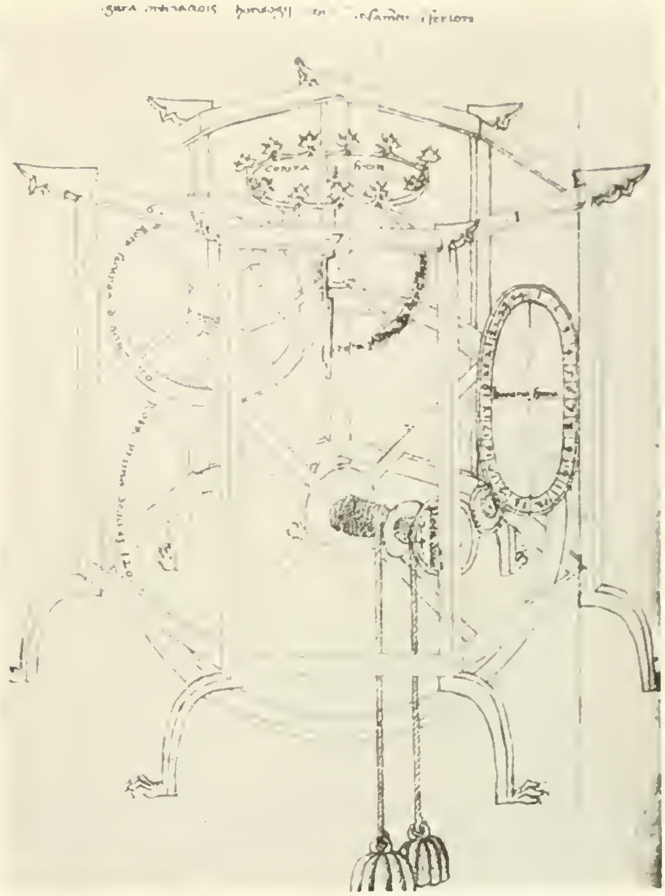

Figure 1.—Framework Structure of the Astronomical Clock of Giovanni de Dondi of Padua, A. D. 1364.

Power and Motion Gearing

It may be readily accepted that the use of toothed wheels to transmit power or turn it through an angle was widespread in all cultures several centuries before the beginning of our era. Certainly, in classical times they were already familiar to Archimedes (born 287 B.C.),[3] and in China actual examples of wheels and moulds for wheels dating from the 4th century

[2] There is a considerable literature dealing with the later evolution of perpetual motion devices. The most comprehensive treatment is H. Dircks, *Perpetuum mobile*, London, 1861; 2nd ser., London, 1870. So far as I know there has not previously been much discussion of the history of such devices before the renaissance.

[3] For the early history of gearing in the West see C. Matschoss, *Geschichte des Zahnrades*, Berlin, 1940. Also F. M. Feldhaus, *Die geschichtliche Entwicklung des Zahnrades in Theorie und Praxis*, Berlin, 1911.

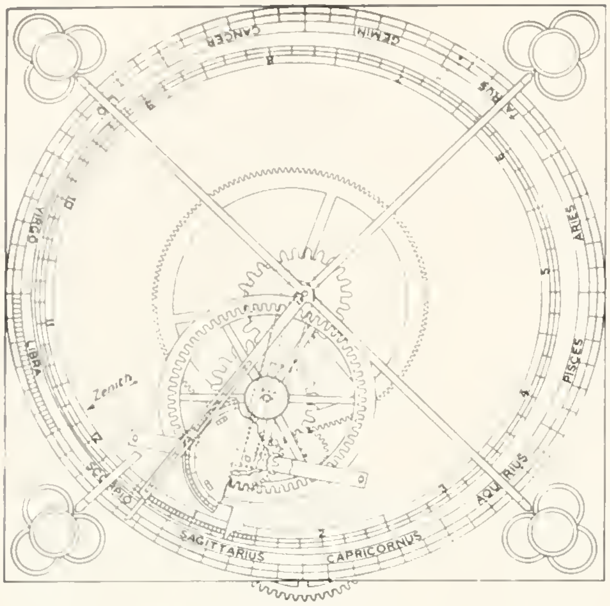

Figure 2. ASTRONOMICAL CLOCK of de Dondi, showing gearing on the dial for Mercury and escapement crown wheel. Each of the seven side walls of the structure shown in figure 1 was fitted with a dial.

B.C. have been preserved.[4] It might be remarked that these "machine" gear wheels are characterized by having a "round number" of teeth (examples with 16, 24 and 40 teeth are known) and a shank with a square hole which fits without turning on a squared shaft. Another remarkable feature in these early gears is the use of ratchet-shaped teeth, sometimes even twisted helically so that the gears resemble worms intermeshing on parallel axles.[5] The existence of windmills and watermills testifies to the general familiarity, from classical times and through the middle ages, with the use of gears to turn power through a right angle.

Granted, then, this use of gears, one must guard against any conclusion that the fine-mechanical use of gears to provide special ratios of angular movement was similarly general and widespread. It is customary to adduce here the evidence of the hodometer (taximeter) described by Vitruvius (1st century B.C.) and by Hero of Alexandria (1st century A.D.) and the ingenious automata also described by this latter author and his Islamic followers.[6] One may also cite the use of the reduction gear chain in power machinery as used in the geared windlass of Archimedes and Hero.

Unfortunately, even the most complex automata described by Hero and by such authors as Ridwān contain gearing in no more extensive context than as a means of transmitting action around a right angle. As for the windlass and hodometer, they do, it is true, contain whole series of gears used in steps as a reduction mechanism, usually for an extraordinarily high ratio, but here the technical details are so etherial that one must doubt whether such devices were actually realized in practice. Thus Vitruvius writes of a wheel 4 feet in diameter and having 400 teeth being turned by a 1-toothed pinion on a cart axle, but it is very doubtful whether such small teeth, necessarily separated by about 3/8 inch, would have the requisite ruggedness. Again, Hero mentions a wheel of 30 teeth which, because of imperfections, might need only 20 turns of a single helix worm to turn it! Such statements behove caution and one must consider whether we have been misled by the 16th- and 17th-century editions of these authors, containing reconstructions now often cited as authoritative but then serving as working diagrams for practical use in that age when the clock was already a familiar and complex mechanism. At all events, even if one admits without substantial evidence that such gear reduction devices were familiar from Hellenistic times onwards, they can hardly serve as more than very distant ancestors of the earliest mechanical clocks.

Mechanical Clocks

Before proceeding to a discussion of the controversial evidence which may be used to bridge this gap between the first use of gears and the fully-developed mechanical clock we must examine the other side of this gap. Recent research on the history of early me-

[4] A general account of these important archaeological objects will be published by J. Needham, *Science and civilisation in China*, Cambridge, 1959(?), vol. 4. The original publications (in Chinese) are as follows: Wang Chen-to, "Investigations and reproduction in model form of the south-pointing carriage and hodometer," *National Peiping Academy Historical Journal*, 1937, vol. 3, p. 1. Liu Hsien-chou, "Chinese inventions in horological engineering," *Ch'ing-Hua University Engineering Journal*, 1956, vol. 4, p. 1.

[5] For illustrations of intermeshing worms in Indian cotton mills, see Matschoss, *op. cit.* (footnote 3), figs. 5, 6, 7, p. 7.

[6] It is interesting to note that the Chinese hodometer was contemporary with that of Hero and Vitruvius and very similar in design. There is no evidence whatsoever upon which to decide whether there may have been a specific transmission of this invention or even a "stimulus diffusion."

chanical clocks has demonstrated certain peculiarities most relevant to our present argument.

THE EUROPEAN TRADITION

If one is to establish a *terminus ante quem* for the appearance of the mechanical clock in Europe, it would appear that 1364 is a most reasonable date. At that time we have the very full mechanical and historical material concerning the horological masterpiece built by Giovanni de Dondi of Padua,[7] and probably started as early as 1348. It might well be possible to set a date a few decades earlier, but in general as one proceeds backwards from this point, the evidence becomes increasingly fragmentary and uncertain. The greatest source of doubt arises from the confusion between sundials, waterclocks, hand-struck time bells, and mechanical clocks, all of which are covered by the term *horologium* and its vernacular equivalents.

Temporarily postponing the consideration of evidence prior to *ca.* 1350, we may take Giovanni de Dondi as a starting point and trace a virtually unbroken lineage from his time to the present day. One may follow the spread of clocks through Europe, from large towns to small ones, from the richer cathedrals and abbeys to the less wealthy churches.[8] There is the transition from the tower clocks—showpieces of great institutions—to the simple chamber clock designed for domestic use and to the smaller portable clocks and still smaller and more portable pocket watches. In mechanical refinement a similar continuity may be noted, so that one sees the cumulative effect of the introduction of the spring drive (*ca.* 1475), pendulum control (*ca.* 1650), and the anchor escapement (*ca.* 1680). The transition from de Dondi to the modern chronometer is indeed basically continuous, and though much research needs to be done on special topics, it has an historical unity and seems to conform for the most part to the general pattern of steady mechanical improvement found elsewhere in the history of technology.

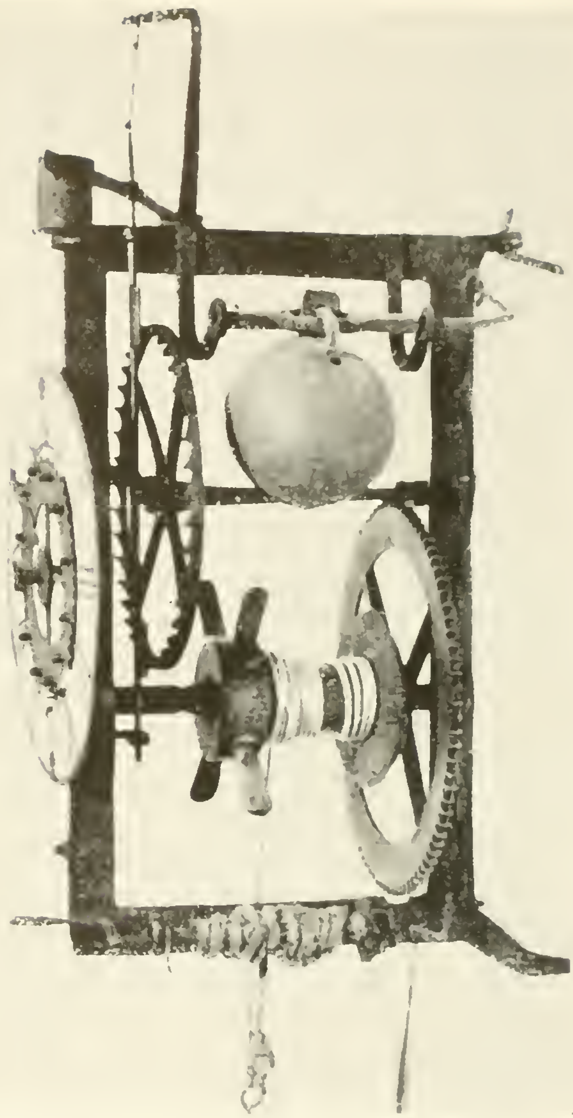

Figure 3. German Wall Clock, Probably About 1450, showing the degeneration in complexity from that of de Dondi's clock.

[7] A summary of the content of the manuscript sources, illustrated by the original drawings, has been published by H. Alan Lloyd, *Giovanni de Dondi's horological masterpiece, 1364*, without date or imprint (?Lausanne, 1955), 23 pp. It should be remarked that de Dondi declines to describe the workings of his crown and foliot escapement (though it is well illustrated) saying that this is of the "common" variety and if the reader does not understand such simple things he need not hope to comprehend the complexities of this mighty clock. But this may be bravado to quite a large degree.

[8] See, for example, the chronological tables of the 14th century and the later mentions of clocks in E. Zinner, *Aus der Frühzeit der Räderuhr*, Munich, 1954, p. 29 ff. Unfortunately this very complete treatment tends to confuse the factual and legendary sources prior to the clock of de Dondi; it also accepts the very doubtful evidence of the "escapement" drawn by Villard of Honnecourt (see p. 107). An excellent and fully illustrated account of monumental astronomical clocks throughout the world is given by Alfred Ungerer, *Les horloges astronomiques*, Strasbourg, 1931, 514 pp. Available accounts of the development of the planetarium since the middle ages are very brief and especially weak on the early history: Helmut Werner, *From the Aratus globe to the Zeiss planetarium*, Stuttgart, 1957; C. A. Crommelin, "Planetaria, a historical survey," *Antiquarian Horology*, 1955, vol. 1, pp. 70–75.

Most remarkable however is the earliest period of this seemingly steady evolution. Side by side with the advances made in the earliest period extending for less than two centuries from the time of de Dondi one may see a spectacular process of degeneration or devolution. Not only is de Dondi's the earliest clock of which we have a full and trustworthy account, it is also far more complicated than any other (see figs. 1, 2) until comparatively modern times! Moreover, it was not an exceptional freak. There were others like it, and one cannot therefore reject as accidental this process of degeneration that occurs at the very beginning of the certain history of the mechanical clock in Europe.

On the basis of such evidence I have suggested elsewhere [9] that the clock is "nought but a fallen angel from the world of astronomy." The first great clocks of medieval Europe were designed as astronomical showpieces, full of complicated gearing and dials to show the motions of the Sun, Moon and planets, to exhibit eclipses, and to carry through the involved computations of the ecclesiastical calendar. As such they were comparable to the orreries of the 18th century and to modern planetariums: that they also showed the time and rang it on bells was almost incidental to their main function. One must not neglect, too, that it was in their glorification of the rationality of the cosmos that they had their greatest effect. Through milleniums of civilization, man's understanding of celestial phenomena had been the very pinnacle of his intellect, and then as now popular exhibition of this sort was just as necessary, as striking, and as impressive. One does not have to go far to see how the paraphernalia of these early great astronomical clocks had great influence on philosophers and theologians and on poets such as Dante.

