The Study of Time II

Proceedings of the Second Conference of the International Society for the Study of Time Lake Yamanaka—Japan

Edited by

J. T. Fraser and N. Lawrence

With 80 Figures

Springer-Verlag
Berlin Heidelberg New York 1975

NOTES

1. Derek de Solla Price: "Automata and the Origins of Mechanism and Mechanistic Philosophy," *Technology and Culture* V (1964), 9-23.

   Derek de Solla Price: "On the Origin of Clockwork, Perpetual Motion Devices and the Compass," *United States National Museum Bulletin 218: Contributions from the Museum of History and Technology*, Paper 6, Washington, D.C. 1959, 81-112.

   Derek de Solla Price: *Science Since Babylon*, New Haven: Yale University Press 1961, chapter 2: 23-44.

2. Sharon Gibbs: "Greek and Roman Sundials," Doctoral Dissertation, Department of History and Medicine, Yale University, University Microfilms Dissertation No. 73-14334, 1972.

3. e.g. See C. Hose and W. McDougall: *Pagan Tribes of Borneo*, London: Macmillan 1912.

4. Joseph V. Noble and Derek de Solla Price: "The Water Clock in the Tower of Winds," *American Journal of Archaeology* 72 (1968), 345-55.

5. "The ☆, ✡, and ○ and Other Geometrical and Scientific Talismans and Symbolisms," *Changing Perspectives in the History of Science, Essays in Honour of Joseph Needham*, (eds Mikulas Teich & Robert Young) London: Heinemann Educational Books *1973*, 250-64.

6. Early accounts of my researches on this instrument have appeared in "An Ancient Greek Computer," *Scientific American* 201 (1959), 60-67, and *Science Since Babylon*, New Haven: Yale University Press 1961, chapter 2: 23-44; the new evidence will be published in a full monograph later in 1974 in *Transactions of the American Philosophical Society*.

Monasticism and the First Mechanical Clocks

J.D. NORTH

John David

Had I been speaking in an ancient Athenian law court rather than in modern Japan, my address would have been timed, not by a chess clock but by a clepsydra. Aristophanes[1] and Aristotle[2] both testify to its use in the courts, and the custom was still remembered in the time of Lucian, or a little later, when he or an imitator reported that Demades had made fun of Demosthenes for preferring water to wine. 'Others spoke to water, but Demosthenes wrote to it '.[3] Roman senators timed their discourse by means of the clepsydra, as Pliny, Cicero and others bear out; and Cicero indicates that the very acts of asking and giving leave to speak were described, respectively, as ' seeking the clock ' and ' giving the clock '.[4] The clepsydra was used in ancient Greece for timing military watches[5] and for astronomical measurement.[6] It is said that according to Lucian it was used – and if this were not so dubious a reference it would be the oldest historical reference to such a use – for sounding a bell.[7] There is nothing intrinsically surprising about a Greek hydraulic automaton capable of sounding a bell at regular intervals, for Ctesibius had previously, by means described in some detail by Vitruvius, that is, by hydraulic timepieces, caused figures to move, pillars to turn, stones and eggs to fall, trumpets to sound, and other displays *(parerga)*.[8] Other winter timepieces described by Vitruvius, driven likewise by water power, required a measure of astronomical understanding if they were to be used to yield the time, having as they did an astrolabe dial.[9]

I mention these early literary references not merely as an introduction to the medieval scene, but as a reminder that a timepiece is much more than a mechanism. To attempt to understand it in isolation from its human setting is to forget that it was made in the first place in response to specific human needs. As those needs altered, its form tended to change, and there might be times when its very survival was in jeopardy. It is doubtful, for example, whether in a simple agricultural society much meaning would be found in an Athenian clepsydra, let alone in a Vitruvian astrolabe dial. However dark or bright a historian might be inclined to find the first few bucolic centuries following the final collapse of the Roman Empire, one thing seems certain: if the Vitruvian tradition was handed down within the West, it was by the chance preservation of text or artefact in a society hostile to the civilization which gave birth to the underlying rationale. In Islam conditions were ostensibly more favourable, and the tradition of hydraulic automata was positively enriched, helped by a religion that encouraged astronomical expertise of a high order,[10] not to say by a climate that seldom encouraged water to freeze. In due course, Europe became more conscious of the need to learn from the past, and something significantly new was added to the ancient tradition of anaphoric clocks, this without much by way of the mediation of Islamic thought. The institution chiefly responsible, both for preservation and for development, was the Church.

This should not be very surprising. The Church was rich and powerful. It controlled almost all academic education. It could afford to employ the best available craftsmen, and numbered among the lay brethren attached to the monasteries must have been some of the most skilful artisans of the time.[11] The monastic orders had played an important part in the development of the many mills and contrivances which could be powered by a waterwheel, which thus made more time available to the monks for their proper vocation of prayer and meditation. (The Cistercian rule enjoined monks to build near rivers so as to make best use of water power.) The administrative machinery for such a vast enterprise as the construction of a large mechanical clock was available nowhere outside the Church and the courts of princes. The transmission of power by means of gearing, rope, and pulley, was admittedly a part of a common stock of craft-knowledge from ancient times. One must be wary of exaggerating the conceptual difficulty inherent in these ideas. The principle of the rope drive, for example, should be immediately evident to anyone who lets slip the windlass as he hoists up a bucket from a well.[12] But the mathematics of gear-trains – and this is especially true of astronomical trains – were the province of the well educated alone. And education of the appropriate sort was the monopoly of the Church.

The Church was a feudal force, and through the close regulation of the monastic day a measure of regularity was imposed on society at large. With or without automatic control, the canonical hours of the monastic life were struck eight times daily on a tower bell which, in summoning the monks to prayer by day and by night, was heard far beyond the confines of the cloister. The rules for the market of Salisbury, for example, in the early years of the fourteenth century, refer specifically to the striking of the cathedral clock,[13] and there are even cases where the Church obliged the townsmen to maintain a church clock. I do not want to give the impression that people outside the churches had no wish to keep their own time: in Cologne, for instance, a guild of water-clock makers was already in existence in 1183, while by 1220 they occupied a whole street, the *Urlogingasse*.[14] Within the Church, however, timekeeping – which had at first been no more than an aid to the regulation of worship – soon became almost a necessary ingredient of ritual. In due course, timekeeping was to encompass the drama of a mechanical cosmos, combined with a wide range of more earthly amusements: striking jacks, jousting knights, wheels of fortune, and in fact all that the Vitruvian word *parerga* might have signified. Not that we should exaggerate the element of drama, or melodrama, to the exclusion of all else. If the concept of precision in timekeeping had been unknown in the fourteenth century, Chaucer could hardly have written, as he did in the *Nun's Priest's Tale*, of the cock Chaunticleer thus:

> 'Wel sikerer was his crowyng in his logge
> Than is a clokke or an abbey orlogge.'[15]

In lands where the Sun does not always shine, and in a community for which the first cockcrow of the day was not early enough for the call to matins, some sort of clock was sorely needed. A classic list of references to early examples has gradually accumulated, and I have no wish to tread more than absolutely necessary on already well-trodden ground, but it is impossible to appreciate the mechanical clock without a knowledge of the role played by its predecessors. There is no good reason to suppose that knowledge of the water clock in the West depended on its importation from Islam. Considerable doubt attaches to the story that there were diplomatic relations between Charlemagne and Harun al-Rashid, as are presupposed by the legend that the Caliph sent the Christian emperor a water-clock, a silk tent, and so on.[16] The oldest detailed account of the construction of a water-driven alarm is in a tenth or eleventh-century manuscript, now unfortunately incomplete, from the Benedictine monastery of Santa Maria de Ripoll, at the foot of the Pyrenees.[17] The text does not appear to be a translation from an Arabic original. There is every indication that the hydraulic driving mechanism, of which the description is lost, did not turn any astronomical dial, but merely a dial to help in setting the alarm. The weight-operated striking mechanism was very simple: an ordinary rope-and-weight drive turned on an axle which acted as a flail on small bells hanging from a rod. This very primitive device had to be re-set after each use. This re-setting was perhaps done by the sacristan, as is explained in the Cistercian Rule which dates from the early part of the twelfth century.[18] In Rule XCIV, the sacrist was instructed to set the clock *(horologium temperare)* and cause it to sound *(facere sonare)* on winter weekdays before lauds, unless it was daylight. He was to use it to awaken himself before vigils each day, before lighting up the church. In Rules LXXIV and LXXXIII, the brethren and sacrist were told to ring the larger bell (*signum* or *campana*) on hearing the clock *(horologium)*. These are not the earliest constitutions known that relate to the subject. In the eleventh century, William, abbot of Hirsau, gave similar instructions to the sacristan, using words which echoed the Cluniac rule and also the ancient customs of the monastery of St Victor in Paris, where the registrar *(matricularius)*, the sacristan's companion, was to adjust the clock.[19] Such adjustment was necessitated by the use of unequal hours.[20] Similar commentary on the Benedictine Rule confirms that the same customs were adopted generally.