It is the thesis of this part of my argument that the ordinary time-telling clock is no affiliate of the other simple time-telling devices such as sundials, sand glasses and the elementary water clocks. Rather it should be considered as a degenerate branch from the main stem of mechanized astronomical devices (I shall call them protoclocks), a stem which can boast a continuous history filling the gap between the appearance of simple gearing and the complications of de Dondi. We shall return to the discussion of this main stem after analyzing the very recently discovered parallel stem from medieval China, which reproduced the same evolution of mechanized astronomical devices and incidental time telling. Of the greatest significance, this stem reveals the crucial independent invention of a mechanical escapement, a feature not found in the European stem in spite of centuries of intensive historical research and effort.

THE CHINESE TRADITION

For this section I am privileged to draw upon a thrilling research project carried out in 1956 at the University of Cambridge by a team consisting of Dr. Joseph Needham, Dr. Wang Ling, and myself.[10] In the course of this work we translated and commented on a series of texts most of which had not hitherto been made available in a Western tongue and, though well known in China, had not been recognized as important for their horological content. The key text with which we started was the "Hsin I Hsiang Fa Yao," or "New Design for a (mechanized) Armillary (sphere) and (celestial) Globe," written by Su Sung in A.D. 1090. The very full historical and technical description in this text enabled us to establish a glossary and basic understanding of the mechanism that later enabled us to interpret a whole series of similar, though less extensive texts, giving a history of prior development of such devices going back to the introduction of this type of escapement by I-Hsing and Liang Ling-tsan, in A.D. 725, and to what seems to be the original of all these Chinese astronomical machines, that built by Chang Hêng *ca.* A. D. 130. Filling the gaps between these landmarks are several other similar texts, giving ample evidence that the Chinese development is continuous and, at least from Chang Hêng onwards, largely independent of any transmissions from the West.

So far as we can see, the beginning of the chain in China (as indeed in the West) was the making of simple static models of the celestial sphere. An armillary sphere was used to represent the chief imaginary circles (*e.g.*, equator, ecliptic, meridians, etc.), or a solid celestial globe on which such circles could be drawn, together with the constellations of the fixed

[9] Derek J. Price, "Clockwork before the clock," *Horological Journal*, 1955, vol. 97, p. 810, and 1956, vol. 98, p. 31.

[10] For the use of this material I am indebted to my co-authors. I must also acknowledge thanks to the Cambridge University Press, which in the near future will be publishing our monograph, "Heavenly Clockwork." Some of the findings of this paper are included in shorter form as background material for that monograpn. A brief account of the discovery of this material has been published by J. Needham, Wang Ling, and Derek J. Price, "Chinese astronomical clockwork," *Nature*, 1956, vol. 177, pp. 600–602.

stars. The whole apparatus was then mounted so that it was free to revolve about its polar axis and another ring or a casing was added, external and fixed, to represent the horizon that provided a datum for the rising and setting of the Sun and the stars.

In the next stage, reached very soon after this, the rotation of the model was arranged to proceed automatically instead of by hand. This was done, we believe, by using a slowly revolving wheel powered by dripping water and turning the model through a reduction mechanism, probably involving gears or, more reasonably, a single large gear turned by a trip lever. It did not matter much that the time-keeping properties were poor in the long run; the model moved "by itself" and the great wonder was that it agreed with the observed heavens "like the two halves of a tally."

In the next, and essential, stage the turning of the water wheel was regulated by an "escapement" mechanism consisting of a weighbridge and trip levers so arranged that the wheel was held in check, scoop by scoop, while each scoop was filled by the dripping water, then released by the weighbridge and allowed to rotate until checked again by the trip-lever arrangement. Its action was similar to that of the anchor escapement, though its period of repose was much longer than its period of motion and, of course, its timekeeping properties were controlled not only by the mechanics of the device but also by the rate of flow of the dripping water.

The Chinese escapement may justifiably be regarded as a missing link, just halfway between the elementary clepsydra with its steady flow of water and the mechanical escapement in which time is counted by chopping its flow into cycles of action, repeated indefinitely and counted by a cumulating device. With its characteristic of saving up energy for a considerable period (about 15 minutes) before letting it go in one powerful action, the Chinese escapement was particularly suited to the driving of jackwork and other demonstration devices requiring much energy but only intermittent activity.

In its final form, as built by Su Sung after many trials and improvements, the Chinese "astronomical clock-tower" must have been a most impressive object. It had the form of a tower about 30 feet high, surmounted by an observation platform covered with a light roof (see fig. 4). On the platform was an armillary sphere designed for observing the heavens. It was turned by the clockwork so as to follow the diurnal rotation and thus avoid the distressing computations caused by the change of coordinates necessary when fixed alt-azimuth instruments were used. Below the platform was an enclosed chamber containing the automatically rotated celestial globe which so wonderfully agreed with the heavens. Below this, on the front of the tower was a miniature pagoda with five tiers; on each tier was a doorway through which, at due moment, appeared jacks who rang bells, clanged gongs, beat drums, and held tablets to announce the arrival of each hour, each quarter (they used 100 of them to the day) and each watch of the night. Within the tower was concealed the mechanism; it consisted mainly of a central vertical shaft providing power for the sphere, globe, and jackwheels, and a horizontal shaft geared to the vertical one and carrying the great water wheel which seemed to set itself magically in motion at every quarter. In addition to all this were the levers of the escapement mechanism and a pair of norias by which, once each day, the water used was pumped from a sump at the bottom to a reservoir at the top, whence it descended to work the wheel by means of a constant level tank and several channels.

There were many offshoots and developments of this main stem of Chinese horology. We are told, for example, that often mercury and occasionally sand were used to replace the water, which frequently froze in winter in spite of the application of lighted braziers to the interior of the machines. Then again, the astronomical models and the jackwork were themselves subject to gradual improvement: at the time of I-Hsing, for example, special attention was paid to the demarcation of ecliptic as well as the normal equatorial coordinates; this was clearly an influx from Hellenistic-Islamic astronomy, in which the relatively sophisticated planetary mathematics had forced this change not otherwise noted in China.

By the time of the Jesuits, this current of Chinese horology, long since utterly destroyed by the perils of wars, storms, and governmental reforms, had quite been forgotten. Matteo Ricci's clocks, those gifts that aroused so much more interest than European theological teachings, were obviously something quite new to the 16th-century Chinese scholars; so much so that they were dubbed with a quite new name, "self-sounding bells," a direct translation of the word "clock" (*glokke*). In view of the fact that the medieval Chinese escapement may have been the basis of European horology, it is a curious twist of fate that the high regard of the Chinese for

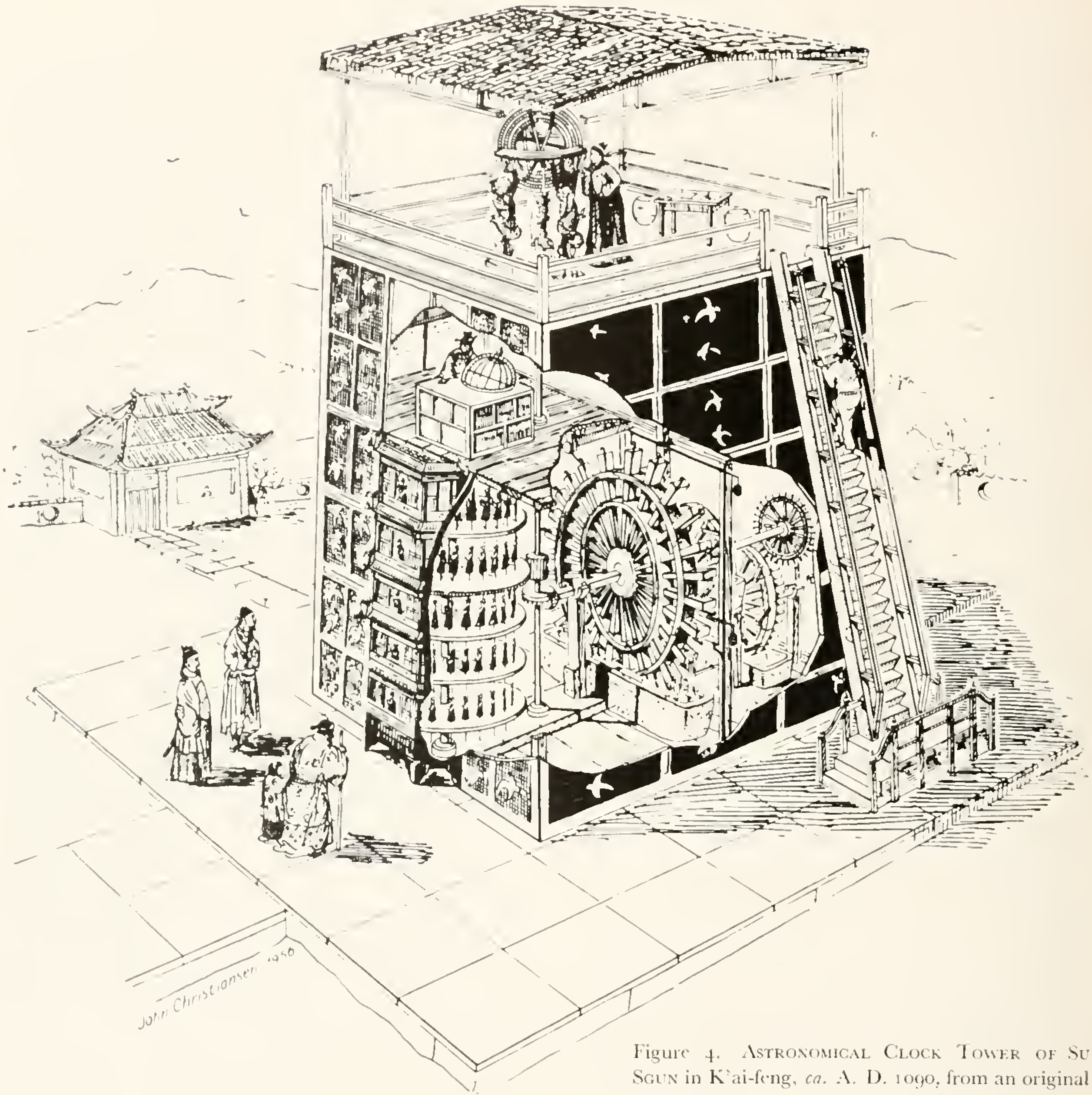

Figure 4. ASTRONOMICAL CLOCK TOWER OF SU SGUN in K'ai-feng, *ca.* A. D. 1090, from an original drawing by John Christiansen. (*Courtesy of Cambridge University Press.*)

European clocks should have prompted them to open their doors, previously so carefully and for so long kept closed against the foreign barbarians.

Mechanized Astronomical Models

Now that we have seen the manner in which mechanized astronomical models developed in China, we can detect a similar line running from Hellenistic time, through India and Islam to the medieval Europe that inherited their learning. There are many differences, notably because of the especial development of that peculiar characteristic of the West, mathematical astronomy, conditioned by the almost accidental conflux of Babylonian arithmetical methods with those of Greek geometry. However, the lines are surprisingly similar, with the exception only of the crucial invention of the escapement, a feature which seems to be replaced by the influx of ideas connected with perpetual motion wheels.

Most interesting and frequently cited is the bronze planetarium said to have been made by Archimedes and described in a tantalisingly fragmentary fashion by Cicero and by later authors. Because of its importance as a prototype, we give the most relevant passages in full.[11]

Cicero's descriptions of Archimedes' planetarium are (italics supplied):

Gaius Sulpicius Gallus . . . at a time when . . . he happened to be at the house of Marcus Marcellus, his colleague in the consulship [166 B.C.], ordered the celestial globe to be brought out which the grandfather of Marcellus had carried off from Syracuse, when that very rich and beautiful city was taken [212 B.C.]. . . . Though I had heard this globe (sphaerae) mentioned quite frequently on account of the fame of Archimedes, when I saw it I did not particularly admire it; for that other celestial globe, also constructed by Archimedes, which the same Marcellus placed in the temple of Virtue, is more beautiful as well as more widely known among the people. But when Gallus began to give a very learned explanation of the device, I concluded that the famous Sicilian had been endowed with greater genius than one would imagine possible for human being to possess. For Gallus told us that the other kind of celestial globe, which was solid and contained no hollow space, was a very early invention, the first one of that kind having been constructed by Thales of Miletus, and later marked by Eudoxus of Cnidus—a disciple of Plato, it was claimed—with constellations and stars which are fixed in the sky. He also said that many years later Aratus . . . had described it in verse. . . . But this newer kind of globe, he said, on which were delineated the motions of the sun and moon and of those five stars which are called wanderers, or, as we might say, rovers [*i. e.*, the five planets], contained more than could be shown on the solid globe, and the invention of Archimedes deserved special admiration because he had thought out a way to represent accurately by a single device for turning the globe, those various and divergent movements with their different rates of speed. And when Gallus moved [*i.e.*, set in motion] the globe, it was actually true that the moon was always as many revolutions behind the sun on the *bronze* contrivance as would agree with the number of days it was behind in the sky. Thus the same eclipse of the sun happened on the globe as would actually happen, and the moon came to the point where the shadow of the earth was at the very time when the sun (appeared?) out of the region . . [several pages are missing in the manuscript; there is only one].

De republica, I, xiv (21–22), Keyes' translation.

When Archimedes put together in a globe the movements of the moon, sun and five wandering [planets], he brought about the same effect as that which the god of Plato did in the Timaeus when he made the world, so that one revolution produced dissimilar movements of delay and acceleration.

Tusculanae disputationes, I, 63.

Later descriptions from Ovid, Lactantius, Claudian, Sextus Empiricus, and Pappus, respectively, are (italics supplied):

There stands a globe suspended by a Syracusan's skill in an enclosed bronze [frame, or sphere—or perhaps, in enclosed air], a small image of the immense vault [of heaven]; and the earth is equally distant from the top and bottom; that is brought about by its [*i. e.*, the outer bronze globe's] round form. The form of the temple [of Vesta] is similar. . . .

Ovid, *Fasti* (1st century, A.D.), VI, 277–280, Frazer's translation.

The Sicilian Archimedes, was able to make a reproduction and model of the world in concave *brass* (concavo aere similitudinem mundi ac figuram); in it he so arranged the *sun* and *moon* and resembling the celestial revolutions (caelestibus similes conversionibus); and while it revolved it exhibited not only the accession and recession of the sun and the waxing and waning of the moon (incrementa deminutionesque lunae), but also the unequal *courses of the stars*, whether fixed or wandering.