There can be little doubt that mechanisms were operated by water. The supporting evidence is well known, and has been ably summarized by C.B. Drover.[21] There was the fire of 1198 at Bury St Edmund's abbey, which the clock doubly helped to extinguish, first by rousing the master of the vestry, and secondly by providing water. There are the fragments of slate dating from 1267 or 1268 from Villers Abbey near Brussels, relating to the method of setting a water-clock by the Sun. There are the Alfonsine books of the next decade, which describe both a water-clock and a mercury-clock.[22] There is the clock case of about 1250, drawn in the sketch book of Villard de Honnecourt. And then there is the illustration to which it was the aim of Drover's article to draw attention, an illustration of almost exactly the same period as Villard's, showing a similar clock-case.

The illustration is from a moralized Bible of extraordinary richness.[23] The prophet Isaiah is shown giving the sick king Hezekiah a sign from the Lord that fifteen years will be added to his days. This was done 'that the Sun would be moved back ten degrees in the clock'.[24] I shall discuss this illustration briefly here since it seems to me that it has been misinterpreted by Lynn White Jnr. in a work which is so well known and generally so accurate on points of detail that his version is likely to become canonical.[25]

The medallion illumination illustrates 2 Kings XX.5-11. The same story is told in Isaiah XXXVIII.8. The Bodleian manuscript is one of three needed to complete the original Bible, and the Isaiah passage is to be found in the complementary manuscript in the Bibliothèque Nationale, MS Lat. 11560, f.120r, where, sad to say, there is no comparable illustration, owing to the different wording of the Vulgate.[26] Both illustrations show a symbol denoting the Sun, which is emphatically not a 'fan-escapement to slow the action of the chime, at the striking of the hours, by friction with the air'[27] but is a representation in accordance with a perfectly standard convention.[28] The fifteen divisions of the only visible wheel might be significant, but in view of thirteenth-century artistic conventions, it is unlikely that the number does more than pick up the '15' of the years mentioned in the text, as seems to have happened in the Isaiah illustration. It is certainly rash to conclude that since 15 degrees represent an equinoctial hour, therefore the wheel was probably meant to turn once every hour. In any case, the wheel seems to have about 24 teeth, which rather suggests that it might have been meant to turn once in a day.

The clock clearly has some sort of rope drive, but there are several mechanical reasons for thinking that it did not work on the same principle as the Alfonsine mercury clock. (In the latter, a couple created by viscous forces, as mercury flows between radially divided compartments of a wheel, is opposed by a couple created by a rope drive, thus establishing dynamic equilibrium in the wheel, which turns slowly.) Not the least of the objections to this interpretation of the biblical painting is that water is there shown clearly gushing forth from an animal's head spout into a cistern below the clock. There are unsolved problems of interpretation, certainly,[29] but it is difficult to avoid the general conclusion that, however it worked, the clock was mechanically a simple affair, offering little more than encouragement to the men who would make the first purely mechanical clocks.

Within a century, however, two clocks were begun, by Richard of Wallingford and Giovanni de' Dondi respectively, which were so extraordinarily complex that in the sixteenth century the first could be described as even then surpassing all others in Europe,[30] while the second was so intricate that Charles V could find only one technician, Gianello Torriano, who was capable of repairing it, others having failed.[31] How may we explain such a technological advance, for which there were very few parallels in the Middle Ages and few indeed before the industrial revolution of the eighteenth century?

I must first remind you of that remarkable passage to which Lynn Thorndike first drew attention, in the commentary written by Robertus Anglicus in 1271 on the most widely used of all medieval astronomical textbooks, the *De Sphera* of Sacrobosco.[32] After a discussion of equal and unequal hours,[33] Robert goes on at some length:

> Nor is it possible for any clock *(horologium)* to follow the judgment of astronomy with complete accuracy. Yet clockmakers *(artifices horologiarum)* are trying to make a wheel which will make one complete revolution for every one of the equinoctial circle [i.e. the celestial equator], but they cannot quite perfect their work. If they could, it would be a really accurate clock 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 disk *(circulum)* of uniform weight in every part, as far as could possibly be done. Then a lead weight should be hung from the axis of that wheel, and this weight should move that wheel so that it would complete one revolution from sunrise to sunrise, minus approximately as much time as it takes about one degree to rise.[34]