Lactantius, *Institutiones divinae* (4th century, A.D.), II, 5, 18.

Archimedes' sphere. When Jove looked down and saw the heavens figured in a sphere of *glass*, he laughed and said to the other gods: "Has the power of mortal effort gone so far? Is my handiwork now mimicked in a fragile globe?" An old man of Syracuse had imitated on earth the laws of the heavens, the order of nature, and the ordinances of the gods. Some hidden influence within the sphere directs the various courses of the *stars* and actuates the lifelike mass with definite motions. A false *zodiac* runs through a year of its own and a toy *moon* waxes and wanes month by month. Now bold invention rejoices to make its own heaven revolve and sets the *stars* [planets?] in motion by human wit . . .

Claudian, *Carmina minora* (*ca.* A.D. 400), LI (LXVIII), Platnaure's translation.

The things that move by themselves are more wonderful than those which do not. At any rate, when we behold an Archimedean sphere in which the sun and the rest of the stars move, we are immensely impressed by it, not by Zeus because we are amazed at the *wood*, or at the movements of these [bodies], but by the devices and causes of the movements.

Sextus Empiricus, *Adversus mathematicos* (3rd century, A.D.), IX, 115, Epps' translation.

[11] For these translations from classical authors I am indebted to Professor Loren MacKinney and Miss Harriet Lattin, who had collected them for a history, now abandoned, of planetariums. I am grateful for the opportunity of giving them here the mention they deserve.

Mechanics understand the making of spheres and know how to produce a model of the heavens (with the courses of the stars moving in circles?) by mean of equal and circular motions of *water*, and Archimedes the Syracusan, according to some, knows the cause and reasons for all of these.

Pappus (3rd century, A.D.), *Works* (Hultsch edition), VIII, 2, Epps' translation.

A similar arrangement seems to be indicated in another mechanized globe, also mentioned by Cicero and said to have been made by Posidonius:

But if anyone brought to Scythia or Britain the globe (sphaeram) which our friend Posidonius [of Apameia, the Stoic philosopher] recently made, in which each revolution produced the same (movements) of the *sun* and *moon* and *five* wandering stars as is produced in the sky each day and night, who would doubt that it was by exertion of reason? . . . Yet doubters . . . think that Archimedes showed more knowledge in producing movements by revolutions of a globe than nature (does) in effecting them though the copy is so infinitely inferior to the original . . .

De natura deorum, II, xxxiv-xxxv (88), Yonge's translation.

In spite of the lack of sufficient technical details in any case, these mechanized globe models, with or without geared planetary indicators (which would make them highly complex machines), bear a striking resemblance to the earliest Chinese device described by Chang Hêng. One must not reject the possibility that transmission from Greece or Rome could have reached the East by the beginning of the 2nd century, A.D., when he was working. It is an interesting question, but even if such contact actually occurred, very soon afterwards, as we shall see, the western and eastern lines of evolution parted company and evolved so far as can be seen, quite independently until at least the 12th century.

The next Hellenistic source of which we must take note is a fragmentary and almost unintelligible chapter in the works of Hero of Alexandria. Alone and unconnected with his other chapters this describes a model which seems to be static, in direct contrast to all other devices which move by pneumatic and hydrostatic pressures; it may well be conjectured that in its original form this chapter described a mechanized rather than a static globe:

The World represented in the Centre of the Universe: The construction of a transparent globe containing air and liquid, and also of a smaller globe, in the centre, in imitation of the World. Two hemispheres of glass are made; one of them is covered with a plate of bronze, in the middle of which is a round hole. To fit this hole a light ball, of small size, is constructed, and thrown into the water contained in the other hemisphere: the covered hemisphere is next applied to this, and, a certain quantity of the liquid having been removed from the water, the intermediate space will contain the ball; thus by the application of the second hemisphere what was proposed is accomplished.

Pneumatics, XLVI, Woodcroft's translation.

It will be noted that these earliest literary references are concerned with pictorial, 3-dimensional models of the universe, moved perhaps by hand, perhaps by waterpower; there is no evidence that they contained complicated trains of gears, and in the absence of this we may incline to the view that in at least the earliest such models, gearing was not used.

The next developments were concerned on the one hand with increasing the mathematical sophistication of the model, on the other hand with its mechanical complexity. In both cases we are most fortunate in having archaeological evidence which far exceeds any literary sources.

The mathematical process of mapping a sphere onto a plane surface by stereographic projection was introduced by Hipparchus and had much influence on astronomical techniques and instruments thereafter. In particular, by the time of Ptolemy (*ca.* A.D. 120) it had led to the successive inventions of the anaphoric clock and of the planispheric astrolabe.[12] Both these devices consist of a pair of stereographic projections, one of the celestial sphere with its stars and ecliptic and tropics, the other of the lines of altitude and azimuth as set for an observer in a place at some particular latitude.

In the astrolabe, an openwork metal rete containing markings for the stars, etc., may be rotated by hand over a disc on which the lines of altitude and azimuth are inscribed. In the anaphoric clock a disc engraved with the stars is rotated automatically behind a fixed grille of wires marking lines of altitude and azimuth. Power for rotating the disc is provided by a float rising in a clepsydra jar and connected, by a rope or chain passing over a pulley to a counterweight or by a rack and pinion, to an axle which supported the rotating disc and communicated this motion to it.[13]

[12] A. G. Drachmann, "The plane astrolabe and the anaphoric clock," *Centaurus*, 1954, vol. 3, pp. 183–189.

[13] A fuller description of the anaphoric clock and cognate waterclocks is given by A. G. Drachmann, "Ktesibios, Philon and Heron," *Acta Historica Scientiarum Naturalium et Medicinalium*, Copenhagen, 1948, vol. 4.

Figure 5.—Plate of Salzburg Anaphoric Clock, a reconstruction (see footnote 14) based on a photograph of the remaining fragment. (*Courtesy of Oxford University Press.*)

Parts of two such discs from anaphoric clocks have been found, one at Salzburg [14] and one at Grand in the Vosges,[15] both of them dating from the 2nd century A. D. Fortunately there is sufficient evidence to reconstruct the Salzburg disc and show that it must have been originally about 170 cm. in diameter, a heavy sheet of bronze to be turned by the small power provided by a float, and a large and impressive device when working (see fig. 5).

[14] First published by O. Benndorf, E. Weiss, and A. Rehm, *Jahreshefte des österreichischen archäologischen Institut in Wien*, 1903, vol. 6, pp. 32–49. I have given further details of its construction in *A history of technology*, ed. Singer, Holmyard, and Hall, 1957, vol. 3, pp. 604–605.

[15] L. Maxe-Werly, *Mémoires de la Société Nationale des Antiquaires de France*, 1887, vol. 48, pp. 170–178.

Literary accounts of the anaphoric clock have been analyzed by Drachmann; there is no evidence of the representation of planets moved either by hand or by automatic gearing, only in the important case of the sun was such a feature included of necessity. A model "sun" on a pin could be plugged in to any one of 360 holes drilled in at equal intervals along the band of the ecliptic. This pin could be moved each day so that the anaphoric clock kept step with the seasonal variation of the times of sunrise and sunset and the lengths of day and night.

The anaphoric clock is not only the origin of the astrolabe and of all later planetary models, it is also the first clock dial, setting a standard for "clockwise" rotation, and leaving its mark in the rotating dial and stationary pointer found on the earliest time-

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keeping clocks before the change was made to a fixed dial and moving hand.

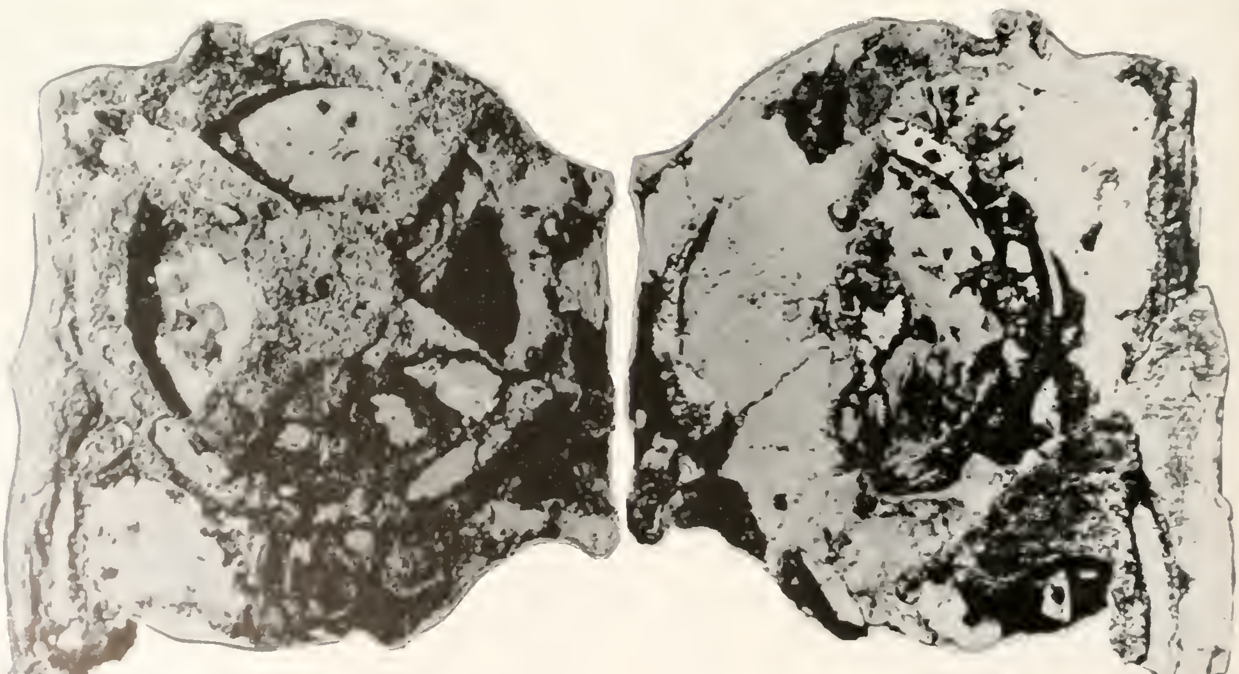
We come finally to a piece of archaeological evidence that surpasses all else. Though badly preserved and little studied it might well be the most important classical object ever found; entailing a complete re-estimation of the technical prowess of the Hellenistic Greeks. In 1901 a sunken treasure ship was discovered lying off the island of Antikythera, between Greece and Crete.[16] Many beautiful classical works of statuary were recovered from it, and these are now amongst the greatest treasures of the National Museum at Athens, Greece. Besides these obviously desirable art relics, there came to the surface some curious pieces of metal, accompanied by traces of what may have been a wooden casing. Two thousand years under the sea had reduced the metal to a mess of corroded fragments of plates, powdered verdigris, and still recognizable pieces of gear wheels.

If it were not for the established dates for other treasure from this ship, especially the minor objects found, and for traces of inscriptions on this metal device written in letters agreeing epigraphically with the other objects, one would have little doubt in supposing that such a complicated piece of machinery dated from the 18th century, at the earliest. As it is, estimates agree on *ca.* 65 B.C. ± 10 years, and we can be sure that the machine is of Hellenistic origin, possibly from Rhodes or Cos.

The inscriptions, only partly legible, lead one to believe that we are dealing with an astronomical calculating mechanism of some sort. This is born out by the mechanical construction evident on the fragments. The largest one (fig. 6) contains a multiplicity of gearing involving an annular gear working epicyclic gearing on a turntable, a crown wheel, and at least four separate trains of smaller gears, as well as a 4-spoked driving wheel. One of the smaller fragments (fig. 7, bottom) contains a series of movable rings which may have served to carry movable scales on one of the three dials. The third fragment (fig. 7, top) has a pair of rings carefully engraved and gradu-

[16] The first definitive account of the Antikythera machine was given by Perikles Rediadis in J. Svoronos, *Das Athener Nationalmuseum*, Athens, 1908, Textband I, pp. 43–51. Since then, other photographs (mostly very poor) have appeared, and an attempt at a reconstruction has been made by Rear Admiral Jean Theophanidis, *Praktika tes Akademias Athenon*, Athens, 1934, vol. 9, pp. 140–149 (in French). I am deeply grateful to the Director of the Athens National Museum, M. Karouzos, for providing me with an excellent new set of photos, from which figures 6–8 are now taken.

Figure 6.—Antikythera Machine, Largest Fragment. (*Photo courtesy of National Museum, Athens.*)



ated in degrees of the zodiac (this is, incidentally, the oldest engraved scale known, and micrometric measurements on photographs have indicated a maximum inaccuracy of about $\frac{1}{2}°$ in the 45° present).

Unfortunately, the very difficult task of cleaning the fragments is slow, and no publication has yet given sufficient detail for an adequate explanation of this object. One can only say that although the problems of restoration and mechanical analysis are peculiarly great, this must stand as the most important scientific artifact preserved from antiquity.