This all suggests that no form of mechanical escapement was known to the writer in 1271, and the simple arrangement he describes is not incompatible with the water-clock illustration discussed earlier. Within a few years, however, the number of documentary references to *horologia* grows so very rapidly that we can only suppose the mechanical escapement to have been found at last. C.F.C. Beeson is persuasive in arguing that the earliest of all European records of a clock with such a control is that of 1283, in the Annals of Dunstable Priory in Bedfordshire.[35] This was a house of Austin canons. The clock was set up alongside a great painted crucifixion scene, with attendant images of Mary and John, on the rood-screen and loft, or gallery. Beeson follows with records from Exeter Cathedral (1284), Old St Paul's, London (1286), Merton College, Oxford (1288?), Norwich Cathedral Priory (1290), Ely Abbey, a house of Benedictine monks in Cambridgeshire (1291), and Christchurch Cathedral,

Canterbury (1292), all before the turn of the century. Taken singly, the records are easy to view with scepticism, but taking them together, and noting especially that relatively large sums of money are involved in payment for the materials used, they persuade us that the mechanical clock had indeed arrived on the scene. When the *orologiarius* Bartholomew drew 281 rations for three quarters and eight days in 1286 at St Paul's, he was surely not building either a sundial or a water clock.

Although it is possible to be reasonably precise as to the time of the invention, the place of origin of the mechanical clock is entirely unknown. Italy has been canvassed, mainly, one suspects, on the grounds that Italy was always a century in advance of the rest of Europe. The earliest acceptable Italian record of which I am aware, however, relates to the year 1309, when an iron clock *(horologium)* was set up in Sant' Eustorgio in Milan.[36] A bell on the bridge at Caen was in 1314 associated with a clock *(l'orloge)* there and according to its inscription served the common people, but this need not have been a purely mechanical clock, and in the absence of further documentation its watery surroundings do not encourage the idea that it was so. The known early English records are at the present time much the richest in Europe, and I am obliged to give most of my attention to them; but I certainly do not suppose that the mechanical escapement was for this reason an English invention. I find it hard to believe, nevertheless, that any early centre of clock-building could have been more advanced than that which took in Norwich and St Albans, and most of what I have to say will relate to the remarkable work done in these two places.

The Sacrist's Rolls of Norwich Cathedral from 1321 to 1325 contain the first extensive financial records concerning the construction and installation of a large mechanical clock.[37] The man in charge of the work was one Roger Stoke, who later worked at St Albans, and who was in both places assisted by Laurence Stoke. The clock had a very large astronomical dial -- it was of iron plate and weighed 57 lb -- with models of the Sun and Moon, automata, including 59 sculpted images (done by one Adam, a wood-carver), and a choir or procession of monks. There was much colouring and guilding. Smiths, carpenters, masons, plasterers and bell-founders were engaged over a period of three years. The competence of most of the craftsmen concerned seems to have been equal to the occasion, but the making of the main astronomical dial went less smoothly than the rest. In 1323 the fabrication of the large plate was entrusted to Robert of the Tower (Robert de Turri) in London, but in his hands the whole work was ruined. The man was himself ruined *(depauperatus)*, and only 10 of the 18 shillings advanced to him could be recovered. Other artisans proved to be equally ineffectual, ruining the material in their attempts. Men were sent from Norwich to London for news of progress, but at length it was necessary for Roger Stoke himself to ride to London to supervise the engraving of the plate. The total cost of the clock was in excess of £52. There are many ways of working out a modern monetary equivalent, none very satisfactory; but in terms of the salary of the best craftsmen of the time, this amounts to around $250,000, in modern American terms.

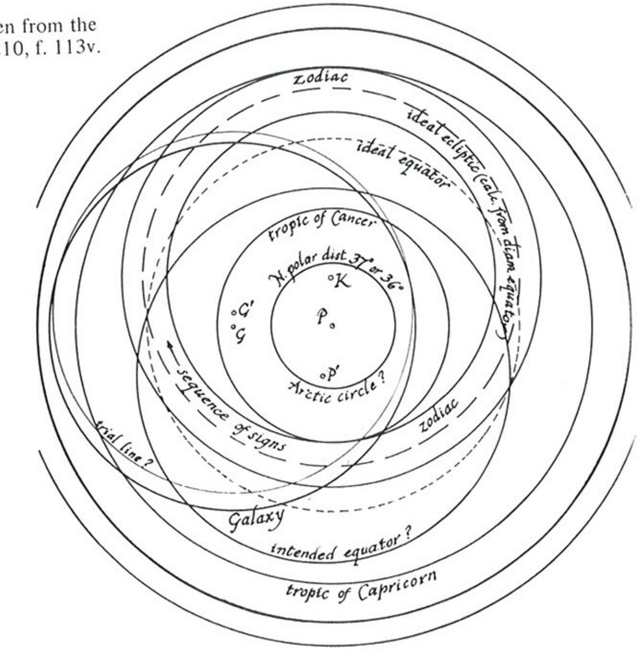
Complex as the Norwich clock obviously was, it was as nothing by comparison with that designed by Richard of Wallingford, however similar the two might possibly have appeared outwardly. Before considering the mechanical intricacies of the St Albans clock, I should like to consider that aspect of the clock which gave so much trouble to the Norwich builders, namely the dials. These had the same general appearance as an astrolabe, showing the daily rotation of the sky -- the stars, and perhaps the Sun and Moon -- against a second 'map' of the observer's coordinate lines and unequal hour lines, the horizon and the meridian being chief of these. We know that the Vitruvian anaphoric clock had such a dial,[38] and it is of some interest to ask whether the ancient tradition was ever completely lost.

I shall offer two tentative arguments for supposing that the tradition had some sort of continuity. The first rests on the fact that there is documentary evidence for the survival from Roman, as opposed to Islamic, sources of the tradition of mapping the sky in stereographic projection in the manner required for the main dial – the most difficult theoretical aspect of the construction. Parts of two discs from anaphoric clocks have been found, one at Salzburg, and one at Grand in the Vosges, both of the 2nd century A.D.[39] Judging by the Salzburg disc, the Sun was not moved mechanically with respect to the stars, but was simply plugged into one of 360 or 365 holes distributed around the ecliptic. Other astrolabe dials are those of the water-clocks of Islam, but here one must be cautious and remember the fallacy of *post hoc ergo propter hoc*. In the Islamic world the dial generally resembled the conventional astrolabe, with its pierced star map placed between observer and the plate of local coordinates. The same seems to have been true of the thirteenth-century Alfonsine dials, which were presumably inspired by Islamic sources.[40] In the European tradition it seems to have been far more often the other way round. In this way, it was possible to paint the constellations in as much detail as was thought desirable. The flimsy overlay of wires representing a horizon, meridian, unequal hour lines, and so forth, offered no great obstacle to vision.[41] Bearing the typical European arrangement in mind, there is a certain class of manuscript illustrations dating from the ninth century onwards which closely parallel the anaphoric clock tradition in the West, as I shall explain in a short digression.

By the ninth century,encyclopaedists like Scot Erigena and Isidore of Seville had brought the contents of several late Roman authors to the notice of the educated few, while Lupitus, Hermann and possibly Gerbert, in the tenth century, drew on Arabic sources for their writings on the astrolabe.[42] It is in association with the ancient writings of Aratus (as transmitted by Germanicus), Hyginus and Macrobius on Cicero, however, that we find a certain class of extremely interesting manuscript illustration of this period.[43] One fine example included with scholia to Aratus is in a manuscript of the early ninth century now in Munich.[44] At first sight this is merely a planisphere, showing the constellations pictorially, with one very clearly marked circle. This proves to represent not the ecliptic, but the galaxy, the Milky Way. On closer examination, however, no fewer than eight circles are revealed within the outer pair bounding the planisphere, all in approximate – and not accidental – stereographic projection. Whoever painted this diagram seems to have known the principles of astrolabe projection well. He was certainly not merely painting an ordinary astrolabe rete, since the Milky Way is never – at least to my knowledge – found on an astrolabe, while there is also on the painting an uncharacteristic circle with north polar distance of about 37°. This could be a zenith-track for geographical latitude 53° N,[45] although it is more probably an arctic circle set to a conventional 36° (the height of the Pole at Rhodes). The stars are, moreover, drawn with the signs in a clockwise order, and not as on an astrolabe. I shall return to this point later.[46]

A second, but somewhat different illustration of the same period, also associated with scholia to Aratus, is to be found in the Berlin Codex Phillippicus 1830 at ff. 11 and 12. It is redrawn, perhaps not absolutely accurately, by Georg Thiele,[47] and on the evidence of his drawing it is impossible to know whether the original is as carelessly drafted as it appears to be from Thiele's version. Now, however, we note that this diagram has the sense of rotation of the zodiacal signs as found on an ordinary astrolabe rete, unlike that of the Munich diagram. Yet another example of this type of illustration, which can now be examined in colour in a modern printed source, occurs in a twelfth-century Spanish manuscript.[48] Thiele's *Antike Himmelsbilder* is a useful source of precise information on the texts with which these illustrations are associated, and the book is in fact prefaced with a list of 2

Fig. 1. Construction lines taken from the constellation map of C.L.M. 210, f. 113v.



Notes on the constellation map of C.L.M. 210, f. 113v.