Some technical details can be gleaned however. The shape of the gear teeth appears to be almost exactly equilateral triangles in all cases (fig. 8), and square shanks may be seen at the centers of some of the wheels. No wheel is quite complete enough for a count of gear teeth, but a provisional reconstruction by Theophanidis (fig. 9) has shown that the appearances are consistent with the theory that the

Figure 7.—Antikythera Machine, Two Smaller Fragments. (*Photo courtesy of National Museum, Athens.*)

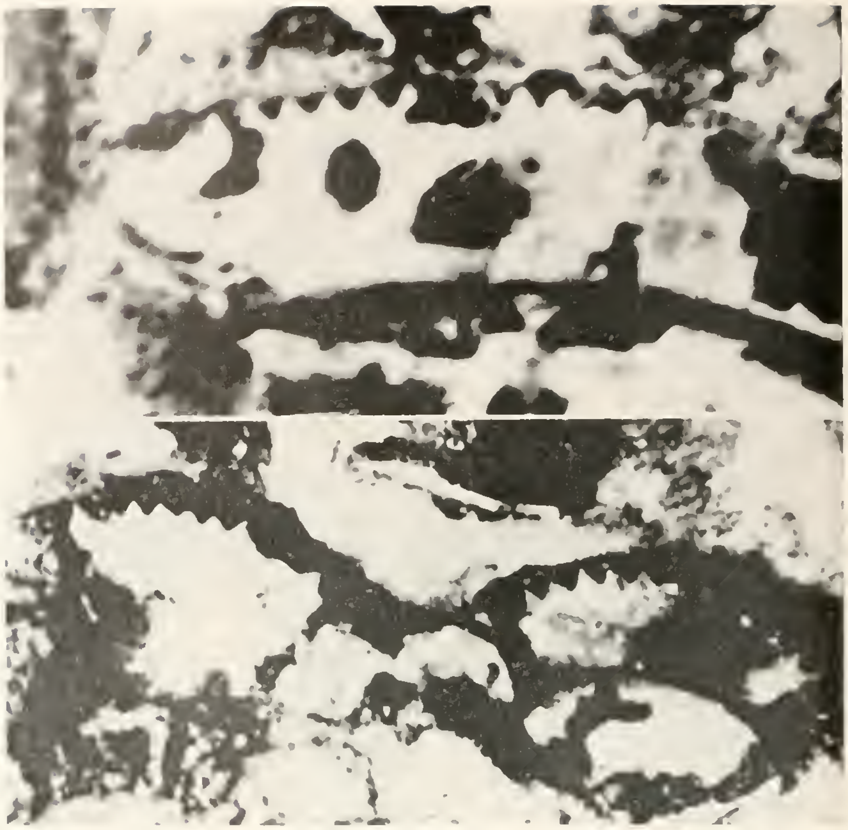


Figure 8.—Antikythera Machine, Detail from Figure 6, showing gearing. (*Photo courtesy of National Museum, Athens.*)

purpose of the gears was to provide the correct angular ratios to move the sun and planets at their appropriate relative speeds.

Thus, if the evidence of the Antikythera machine is to be taken at its face value, we have, already in classical times, the use of astronomical devices as complicated as any clock. In any case, the material supplied by the works ascribed to Archimedes, Hero, and Vitruvius, and the more certain evidence of the anaphoric clocks is sufficient to show that there was a strong classical tradition of such machines, a tradition that inspired, even if it did not directly influence, later developments in Islam and Europe on the one side, and, just possibly, China on the other.

Note added in proof:

Since the above lines were written, I have been privileged to make a full examination of the fragments in the National Museum in Athens. As a result we can read much more inscription and make out many more details of the mechanism. The cleaning and disentangling of the fragments by the museum staff has proceeded to the stage where one can assert much more positively that the device was an astronomical computer for sidereal, solar, lunar, and possibly also planetary phenomena. (See my article in the *Scientific American*, June 1959, vol. 200, No. 6, pp. 60–67). Relevant to the present study, it must also be noted at this point that the machine is now shown to be strongly related to the geared astrolabe of al-Birun and thereby the Hellenistic, Islamic, and European developments are drawn together even more tightly.

Let us now turn our attention to those civilizations which were intermediaries, geographically and culturally, between Greece and medieval Europe, and between both of these and China. From India there are only two references, very closely related and appearing in the best known astronomical texts in connection with descriptions of the armillary sphere and celestial globe. These texts are both quite garbled, but so far as one may understand them, it seems that the types of spheres and globes mentioned

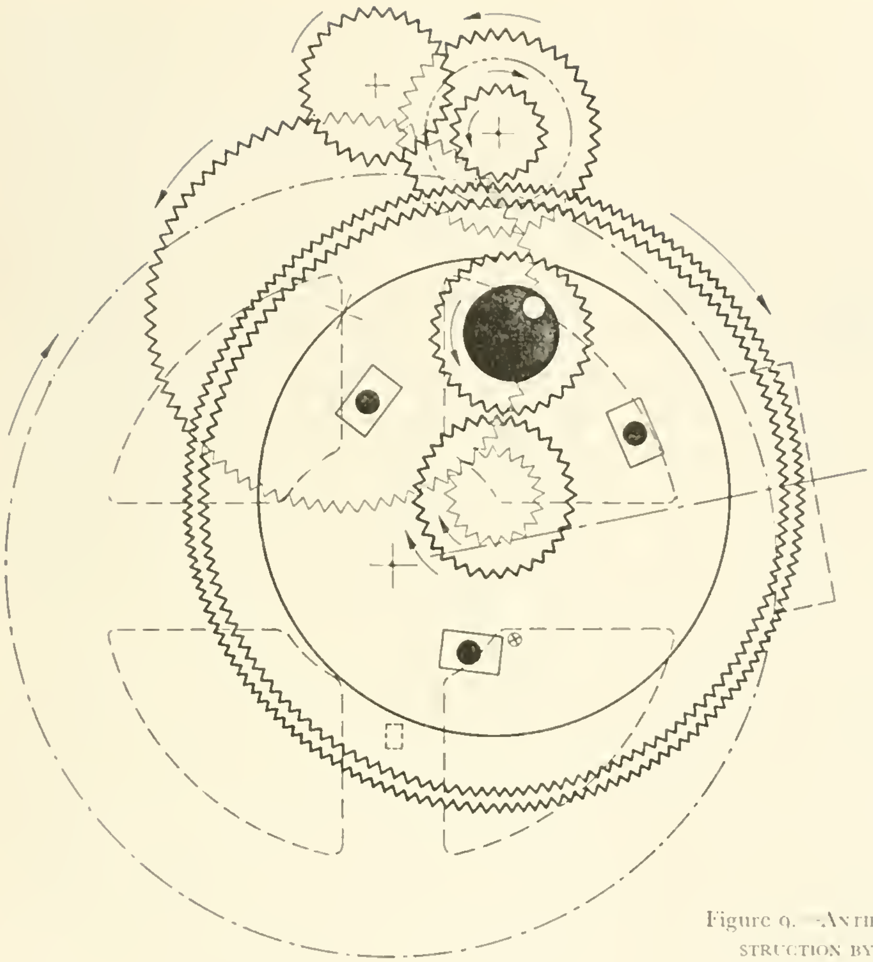


Figure 9.—ANTIKYTHERA MACHINE, PARTIAL RECONSTRUCTION BY THEOPHANIDIS (see footnote 16).

are more akin to those current in China than in the West. The relevant portions of text are as follows (italics supplied):

The circle of the horizon is midway of the sphere. As covered with a casing and as left uncovered, it is the sphere surrounded by Lokāloka [the mountain range which formed the boundary of the universe in puranic geography]. By the application of water is made ascertainment of the revolution of time. One may construct a sphere-instrument combined with quicksilver: this is a mystery; if plainly described, it would be generally intelligible in the world. Therefore let the supreme sphere be constructed according to the instruction of the preceptor [guru]. In each successive age this construction, having become lost, is, by the Sun's favour, again revealed to some one or other, at his pleasure. So also, one should construct instruments in order to ascertain time. When quite alone, one should apply quicksilver to the wonder-causing instrument. By the gnomon, staff, arc, wheel, instruments for taking the shadow of various kinds, . . . By water-instruments, the vessel, by the peacock, man, monkey, and by stringed sand-receptacles one may determine time accurately. Quicksilver-holes, water, and cords, and oil and water, mercury and sand are used in these: these applications, too, are difficult.

Sūrya Siddhānta, xiii, 15–22,
E. Burgess' translation, New Haven, 1860.

A self-revolving instrument [or swayamvaha yantra]: Make a wheel of light wood and in its circumference put hollow spokes all having bores of the same diameter, and let them be placed at equal distances from each other; and let them also be placed at an angle verging somewhat from the perpendicular: then half fill these hollow spokes with mercury; the wheel thus filled will, when placed on an axis supported by two posts, revolve of itself.

Or scoop out a canal in the tire of the wheel and then plastering leaves of the Tala tree over this canal with wax, fill one half of this canal with water and the other half with mercury, till the water begins to come out, and then cork up the orifice left open for filling the wheel. The wheel will then revolve of itself, drawn around by the water.

Description of a syphon: Make up a tube of copper or other metal, and bend it in the form of an Ankus'a or elephant hook, fill it with water and stop up both ends. And then putting one end into a reservoir of water let the other end remain suspended outside. Now uncork both ends. The water of the reservoir will be wholly sucked up and fall outside.

Now attach to the rim of the before described self-revolving wheel a number of water-pots, and place the wheel and these pots like the water wheel so that the water from the lower end of the tube flowing into them on one side shall set the wheel in motion, impelled by the additional weight of the pots thus filled. The water discharge from the pots as they reach the bottom of the revolving wheel, should be drawn off into the reservoir before alluded to by means of a water-course or pipe.

The self-revolving machine [mentioned by *Lalla*, etc.] which has a tube with its lower end open is a vulgar machine on account of its being dependant, because that which manifests an ingenious and not a rustic contrivance is said to be a machine.

And moreover many self-revolving machines are to be met with, but their motion is procured by a trick. They are not connected with the subject under discussion. I have been induced to mention the construction of these, merely because they have been mentioned by former astronomers.

Siddhānta Siromaṇi, xi, 50–57, L. Wilkinson's translation, revised by Bāpū deva S(h)āstri, Calcutta, 1861.

Before proceeding to an investigation of the content of these texts it is of considerable importance to establish dates for them, though there are many difficulties in establishing any chronology for Hindu astronomy. The *Sūrya Siddhanta* is known to date, in its original form, from the early Middle Ages, *ca.* 500. The section in question is however quite evidently an interpolation from a later recension, most probably that which established the complete text as it now stands; it has been variously dated as *ca.* 1000 to *ca.* 1150 A. D. The date of the *Siddhānta Siromaṇi* is more certain for we know it was written in about 1150 by Bhāskara (born 1114). Thus both these passages must have been written within a century of the great clocktower made by Su Sung. The technical details will lead us to suppose there is more than a temporal connection.

We have already noted that the armillary spheres and celestial globes described just before these extracts are more similar in design to Chinese than to Ptolemaic practice. The mention of mercury and of sand as alternatives to water for the clock's fluid is another feature very prevalent in Chinese but absent in the Greek texts. Both texts seem conscious of the complexity of these devices and there is a hint (it is lost and revealed) that the story has been transmitted, only half understood, from another age or culture. It should also be noted that the mentions of cords and strings rather than gears, and the use of spheres rather than planispheres would suggest we are dealing with devices similar to the earliest Greek models rather than the later devices, or with the Chinese practice.

A quite new and important note is injected by the passage from the Bhāskara text. Obviously intrusive in this astronomical text we have the description of two "perpetual motion wheels" together with a third, castigated by the author, which helps its perpetuity by letting water flow from a reservoir by means of a syphon and drop into pots around the circumference of the wheel. These seem to be the basis also, in the extract from the *Sūrya Siddhanta*, of the "wonder-causing instrument" to which mercury must be applied.

In the next sections we shall show that this idea of a perpetual motion device occurs again in conjunction with astronomical models in Islam and shortly afterwards in medieval Europe. At each occurrence, as here, there are echoes of other cultures. In addition to those already mentioned we find the otherwise mysterious "peacock, man and monkey," cited as parts of the jackwork of astronomical clocks of Islam, associated with the weight drive so essential to the later horology in Europe.

We have already seen that in classical times there were already two different types of protoclocks; one, which may be termed "nonmathematical," designed only to give a visual aid in the conception of the cosmos, the other, which may be termed "mathematical" in which stereographic projection or gearing was employed to make the device a quantitative rather than qualitative representation. These two lines occur again in the Islamic culture area.

Nonmathematical protoclocks which are scarcely removed from the classical forms appear continuously through the Byzantine era and in Islam as soon as it recovered from the first shocks of its formation. Procopius (died *ca.* 535) describes a monumental water clock which was erected in Gaza *ca.* 500.[17] It contained impressive jackwork, such as a Medusa

[17] H. Diels Über die von Prokop beschriebene Kunstuhr von Gaza, *Abhandlungen, Akademie der Wissenschaften*, Berlin, Philos.-Hist. Klasse, 1917, No. 7.

head which rolled its eyes every hour on the hour, exhibiting the time through lighted apertures and showing mythological interpretations of the cosmos. All these effects were produced by Heronic techniques, using hydraulic power and puppets moved by strings, rather than with gearing.

Again in 807 a similarly marvelous exhibition clock made of bronze was sent by Harun-al-Rashid to the Emperor Charlemagne; it seems to have been of the same type, with automata and hydraulic works. For the succeeding few centuries, Islam was in its Golden Age of development of technical astronomy (*ca.* 950–1150) and attention may have been concentrated on the more mathematical protoclocks. Towards the end of the 12th century, however, there was a revival of the old tradition, mainly at the court of the Emperor Saladin (1146–1173) when a great automaton water clock, more magnificent than any hitherto, was erected in Damascus. It was rebuilt, after 1168, by Muḥammad b. ʿAlī b. Rustum, and repaired and improved by his son, Fakhr ad-dīn Riḍwān b. Muḥammad,[18] who is most important as the author of a book which describes in considerable technical detail the construction of this and other protoclocks. Closely associated with his book one also finds texts dealing with perpetual-motion devices, which we shall consider later.

During the century following this horological exuberance in Damascus, the center of gravity of Islamic astronomy shifted from the East to the Hispano-Moorish West. At the same time there comes more evidence that the line of mathematical protoclocks had not been left unattended. This is suggested by a description given by Trithemius of another royal gift from East to West which seems to have been different from the automata and hydraulic devices of the tradition from Procopius to Riḍwān:[19]

> In the same year [1232] the Saladin of Egypt sent by his ambassadors as a gift to the emperor Frederic a valuable machine of wonderful construction worth more than five thousand ducats. For it appeared to resemble internally a celestial globe in which figures of the sun, moon, and other planets formed with the greatest skill moved, being impelled by weights and wheels, so that performing their course in certain and fixed intervals they pointed out the hour night and day with infallible certainty; also the twelve signs of the zodiac with certain appropriate characters, moved with the firmament, contained within themselves the course of the planets.