1. The projection is from the *south* pole, as on an astrolabe, but the stars are depicted *as seen*, and with the order to the signs reversed, as on known astrolabes.
2. The tropics are not drawn with our convention, for one touches the northern limit of the zodiac band, the other the southern limit.
3. The hesitant way in which the circle centred at G' is drawn, together with the equality of its radi and that of the circle centred at G, and their proximity, suggests that the former is a trial line, or mistake. Neither can be the projection of a great circle, whether from P, P' or K. See below.
4. The circle centred at P' appears to be the intended equator, since no other line will serve, and sin the diameter is correct. In stereographic projection, however, the equator would be centred at P. see the dotted line. (The tropics must be concentric with the equator.)
5. The small circle centred at P has a north polar distance of about 37°, and could mark the arctic circle in keeping with one ancient convention (36° = latitude of Rhodes). Alternatively, it could the locus of the zenith point for an observer in a latitude of approximately 53°. (The MS was fo some time in the library of St Emmerammus, in Ratisbon.)
6. The catalogue entry on C.L.M. 210 has

> 'f. 114 Excerptum de astrologia . Adiecta est picta caeli tabula. Inc.: Duo sunt extremi vertices mundi quos appellant polos ... '

This text was edited by E. Maass in 1898.

manuscripts (but not all of them illustrated).

I have no wish to suggest that these diagrams were copied from an anaphoric clock plate, but they show that at least from the time of the ninth century the necessary skills for making such a plate were once again available in Europe, and that Pacificus, Archdeacon of Verona, could well have had on the clock mentioned in his epitaph a 'song of the heavens' in the form of an astrolabe dial of one sort or another.[49] It is quite possible, of course, that the medieval illustrations were copied from ancient examplars which were themselves taken from anaphoric dials, or were even done by craftsmen skilled at both arts.

Coming down for a moment to the thirteenth century and another record of an astrolabe dial, this time from northern Italy, we find what is probably the oldest extant detailed description of the sequence and counts of the wheels of a planetary model.[50] This was probably water-driven, if it was ever built, and if so it must have demanded many advanced technological skills.[51] The device had an astrolabe dial in a vertical plane,[52] and it exhibited a number of Ptolemaic planetary motions. It is not at all unlikely, however, that the description related to a non-European device, perhaps that given to the Emperor Frederick II, in 1232, by the ambassadors of al-Ashraf, Sultan of Damascus. This highly valued gift was presumably lost in the seige of Parma in 1248, with the Emperor's treasury, his insignia, some of his ministers and, no less significantly, his harem.

I now come to my second argument — and one which is, I think, much stronger than the first — for supposing that there was a tenuous European continuity in the transmission of the ancient tradition of putting astrolabe dials on clocks. If we look at the astrolabe dials of the great European cathedral and abbey clocks of later centuries, we find that they are for the most part in stereographic projection from the north pole, rather than — as with almost every known portable astrolabe — from the south. This is true of the clocks at Valenciennes, Münster, Prague, Bourges, Doberan, Lübeck, Lund, Stralsund and Ulm, for example. Notre Dame at St Omer, and Berne, were relatively rare specimens in south projection, and like the Alfonsine mercury clock and the De' Dondi clock, they had a rete of stars which was turned by the mechanism. In the typical anaphoric clock, however, and in the Salzburg fragment, and in Richard of Wallingford's clock at St Albans, while the projection was from the south pole, the rete was fixed and was a rete of hours, rather than of stars. If the Phillippicus and Osma manuscripts had been drawn from a moving plate, this would have been in the same tradition.[53] I would therefore like to suggest, very tentatively, that Richard of Wallingford was following an ancient tradition perpetuated, whether by artefact or document, within the monasteries of northern Europe. And lest it seem that the probabilities are high that a fourteenth-century author should hit on the ancient arrangement by chance, it should be noted that there are sixteen possible arrangements of a rete and plate, and that no fewer than five of these are actually found in use among the clocks I have mentioned.[54]

The first English clocks seem to have been made almost wholly of iron, and to have been of large dimensions: a frame three or four feet across was not unusual, and the frame of the St Albans clock was probably more than twice as great as this. De' Dondi's clock, of the mid-fourteenth century, was of brass and much smaller, while in the inventory of Charles V it is recorded that Philippe le Bel, who died in 1314, possessed a clock of an even more costly metal, silver, 'une reloge d'argent, avec deux contre poix d'argent empliz de plomb'.