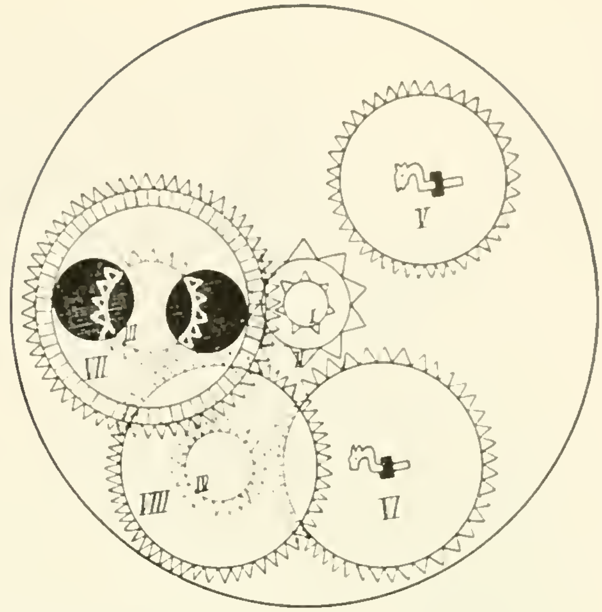


Figure 10. Calendrical Gearing Designed by al-Biruni, *ca.* A. D. 1000. The gear train count is 40–10+7–59+19–59+24–48. The gear of 48 therefore makes 19 (annual) rotations while that of 19–59 shows 118 double lunations of 29+30=59 days. The gear of 40 shows a (lunar) rotation in exactly 28 days, and the center pinions 7+10 rotate in exactly one week. After Wiedemann (see footnote 20).

The phrase "resembled internally" is of especial interest in this passage; it may perhaps arise as a mistranslation of the technical term for stereographic projection of the sphere, and if so the device might have been an anaphoric clock or some other astrolabic device.

This is made more probable by the existence of a specifically Islamic concentration on the astrolabe, and on its planetary companion instrument, the equatorium, as devices for mechanizing computation by use of geometrical analogues. The ordinary planispheric astrolabe, of course, was known in Islam from its first days until almost the present time. From the time of al-Biruni (*ca.* 1000)—significantly, perhaps, he is well known for his travel account of India—there is remarkable innovation.

Most cogent to our purpose is a text, described for the first time by Wiedemann,[20] in which al-Biruni

[18] L. A. Mayer, *Islamic astrolabists and their works*, Geneva, 1956, p. 62.

[19] The translation which follows is quoted from J. Beckmann, *op. cit.* (footnote 1), p. 349.

[20] E. Wiedemann, "Ein Instrument das die Bewegung von Sonne und Mond darstellt, nach al Biruni," *Der Islam*, 1913, vol. 4, p. 5.

Figure 11. Geared Astrolabe by Muhammad b. Abī Bakr of Isfahan, A. D. 1221–1222.
(*Photo courtesy of Science Museum, London.*)

explains how a special train of gearing may be used to show the revolutions of the sun and moon at their relative rates and to demonstrate the changing phase of the moon, features of fundamental importance in the Islamic (lunar) calendrical system. This device necessarily uses gear wheels with a "non-round" number of teeth (*e.g.*, 7, 19, 59) as dictated by the astronomical constants involved (see fig. 10). The teeth are shaped like equilateral triangles and square shanks are used, exactly as with the Antikythera machine. Horse-headed wedges are used for fixing; a tradition borrowed from the horse-shaped *Faras* used to fasten the traditional astrolabe. Of special interest for us is the lunar phase diagram, which is just the same in form and structure as the lunar volvelle that occurs later in horology and is still so commonly found today, especially as a decoration for the dial of grandfather clocks.

Biruni's calendrical machine is the earliest complicated geared device on record and it is therefore all the more significant that it carries a feature found in later clocks. From the manuscript description alone one could not tell whether it was designed for automatic action or merely to be turned by hand. Fortunately this point is made clear by the most happy survival of an intact specimen of this very device, without doubt the oldest geared machine in existence in a complete state.

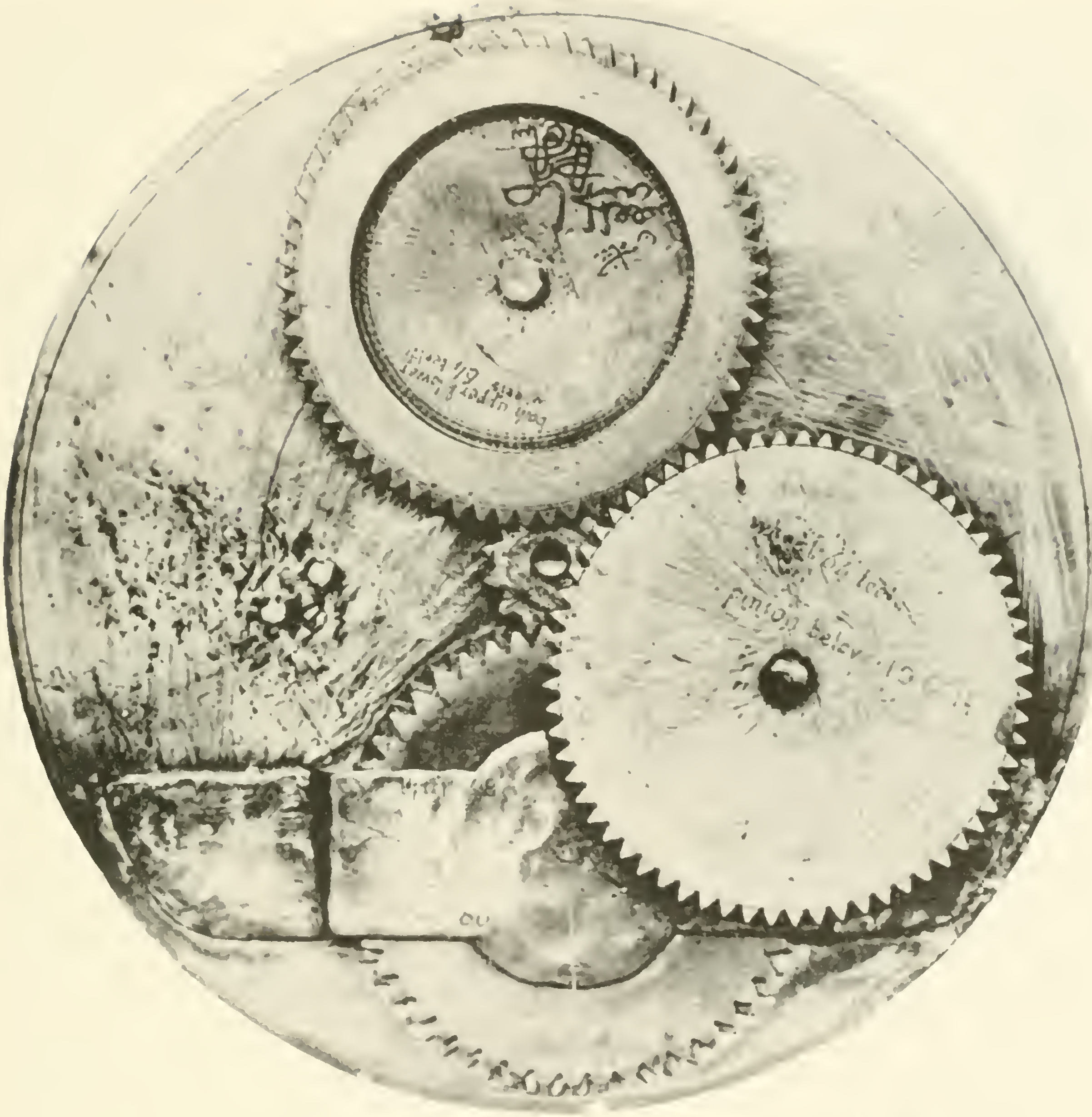


Figure 12. GEARING FROM ASTROLABE SHOWN IN FIGURE 11. The gear train count is as follows: 48–13+8–64–64-64–10–60. The pinion of 8 has been incorrectly replaced by a more modern pinion of 10. The gear of 48 should make 13 (lunar) rotations while the double gear of 64 × 64 makes 6 revolutions of double months (of 29–30 days) and the gear of 60 makes a single turn in the hegiral year of 354 days. (*Photo courtesy of Science Museum, London.*)

This landmark in the history of science and technology is now preserved at the Museum of the History of Science, Oxford, England.[21] It is an astrolabe, dated 1221–22 and signed by the maker, Muḥammad b. Abī Bakr (died 1231–32) of Isfahan, Persia (see figs. 11 and 12). The very close resemblance to the design of Biruni is quite apparent, though the gearing has been simplified very cleverly so that only one wheel has an odd number of teeth (13), the rest being

[21] I acknowledge with thanks to the Curator of that museum the permission to reproduce photographs of this instrument. It is item 5 in R. T. Gunther, *Astrolabes of the world*, Oxford, 1932.

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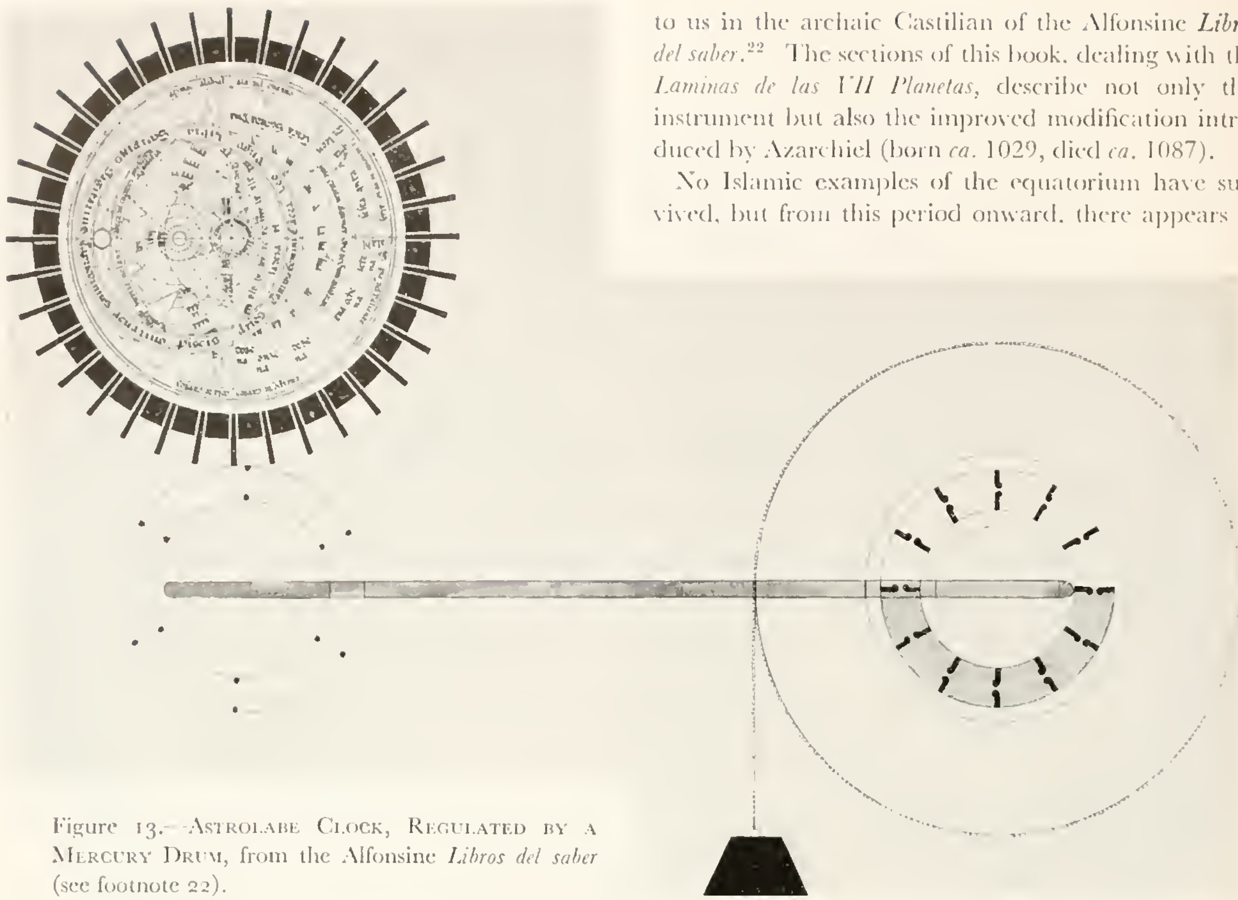

to us in the archaic Castilian of the Alfonsine *Libros del saber*.[22] The sections of this book, dealing with the *Laminas de las VII Planetas*, describe not only this instrument but also the improved modification introduced by Azarchiel (born *ca.* 1029, died *ca.* 1087).

No Islamic examples of the equatorium have survived, but from this period onward, there appears to have been a long and active tradition of them, and ultimately they were transmitted to the West, along with the rest of the Alfonsine corpus. More important for our argument is that they were the basis for the mechanized astronomical models of Richard of Wallingford (*ca.* 1320) and probably others, and for the already mentioned great astronomical clock of de Dondi. In fact, the complicated gearwork and dials of de Dondi's clock constitute a series of equatoria, mechanized in just the same way as the calendrical device described by Biruni.

Figure 13.—Astrolabe Clock, Regulated by a Mercury Drum, from the Alfonsine *Libros del saber* (see footnote 22).

much easier to mark out geometrically (*e.g.*, 10, 48, 60, and 64 teeth). The lunar phase volvelle can be seen through the circular opening at the back of the astrolabe. It is quite certain that no automatic action is intended; when the central pivot is turned, by hand, probably by using the astrolabe rete as a "handle," the calendrical circles and the lunar phase are moved accordingly. Using one turn for a day would be too slow for useful re-setting of the instrument, in practice a turn corresponds more nearly to an interval of one week.