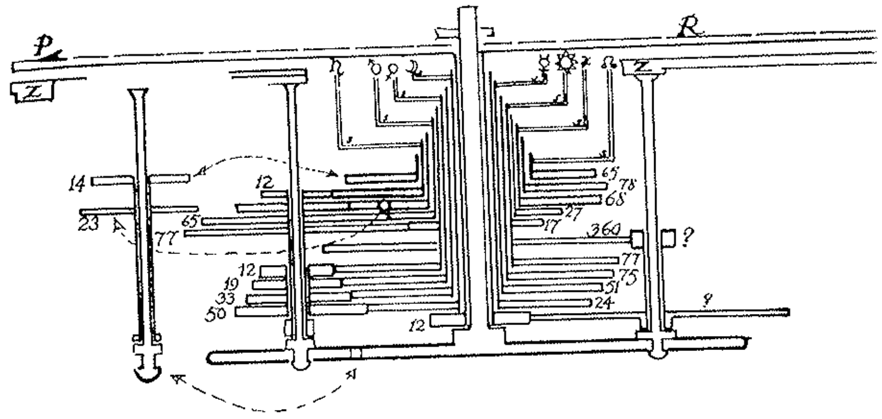


Fig. 2. One possible reconstruction of the 'device of certain remarkable wheels' described in the manuscripts from northern Italy (13th cent.).

R is the rete, Z the zodiac, P the pointer, and C the supporting column. The models of the planets are indicated by their symbols, and the numbers indicate the numbers of teeth on the adjacent wheel. For clarity, one train of gears has been drawn out of position. It is to be inserted in a way indicated by the dotted arrows.

The Church cannot perhaps claim much of the responsibility for the rapid improvement in the quality of metalwork or for the rapidly growing numbers of metal-workers at the end of the thirteenth century and the beginning of the fourteenth. Chain armour was giving way to intricately hinged plate, and cannon were for the first time being employed in European warfare.[55] There was social mobility enough, however, for ecclesiastic and artisan to come together on such a venture as that of making the most elaborate device in metal designed at that time. Some clocks, to be sure, were relatively simple devices, but a high proportion of those early clocks of which we have records were much more simple devices. Some of them showed jacquemarts to amuse or astonish the onlooker, and others perhaps a simple astrolabe dial, but far more significant were those which displayed the daily and annual movements of the Sun, the Moon (and possibly the planets), the phases of the Moon and other astronomical phenomena. At least in its highest form, the mechanical clock was largely the product of an intellectual movement going back to antiquity, and one with which Professor Price's paper very effectively deals.

The tradition of the geared planetarium simply could not have begun or have been maintained without considerable astronomical and mathematical knowledge. The single diurnal movement of the water-clock was something which could be altered at will by adjusting the water-flow; but to interrelate the complex movements of the planets and the cosmos requires a far from trivial ability to compute trains of gears. Since the same ability is needed to compute even the much simpler going and striking trains of a mechanical clock, it seems not unlikely that the first mechanical clocks were the product of the academic world -- and here it is impossible to draw a dividing line between Church and University -- rather than of the unschooled artisan. We need only recall the difficulties encountered in the much simpler matter of engraving an astrolabe dial for the Norwich clock.

Richard of Wallingford was in an excellent position to unite the craft tradition with the academic. As I mentioned earlier, he was the son of a blacksmith of Wallingford in Berkshire. Orphaned at an early age, he was sent by the Prior of the Benedictine house at Wallingford to study at Oxford, where he stayed with one short break from about 1308, when he was roughly 16, until he took the monastic habit at St Albans at the age of 23. After his double ordination, first as deacon (1316) and then as priest (1317), he was sent back to Oxford by his abbot. There he studied philosophy and theology for nine more years, in the course of which he wrote some remarkable pieces on trigonometry and astronomy, as well as astrology -- which was of course almost *de rigeur* at that time. In 1327 he visited St Albans at a time which coincided with the abbot's death. He was himself elected abbot, duly visited Avignon for the papal confirmation, and at length returned to rule his monastery, which was in several ways the most important in England. He had a difficult time. He contracted leprosy on his overseas journey; his abbey was saddled with numerous debts; the townsmen were in revolt against the feudal privileges of the abbey; and there was an inquisition to investigate his fitness to rule. Despite his firmness towards them, however, he appears to have inspired enormous confidence in most of his monks, and when he died after only nine years in office, he left behind him a far greater secular inheritance than did his predecessor. At St Albans he was remembered above all else for his clock.