In addition to this geared development of the astrolabe, the same period in Islam brought forth a new device, the equatorium, a mechanical model designed to simulate the geometrical constructions used for finding the positions of the planets in Ptolemaic astronomy. The method may have originated already in classical times, a simple device being described by Proclus Diadochus (*ca.* 450), but the first general, though crude, planetary equatorium seems to have been described by Abulcacim Abnacahm (*ca.* 1025) in Granada; it has been handed down

It is evident that we are coming nearer now to the beginning of the true mechanical clock, and our last step, also from the Alfonsine corpus of western Islam, provides us with an important link between the ana-

[22] Abulcacim Abnacahm, *Libros del saber*, edition by Rico y Sinobas, Madrid, 1866, vol. 3, pp. 241–271. The design of the instrument has been very fully discussed by A. Wegener, "Die astronomischen Werke Alfons X," *Bibliotheca Mathematica*, 1905, pp. 129–189. A more complete discussion of the historical evolution of the equatorium is given in Derek J. Price, *The equatorie of the planetis*, Cambridge (Eng.), 1955, pp. 119–133.

phoric clock, the weight drive, and a most curious perpetual-motion device, the mercury wheel, used as an escapement or regulator. The Alfonsine book on clocks contains descriptions of five devices in all, four of them being due to Isaac b. Sid (two sundials, an automaton water-clock and the present mercury clock) and one to Samuel ha-Levi Adulafia (a candle clock) they were probably composed just before *ca.* 1276–77.

The mercury clock of Isaac b. Sid consists of an astrolabe dial, rotated as in the anaphoric clock, and fitted with 30 leaf-shaped gear teeth (see fig. 13). These are driven by a pinion of 6 leaves mounted on a horizontal axle (shown very diagrammatically in the illustration) and at the other end of this axle is a wheel on which is mounted the special mercury drum which is powered by a normal weight drive.

It is the mercury drum which forms the most novel feature of this device; the fluid, constrained in 12 chambers so as to just fill 6 of them, must slowly filter through small holes in the constraining walls. In practice, of course, the top mercury surfaces will not be level, but higher on the right so as to balance dynamically the moment of the applied weight on its driven rope. This curious arrangement shows point of resemblance to the Indian "mercury-holes," to the perpetual-motion devices found in the medieval European tradition and also in the texts associated with Riḍwān, which we shall next examine.

It is of the greatest interest to our theme that the Islamic contributions to horology and perpetual motion seem to form a closely knit corpus. A most important series of horological texts, including those of Riḍwān and al-Jazari, have been edited by Wiedemann and Hauser.[23] Other Islamic texts give versions of the water clocks and automata of Archimedes and of Hero and Philo of Alexandria.[24] In at least three cases [25] these texts are found also associated with texts describing perpetual-motion wheels and other hydraulic devices. Three manuscripts of this type have been published in German translation by Schmeller.[26]

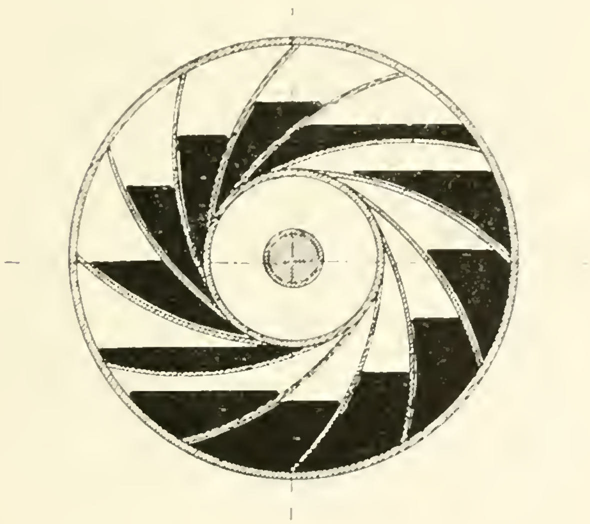

Figure 14.—Islamic Perpetual Motion Wheel, after manuscript cited by Schmeller (see footnote 26).

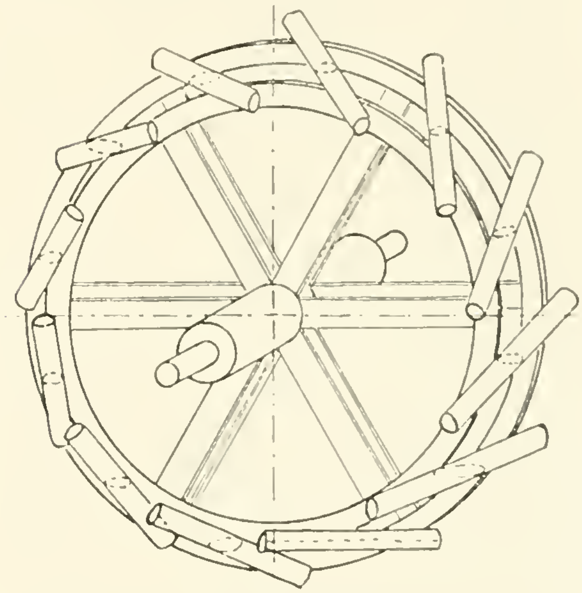

Figure 15.—Another Perpetual Motion Wheel, after the text cited in figure 14.

[23] E. Wiedemann, and F. Hauser, "Über die Uhren im Bereich d. islamischen Kultur," *Nova Acta; Abhandlungen der königliche Leopoldinisch-Carolinische Deutsche Akademie der Naturforscher zu Halle*, 1915, vol. 100, no. 5.

[24] E. Wiedemann, and F. Hauser, *Die Uhr des Archimedes und zwei andere Vorrichtungen*, Halle, 1918.

[25] The manuscripts in question are as follows: Gotha, Kat. v. Pertsch, 3, 18, no. 1348; Oxford, Cod. 954; Leiden, Kat. 3, 288, no. 1414, Cod. 499 Warn; and another similar, Kat. 3, 291, no. 1415, Cod. 93 Gol.

[26] H. Schmeller, Beiträge zur Geschichte der Technik in der Antike und bei den Arabern, Erlangen, 1922 (*Abhandlungen zur Geschichte der Naturwissenschaften und der Medizin* no. 6).

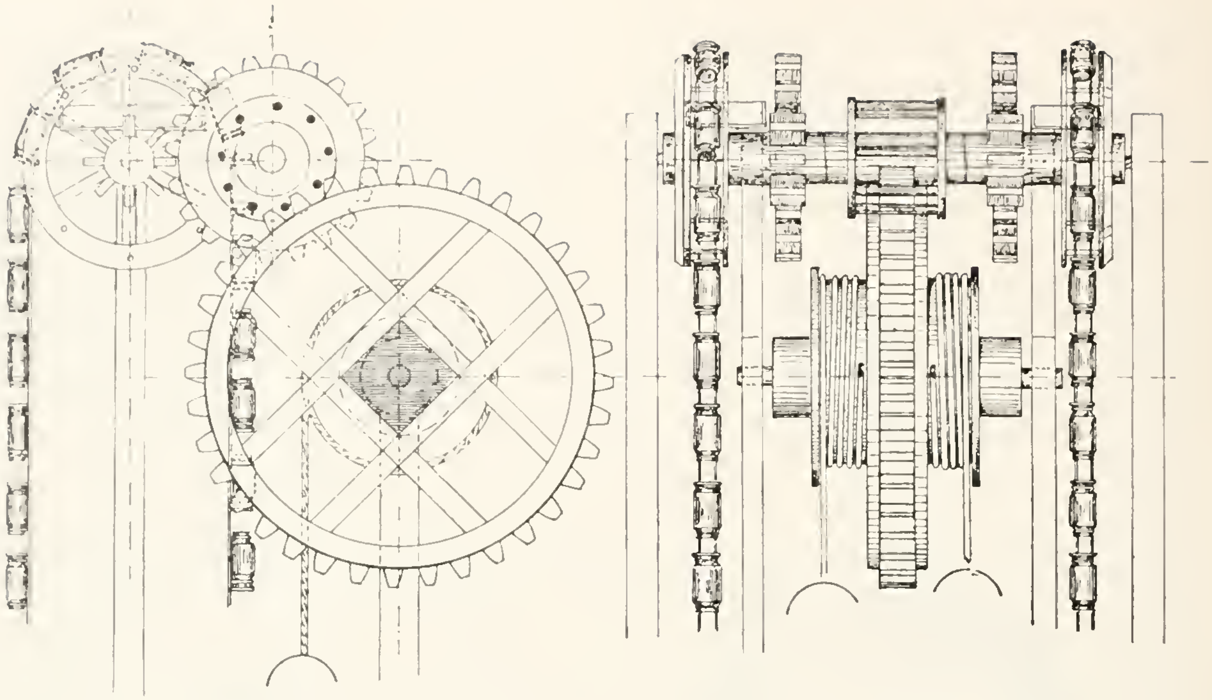

Figure 16.—Islamic Pump Powered by a Weight Drive, after the text cited in figure 14.

The devices include a many chambered wheel (see fig. 14) similar to the Alfonsine mercury "escapement," a wheel of slanting tubes constructed like the noria (see fig. 15), wheels of weights swinging on arms as described by Villard of Honnecourt, and a remarkable device which seems to be the earliest known example of a weight drive. This latter machine is a pump, in which a chain of buckets is used to raise water by passing over a pulley which is geared to a drum powered by a falling weight (see fig. 16); perhaps for balance, the whole arrangement is made in duplicate with common axles for the corresponding parts.

The Islamic tradition of water clocks did not involve the use of gears, though very occasionally a pair is used to turn power through an angle when this is dictated by the use of a water wheel in the automata. In the main, everything is worked by floats and strings or by hydraulic or pneumatic forces, as in Heros devices. The automata are very elaborate, with figures of men, monkeys, peacocks, etc., symbolizing the passage of hours.

MEDIEVAL EUROPE

Echoes from nearly all the developments already noted from other parts of the world are found to occur in medieval Europe, often coming through channels of communication more precisely determinable than those hitherto mentioned. Before the influx of Islamic learning at the time of transmission of the Toledo Tables (12th century) and the Alfonsine Tables (which reached Paris *ca.* 1292), there are occasional references to the most primitive mechanized "visual aids" in astronomy.

The most famous of these occurs in an historical account by Richer of Rheims about his teacher Gerbert (born 946, later Pope Sylvester II, 990–1003). Several instruments made by Gerbert are described in detail; he includes a fine celestial globe made of wood covered with horsehide and having the stars and lines painted in color, and an armillary sphere having sighting tubes similar to those always found on Chinese instruments but never on the Ptolemaic variety. Lastly, he cites "the construction of a sphere, most suitable for recognizing the planets," but unfortunately it is not clear from the description whether or not the model planets were actually to be animated mechanically. The text runs: [27]

> Within this oblique circle (the zodiac on the ecliptic of the globe) he hung the circles of the wandering stars (the planets) with marvellous ingenuity, whose orbits, heights

[27] Once more I am indebted to Professor Loren MacKinney and Miss Harriet Lattin (see footnote 11) for making their collections on Gerbert available to me.

and even the distance from each other he demonstrated to his pupils most effectually. Just how he accomplished this it is unsuitable to enter into here because of its extent lest we should appear to be wandering from our main theme.

Thus, although there is a hint of mechanical complexity, there is really no justification for such an assumption; the description might well imply only a zodiac band on which the orbits of the planets were painted. On the other hand it is not inconceivable that Gerbert could have learned something of Islamic and other extra-European traditions during his period of study with the Bishop of Barcelona—a traveling scholarship that seems to have had many repercussions on the whole field of European scholarship.

Once the floodgates of Arabic learning were opened, a stream of mechanized astronomical models poured into Europe. Astrolabes and equatoria rapidly became very popular, mainly through the reason for which they had been first devised, the avoidance of tedious written computation. Many medieval astrolabes have survived, and at least three medieval equatoria are known. Chaucer is well known for his treatise on the astrolabe; a manuscript in Cambridge, containing a companion treatise on the equatorium, has been tentatively suggested by the present author as also being the work of Chaucer and the only piece written in his own hand.

The geared astrolabe of al-Biruni is another type of protoclock to have been transmitted. A specimen in the Science Museum, London,[28] though unfortunately now incomplete, has a very sophistocated arrangement of gears for moving pointers to indicate the correct relative positions and movements of the sun and moon (see figs. 17 and 18). Like the earlier Muslim example it contains wheels with odd numbers of gear teeth (14, 27, 39); however, the teeth are no longer equilateral in shape, but approximate a more modern slightly rounded form. This example is French and appears to date from *ca.* 1300. Another Gothic astrolabe with a similar gear ring on the rete, said to date from *ca.* 1400 (it could well be much earlier) is now in the Billmeier collection (London).[29]

Turning from the mechanized astrolabe to the mechanized equatorium, we find the work of Richard of Wallingford (1292?–1336) of the greatest interest as providing an immediate precursor to that of de Dondi. He was the son of an ingenious blacksmith, making his way to Merton College, Oxford, then the most active and original school of astronomy in Europe, and winning later distinction as Abbot of St. Albans. A text by him, dated 1326–27, described in detail the construction of a great equatorium, more exact and much more elaborate than any that had gone before.[30] Nevertheless it is evidently a normal manually operated device like all the others. In addition to this instrument, Richard is said to have constructed *ca.* 1320, a fine planetary clock for his Abbey.[31] Bale, who seems to have seen it, regarded it as without rival in Europe, and the greatest curiosity of his time. Unfortunately, the issue was confused by Leland, who identified it as the Albion (*i.e.*, all-by one), the name Richard gives to his manual equatorium. This clock was indeed so complex that Edward III censured the Abbot for spending so much money on it, but Richard replied that after his death nobody would be able to make such a thing again. He is said to have left a text describing the construction of this clock, but the absence of such a work has led many modern writers to support Leland's identification and suppose that the device was not a mechanical clock.

A corrective for this view is to be had from a St. Albans manuscript (now at Gonville and Caius College, Cambridge) that described the methods for setting out toothed wheels for an astronomical horologium designed to show the motions of the planets. Although the manuscript copy is to be dated *ca.* 1340, it clearly indicates that a geared planetary device was known in St. Albans at an early date, and it is reasonable to suppose that this was in fact the machine made by Richard of Wallingford. Unfortunately the text does not appear to give any relevant information about the presence of an escapement or any other regulatory device, nor does it mention the source of power.[32] Now a geared version of the

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[28] Item 198 in Gunther, *op. cit.* (footnote 21). I am grateful to the authorities of that museum for permission to reproduce photographs of this instrument.

[29] Sotheby and Co., London, sale of March 14, 1957, lot 154. The outer rim of the rete has 120 teeth.

[30] The Latin text of the treatise on the Albion, has been transcribed by Rev. H. Salter and published in R. T. Gunther, *Early science in Oxford*, Oxford, 1923, vol. 2, pp. 349–370. An analysis of its design is given in Price, *op. cit.* (footnote 22), pp. 127–130.

[31] Such evidence as there is for the existence and form of the clock is collected by Gunther, *op. cit.* (footnote 30), p. 49.

[32] I have discussed this new manuscript source in "Two medieval texts on astronomical clocks," *Antiquarian Horology*, 1956, vol. 1, no. 10, p. 156. The manuscript in question is ms. 230/116, Gonville and Caius College, Cambridge, folios 11v–14v = pp. 31–36.

Figure 17. French Geared Astrolabe of Trefoil Gothic Design, *ca.* A. D. 1300. The gearing on the pointer is, from the center: (32)/14–45+27–39, the last meshing with a concave annular gear of 180 teeth around the rim of the rete of the astrolabe. A second pointer, geared to this so as to follow the Moon, seems to be lacking. (*Photo courtesy of Science Museum, London.*)

Albion would appear to correspond very closely indeed to the dial-work which forms the greater part of the de Dondi clock, and for this reason we suggest now that the two clocks were very closely related in other ways too. This, circumstantial though it be, is evidence for thinking that the weight drive and some form of escapement were known to Richard of Wallingford, *ca.* 1320. It would narrow the gap between the clock and the protoclocks to less than half a century, perhaps a single generation, in the interval *ca.* 1285–1320. In this connection it may be of interest that Richard of Wallingford knew only the Toledo tables corpus, that of the Alfonsine school did not arrive in England until after his death.

There are, of course, many literary references to the waterclocks in medieval literature. In fact most of these are from quotations which have often been produced erroneously in the history of the mechanical clock, thereby providing many misleading starts for that history, as noted previously in the discussion of the horologium. There are however enough mentions to make it certain that water clocks of some sort were in use, especially for ecclesiastic purposes, from the end of the 12th century onwards. Thus, Jocelin of Brakelond tells of a fire in the Abbey Church of Bury St. Edmunds in the year 1198.[33] The relics would have been destroyed during the night, but just at the crucial moment the clock bell sounded for matins and the master of the vestry sounded the alarm. On this "the young men amongst us ran to get water, some to the well and others to the clock" probably the sole occasion on which a clock served as a fire hydrant.

It seems probable that some of these water clocks could have been simple drip clepsydras, with perhaps a striking arrangement added. A most fortunate discovery by Drover has now brought to light a manuscript illumination that shows that these water clocks, at least by *ca.* 1285, had become more complex and were rather similar in appearance to the Alfonsine mercury drum.[34] The illustration (fig. 19) is from a moralized Bible written in northern France, and accompanies the passage where King Hezekiah is given a sign by the Lord, the sun being moved back ten steps of the clock. The picture clearly shows the central water wheel and below it a dog's head spout gushing water into a bucket supported by chains, with a (weight ?) cord running behind. Above the wheel is a carillon of bells, and to one side a rosette which might be a fly or a model sun. The wheel appears to have 15 compartments, each with a central hole (perhaps similar to that in the Alfonsine clock) and it is supported on a square axle by a bracket, the axle being wedged in the traditional fashion. The projections at the edge of the wheel might be gear teeth, but more likely they are used only for tripping the striking mechanism. If it were not for the running water spout it would be very close to the Alfonsine model; but with this evidence it seems impossible to arrive at a clear mechanical interpretation.

Figure 18.—Gear Train of Pointer in figure 17. (*Photo courtesy of Science Museum, London.*)

[33] *The Chronicle of Jocelin of Brakelond* . . ., H. E. Butler (ed.), London, 1949, p. 106.

[34] C. B. Drover, "A medieval monastic water-clock," *Antiquarian Horology*, 1954, vol. 1, no. 5, pp. 54–58, 63. Because this water clock uses wheels and strikes bells one must reject the evidence of literary reference, such as by Dante, from which the mention of wheels and bells have been taken as positive proof of the existence of mechanical clocks with mechanical escapements. The to-and-fro motion of the mechanical clock escapement is quite an impressive feature, but there seems to be no literary reference to it before the time of de Dondi

From the adjacent region there is another account of a striking water clock, the evidence being inscriptions on slates, discovered in Villers Abbey near Brussels; [35] these may be closely dated as 1267 or 1268 and provide the remains of a memorandum for the sacrist and his assistants in charge of the clock.

Always set the clock, however long you may delay on [the letter "A"] afterwards you shall pour water from the little pot (pottulo) that is there, into the reservoir (cacabum) until it reaches the prescribed level, and you must do the same when you set [the clock] after compline so that you may sleep soundly.

Figure 19.—Manuscript Illumination of a Medieval Waterclock, showing a partitioned wheel, a weight drive, and a carillion for striking. From Drover (see footnote 34).

A quite different sort of evidence is to be had from the writings of Robertus Anglicus in 1271 where one gets the impression that just at this time there was active interest in the attempt to make a weight-driven anaphoric clock and to regulate its motion by some unstated method so that it would keep time with the diurnal rotation of the heavens: [36]

Nor it is possible for any clock to follow the judgment of astronomy with complete accuracy. Yet clockmakers (artifices horologiorum) are trying to make a wheel (circulum) which will make one complete revolution for every one of the equinoctial circle, but they cannot quite perfect their work. But if they could, it would be a really accurate clock (horologium verax valde) and worth more than an astrolabe or other astronomical instrument for reckoning the hours, if one knew how to do this according to the method aforesaid. The method of making such a clock would be this, that a man make a disc (circulum) of uniform weight in every part so far as could possibly be done. Then a lead weight should be hung from the axis of that wheel (axi ipsius rote) and this weight would move that wheel so that it would complete one revolution from sunrise to sunrise, minus as much time as about one degree rises according to an approximately correct estimate. For from sunrise to sunrise, the whole equinoctial rises, and about one degree more, through which degree the sun moves against the motion of the firmament in the course of a natural day. Moreover, this could be done more accurately if an astrolable were constructed with a network on which the entire equinoctial circle was divided up.

The text then continues with technical astronomical details of the slight difference between the rate of rotation of the sun and of the fixed stars (because of the annual rotation of the sun amongst the stars) but it gives no indication of any regulatory device. Again it should be noted, this source comes from France; Robertus, though of English origin, apparently being then a lecturer either at the University of Paris or at that of Montpellier. The date of this passage, 1271, has been taken as a *terminus post quem* for the invention of the mechanical clock. In the next section we shall describe the text of Peter Peregrinus, very close to this in place and date, which describes just such a machine, conflating it with accounts of an armillary sphere, perpetual motion, and the magnetic compass—so bringing all these threads together for the first time in Europe.

[35] *Annales de la Société Royale d'Archéologie de Bruxelles*, 1896, vol. 1 8, pp. 203–215, 404–451. The translation here is cited from Drover, *op. cit.* (footnote 34), p. 56.

[36] L. Thorndike, *The sphere of Sacrobosco and its commentators*, Chicago, 1949, pp. 180, 230.

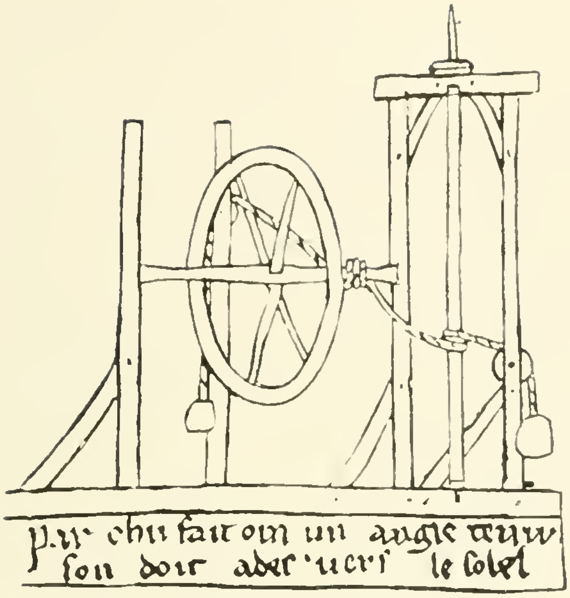

Figure 20. ARRANGEMENT FOR TURNING A FIGURE OF AN ANGEL. It has been alleged that this drawing by Villard represents an escapement. After Lassus (see footnote 37).

We have reserved to the last one section of evidence which may or may not be misleading, the famous notebook of Villard (Wilars) of Honnecourt, near Cambrai. The album, attributed to the period 1240–1251, contains many drawings with short annotations, three of which are of special interest to our investigations.[37] These comprise a steeplelike structure labeled "cest li masons don orcloge" (this is the house of a clock), a device including a rope, wheel and axle (fig. 20), marked "par chu fait om un angle tenir son doit ades vers le solel" (by this means an angel is made to keep his finger directed towards the sun), and a perpetual motion wheel which we shall reserve for later discussion.

The clock tower, according to Drover, shows no place for a dial but suggests the use of bells because of its open structure, suitable for letting out the sound. Moreover, he suggests that the delicacy of the line indicates that it was not really a full-size steeple but rather a small towerlike structure standing only a few feet high within the church. There is, alas, nothing to tell us about the clock it was intended to house; most probably it was a water clock similar to that of the illustrated Bible of *ca.* 1285.

The drawing of the rope, wheel and axles, for turning an angel to point towards the sun can have a simple explanation or a more complicated one. If taken at its face value the wheel on its horizontal axis acts as a windlass connected by the counterpoised rope to the vertical shaft which it turns, thereby moving (by hand) the figure of an angel (not shown) fixed to the top of this latter shaft. Such an explanation was in fact suggested by M. Quicherat,[38] who first called attention to the Villard album and pointed out that a leaden angel existed in Chartres before the fire there in 1836. It is a view also supported from another drawing in the album which describes an eagle whose head is made to turn towards the deacon when he reads the Gospel. Slight pressure on the tail of the bird causes a similar rope mechanism to operate.

A quite different interpretation has been suggested by Frémont;[39] he believes that the wheel may have acted as a fly-wheel and the ropes and counterpoises,

[37] The album was published with facsimiles by J. B. A. Lassus, 1858. An English edition with facsimiles of 33 of the 41 folios was published by Rev. Robert Willis, Oxford, 1859. An extensive summary of this section is given, with illustrations, by J. Drummond Robertson, *The evolution of clockwork*, London, 1931, pp. 11–15.

[38] M. Jules Quicherat, *Revue Archéologique*, 1849, vol. 6.

[39] M. C. Frémont, *Origine de l'horloge à poids*, Paris, 1915.

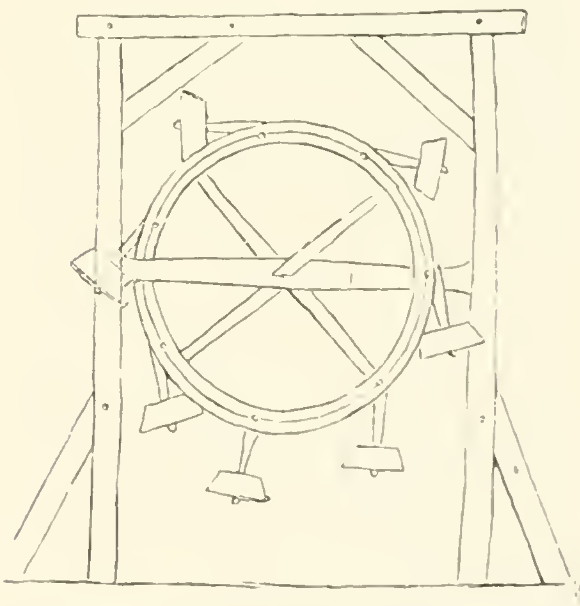

Figure 21. VILLARD'S PERPETUAL MOTION WHEEL, from Lassus (see footnote 37).

turning first one way then the other acted as a sort of mechanical escapement. Such an arrangement is however mechanically impossible without some complicated free-wheeling device between the drive and the escapement, and its only effect would be to oscillate the angel rapidly rather than turn it steadily. I believe that Frémont, over-anxious to provide a protoescapement, has done too much violence to the facts and turned away without good reason from the more simple and reasonable explanation. It is nevertheless still possible to adopt this simple interpretation and yet to have the system as part of a clock. If the left-hand counterpoise, conveniently raised higher than that on the right, is considered as a float fitting into a clepsydra jar, instead of as a simple weight, one would have a very suitable automatic system for turning the angel. On this explanation, the purpose of the wheel would be merely to provide the manual adjustment necessary to set the angel from time to time, compensating for irremediable inaccuracies of the clepsydra.

Having discussed the Villard drawings which are already cited in horological literature, we must draw attention to the fact that this medieval architect also gives an illustration of a perpetual motion wheel. In this case (fig. 21) it is of the type having weights at the end of swinging arms, a type that occurs very frequently at later dates in Europe and is also given in the Islamic texts. We cannot, in this case, suggest that drawings of clocks and of perpetual motion devices occur together by more than a coincidence, for Villard seems to have been interested in most sorts of mechanical device. But even this type of coincidence becomes somewhat striking when repeated often enough. It seems that each early mention of "self-moving wheels" occurs in connection with some sort of clock or mechanized astronomical device.

Having now completed a survey of the traditions of astronomical models, we have seen that many types of device embodying features later found in mechanical clocks evolved through various cultures and flowed into Europe, coming together in a burst of multifarious activity during the second half of the 13th century, notably in the region of France. We must now attempt to fill the residual gap, and in so doing examine the importance of perpetual motion devices, mechanical and magnetic, in the crucial transition from protoclock to mechanical-escapement clock.

Perpetual Motion and the Clock before de Dondi

We have already noted, more or less briefly, several instances of the use of wheels "moving by themselves" or the use of a fluid for purposes other than as a motive power. Chronologically arranged, these are the Indian devices of *ca.* 1150 or a little earlier, as those of Riḍwān *ca.* 1200, that of the Alfonsine mercury clock, *ca.* 1272, and the French Bible illumination of *ca.* 1285. This strongly suggests a steady transmission from East to West, and on the basis of it, we now tentatively propose an additional step, a transmission from China to India and perhaps further West, *ca.* 1100, and possibly reinforced by further transmissions at later dates.

One need only assume the existence of vague traveler's tales about the existence of the 11th-century Chinese clocks with their astronomical models and jackwork and with their great wheel, apparently moving by itself but using water having no external inlet or outlet. Such a stimulus, acting as it did on a later occasion when Galileo received word of the invention of the telescope in the Low Countries, might easily lead to the re-invention of just such perpetual-motion wheels as we have already noted. In many ways, once the idea has been suggested it is natural to associate such a perpetual motion with the incessant diurnal rotation of the heavens. Without some such stimulus however it is difficult to explain why this association did not occur earlier, and why, once it comes there seems to be such a chronological procession from culture to culture.

We now turn to what is undoubtedly the most curious part of this story, in which automatically moving astronomical models and perpetual motion wheels are linked with the earliest texts on magnetism and the magnetic compass, another subject with a singularly troubled historical origin. The key text in this is the famous *Epistle on the magnet*, written by Peter Peregrinus, a Picard, in an army camp at the Siege of Lucera and dated August 8, 1269.[40] In spite of the precise dating it is certain that the work was done long before, for it is quoted unmistakably by Roger Bacon in at least three places, one of which must have been written before *ca.* 1250.[41]

[40] For this, I have used and quoted from the very beautiful edition in English, prepared by Silvanus P. Thompson, London, Chiswick Press, 1902.

[41] See E. G. R. Taylor, "The South-pointing needle," *Imago Mundi*, Leiden, 1951, vol. 8, pp. 1–7 (especially pp. 1, 2).

The *Epistle* contains two parts; in the first there is a general account of magnetism and the properties of the loadstone, closing with a discussion "of the inquiry whence the magnet receives the natural virtue which it has." Peter attributed this virtue to a sympathy with the heavens, proposing to prove his point by the construction of a "terrella," a uniform sphere of loadstone which is to be carefully balanced and mounted in the manner of an armillary sphere, with its axis directed along the polar axis of the diurnal rotation. He then continues:

Now if the stone then move according to the motion of the heavens, rejoice that you have arrived at a secret marvel. But if not, let it be ascribed rather to your own want of skill than to a defect of Nature. But in this position, or mode of placing, I deem the virtues of this stone to be properly conserved, and I believe that in other positions or parts of the sky its virtue is dulled, rather than preserved. By means of this instrument at all events you will be relieved from every kind of clock (horologium), for by it you will be able to know the Ascendant at whatever hour you will, and all other dispositions of the heavens which Astrologers seek after.

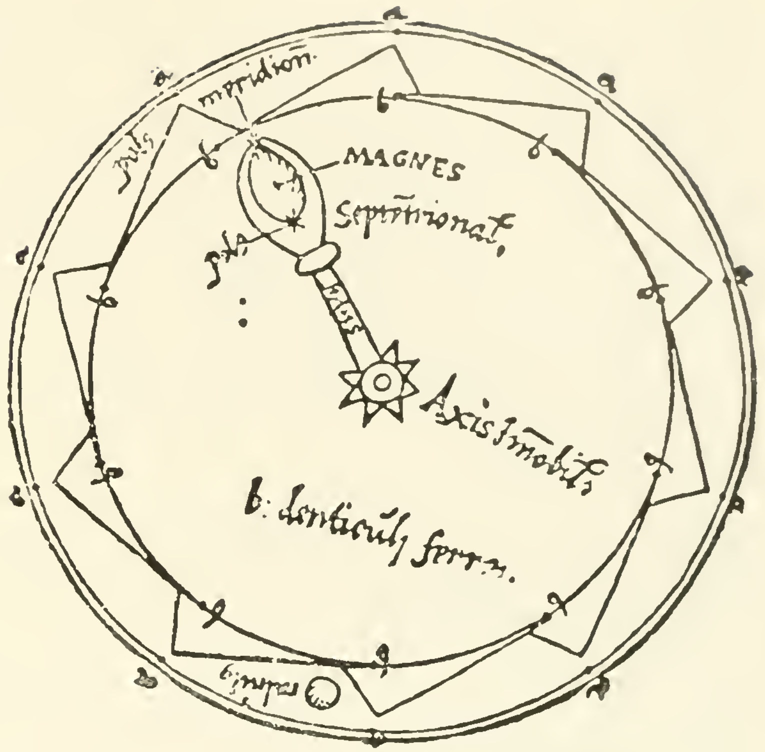

Figure 22.—Magnetic Perpetual Motion Wheel illustrated by Peter Peregrinus; from the edition of S. P. Thompson (see footnote 40).

It should be noted that the device is to be mounted like an astronomical instrument and used like one, rather than as a time teller, or as a simple demonstration of magnetism. In the second part of the *Epistle* Peter turns to practical instruments, describing for the first time, the construction of a magnetic compass consisting of a loadstone or iron needle pivoted with a casing marked with a scale of degrees. The third chapter of this section, concluding the *Epistle*, then continues with the description of a perpetual motion wheel, "elaboured with marvellous ingenuity, in the persuit of which invention I have seen many people wandering about, and wearied with manifold toil. For they did not observe that they could arrive at the mastery of this by means of the virtue, or power of this stone."

This tells us incidentally, that the perpetual motion device was a subject of considerable interest at this time.[42] Oddly enough, Peter does not now develop his idea of the terrella, but proceeds to something quite new, a device (see fig. 22) in which a bar-magnet loadstone is to be set towards the end of a pivoted radial arm with a circle fitted on the inside with iron "gear teeth," the teeth being there not to mesh with others but to draw the magnet from one to the next, a little bead providing a counterweight to help the inertia of rotation carry the magnet from one point of attraction to the next. It is by no means the sort of device that one would naturally evolve as a means of making magnetism work perpetually, and I suggest that the toothed wheel is another instance of some vague idea of protoclocks, perhaps that of Su Sung, being transmitted from the East.

The work of Peter Peregrinus is cited by Roger Bacon in his *De secretis* as well as in the *Opus majus*

[42] I have wondered whether the medieval interest in perpetual motion could be connected with the use of the "Wheel of Fortune" in churches as a substitute for bell-ringing on Good Friday. Unfortunately I can find no evidence for or against the conjecture.

and *Opus minus*. In the first and earliest of these occurs a description, taken from Ptolemy, of the construction of the (observing) armillary sphere. He says that this cannot be made to move naturally by any mathematical device, but "a faithful and magnificent experimentor is straining to make one out of such material, and by such a device, that it will revolve naturally with the diurnal heavenly rotation." He continues with the statement that this possibility is also suggested by the fact that the motions of comets, of tides, and of certain planets also follow that of the Sun and of the heavens. Only in the *Opus minus*, where he repeats reference to this device, does he finally reveal that it is to be made to work by means of the loadstone.

The form of Bacon's reference to Peregrinus is strongly reminiscent of the statement by Robertus Anglicus, already mentioned as an indication of preoccupation with diurnally rotating wheels, at a date (1271) remarkably close to that of the *Epistle* (1269)—so much so that it could well be thought that the friend to which Peter was writing was either Robert himself or somebody associated with him, perhaps at the University of Paris—a natural place to which the itinerant Peter might communicate his findings.

The fundamental question here, of course, is whether the idea of an automatic astronomical device was transmitted from Arabic, Indian, or Chinese sources, or whether it arose quite independently in this case as a natural concomitant of identifying the poles of the magnet with the poles of the heavens. We shall now attempt to show that the history of the magnetic compass might provide a quite independent argument in favour of the hypothesis that there was a 'stimulus' transmission.

The Magnetic Compass as a Fellow-traveler from China

The elusive history of the magnetic compass has many points in common with that of the mechanical clock. Just as we have astronomical models from the earliest times, so we find knowledge of the loadstone and some of its properties. Then, parallel to the development of protoclocks in China throughout the middle ages, we have the evidence analyzed by Needham, showing the use of the magnet as a divinatory device and of the (nonmagnetic) south-pointing chariot, which has been confusedly allied to the story. Curiously, and perhaps significantly the Chinese history comes to a head at just the same time for compasses and clocks, and a prime authority for the Chinese compass is Shen Kua (1030–1093) who also appears in connection with the clock of Su Sung, and who wrote about the mechanized armillary spheres and other models *ca.* 1086.

Another similarity occurs in connection with the history of the compass in medieval Europe. The treatise of Peter Peregrinus, already discussed, provides the first complete account of the magnetic compass with a pivoted needle and a circular scale, and this, as we have seen, may be connected with protoclocks and perpetual-motion devices. There are several earlier references, however, to the use of the directive properties of loadstone, mainly for use in navigation, but these earliest texts have a long history of erroneous interpretation which is only recently being cleared away. We know now that the famous passages in the *De naturis rerum* and *De utensilibus* of Alexander Neckham [43] (*ca.* 1187) and a text by Hugues de Berze [44] (after *ca.* 1204) refer to nothing more than a floating magnet without pivot or scale, but using a pointer at right angles to the magnet, so that it pointed to the east, rather than the north or south. A similar method is described (*ca.* 1200) in a poem by Guyot de Provins, and in a history of Jerusalem by Jacques de Vitry (1215).[45] It is of the greatest interest that, once more, all the evidence seems to be concentrated in France (Neckham was teaching in Paris) though at an earlier period than that for the protoclocks.

The date might suggest the time of the first great wave of transmissal of learning from Islam, but it is clear that in this instance, peculiar for that reason, that Islam learned of the magnetic compass only after it was already known in the West. In the earliest Persian record, some anecdotes compiled by al-'Awfī *ca.* 1230,[46] the instrument used by the captain during a storm at sea has the form of a piece of hollow iron, shaped like a fish and made to float on the water after magnetization by rubbing with a

[43] W. E. May, "Alexander Neckham and the pivoted compass needle," *Journal of the Institute of Navigation*, 1955, vol. 8, no. 3, pp. 283–284.

[44] W. E. May, "Hugues de Berze and the mariner's compass," *The Mariner's Mirror*, 1953, vol. 39, no. 2, pp. 103–106.

[45] H. Balmer, *Beiträge zur Geschichte der Erkenntnis des Erdmagnetismus*, Aarau, 1956, p. 52.

[46] The collection is the *Gami 'al Hikajat;* the relevant passage being given in German translation in Balmer, *op. cit.* (footnote 45), p. 54.

Chronological Chart

Classical Europe

3rd C., B.C. Archimedes planetarium
2nd C., B.C. Hipparchus Stereographic Projection
1st C., B.C. Vitruvius hodometer and water clocks
65, B.C. (*ca.*) Antikythera machine
1st C., A.D. Hero hodometer and water clocks
2nd C., A.D. Salzburg and Vosges anaphoric clocks

Islam

807 Harun-al-Rashid
850 (*ca.*) Earliest extant astrolabes
1000 Geared astrolabe of al-Biruni
1025 Equatorium text
1150 Saladin clock
1200 (*ca.*) Riḍwān water-clocks, perpetual motion and weight drive
1206 al-Jazari clocks, etc.
1221 Geared astrolabe
1232 Charlemagne clock
1243 al-Konpas (compass)
1272 Alfonsine corpus clock with mercury drum, equatoria

Europe

1000 Gerbert astronomical model
1187 Neckham on compass
1198 Jocelin on water clock
1245 Villard clocktower, "escapement," perpetual motion
1267 Villers Abbey clock
1269 Peregrinus, compass and perpetual motion
1271 Robertus Anglicus, animated models and "perpetual motion" clock
1285 Drover's water clock with wheel and weight drive
1300 (*ca.*) French geared astrolabe
1320 Richard of Wallingford astronomical clock and equatorium
1364 de Dondi's astronomical clock with mechanical escapement
later 14th C. Tradition of escapement clocks continues and degenerates into simple time-keepers

China

4th C., B.C. Power gearing
2nd C., A.D. Chang Hêng animated globe hodometer
Continuing tradition of animated astronomical models
725 Invention of Chinese escapement by I-Hsing and Liang Ling-tsan
1074 Shen Kua, clocks and magnetic compass
1080 Su Sung clock built
1101 Su Sung clock destroyed

India

1100 (*ca.*) Sūrya Siddhānta animated astronomical models and perpetual motion
1150 (*ca.*) Siddhānta Siromani animated models and perpetual motion

loadstone; the fishlike form is very significant, for this is distinctly Chinese practice. In a second Muslim reference, that of Bailak al-Qabājaqī (*ca.* 1282), the ordinary wet-compass is termed "al-konbas," another indication that it was foreign to that language and culture.[47]

There is therefore reasonable grounds for supporting the medieval European tradition that the magnetic compass had first come from China, though one cannot well admit that the first news of it was brought, as the legend states, by Marco Polo, when he returned home in 1260. There might well have been another wave of interest, giving the impetus to Peter Peregrinus at this time, but an earlier transmission, perhaps along the silk road or by travelers in crusades, must be postulated to account for the evidence in Europe, *ca.* 1200. The earlier influx does not play any great part in our main story; it arrived in Europe before the transmission of astronomy from Islam had got under way sufficiently to make protoclocks a subject of interest. For a second transmission, we have already seen how the relevant texts seem to cluster, in France *ca.* 1270, around a complex in which the protoclocks seem combined with the ideas of perpetual motion wheels and with new information about the magnetic compass.

[47] Balmer, *op. cit.* (footnote 45), p. 53.

The point of this paper is that such a complex exists, cutting across the histories of the clock, the various types of astronomical machines, and the magnetic compass, and including the origin of "self-moving wheels." It seems to trace a path extending from China, through India and through Eastern and Western Islam, ending in Europe in the Middle Ages. This path is not a simple one, for the various elements make their appearances in different combinations from place to place, sometimes one may be dominant, sometimes another may be absent. Only by treating it as a whole has it been possible to produce the threads of continuity which will, I hope, make further research possible, circumventing the blind alleys found in the past and leading eventually to a complete understanding of the first complicated scientific machines.