Leaving aside, for the present, the nature of the going and striking trains, I will first say something of the general character of the astronomical section, which was built into an adjacent frame. It seems, judging from the manuscripts, that Richard began to write a thoroughly formal treatise on the whole subject of making an astronomical clock, that he completed a first section on the arithmetical tech-

editing his several drafts of chapters describing the actual construction of a clock -- the St Albans clock. A single manuscript of these drafts survives, not in the hand of the author, but copied out for the sacristy at St Albans by a man who had a very poor idea of the best order, and who mixed the drafts with other quite irrelevant texts. The manuscript was later misbound, and a whole gathering is missing, presumably with details of the actual planetary trains hinted at by certain surviving data.

In successive parallel drafts we can see how Richard improves upon his first thoughts until the accuracy of the gear trains he advocates is exemplary. By using a transported correction train to drive the Moon, for example, the theoretical error in its mean motion is only 7 parts in 10^6. But accuracy is not only achieved by the careful determination of gear ratios. The problem of driving the Sun round the zodiac at the correct rate is simply that its speed should be variable. Richard solves this problem by computing an oval gear wheel, with contrate teeth, linked to a long pinion the axis of which is parallel with the plane of the oval wheel. The result is highly accurate, but more to the point, there is absolutely no known historical precedent for gears of this design, which until the discovery of the St Albans manuscript would have been generally thought beyond the potential of medieval technology. (I should say here that the oval wheels of the later De' Dondi clock are of an entirely different sort, and serve a different purpose.) The intricacy of the gear work of the St Albans clock may be judged from another type of wheel, which transmitted power from conchoidal contrate teeth to a worm gear. This offers an excellent solution to the problem of smooth transmission, and -- unlike the oval wheel is still much used.

Among the clock's other refinements, I may mention a half-blackened Moon-globe which, rotating on its axis as the globe moved round the dial, showed the lunar phase. But this was not all. The lunar globe was so placed that it was automatically drawn under a small eclipsing disc whenever the time was ripe for an eclipse of the Moon. I hardly need say that this was an extraordinary feat of design.

Very little about the arrangement of the planets of the clock is now known, but when John Leland saw the clock at the time of the dissolution of the English monasteries, he reported that it included planetary trains and a tidal dial.(English manuscripts of the period are frequently found which tabulate the time of the tides at London Bridge, and a tidal dial would have been a relatively simple affair, following the lunar motion.) And this is a suitable point at which to record the placing of the clock. Like so many abbey clocks, it was put into the south transept of the church, and was therefore rather better protected from the weather than the average tower clock.

The St Albans clock was not completely finished during Richard's lifetime, but there is no reason to suppose that those who finished the work altered his design.[56] Judging by a remark made in chronicles of the abbey after his death, there was no one capable of doing comparable work -- as he had indeed foretold, in excusing his lavish spending on the work on the occasion of his being upbraided by the king who pointed to the poor state of repair of the fabric of the abbey. There was, however, an established clockmaking craft, and it is of the greatest interest that the very Stoke family who had worked at Norwich were also engaged over a long period of time in work on the St Albans clock. Roger and Laurence Stoke were professional *horologiarii*, but they were lay brethren,[57] who must have done other monastic work in the area of England north-east of London. How tight the monastic hold on their profession was, at this period, is difficult to determine for lack of evidence, but the only stylistic parallels I have found with the St Albans clock are with the west country series at Exeter, slight, and mostly concern the simplest aspect of the lunar mechanism.

Finally, I come to the mechanical escapement, that characteristic of the truly mechanical clock which distinguishes it from what went before. It has always been supposed that the first mechanical escapement was the familiar verge and foliot, that is to say, the sort found on the De' Dondi clock, and found on large church clocks throughout Europe, until at length it was replaced by the pendulum. It cannot be said with certainty that this was not the first; but the first escapement of which we have certain knowledge, namely that of the St Albans clock, was substantially different. The clock had two similar escapements, one to control the going train and one to sound the bell at the hour — and on a twenty-four hour system, with a number of strokes equal to the hour. A double-edged pallet was thrown first one way and then the other, each edge being acted upon by one of several radially disposed pins on one or the other of a pair of similar wheels fixed together in parallel planes a suitable distance apart. (The pins on one wheel came mid-way between those on the other.) A vertical verge with cross-bar, carrying weights to adjust the moment of inertia of the verge assembly, and hence the period of swing, oscillated accordingly, and on the striking side of the clock it was these oscillatory swings which caused the bell to be struck. Needless to say, by working with one pallet it was not necessary to traverse the arbor of the crown wheel (or pin wheel) with another arbor. On the other hand, the St Albans mechanism required an extra wheel, and it might well have quickly fallen out of favour on the grounds of expense. I am convinced, however, that it was mechanically more efficient than the common verge and crown wheel. To distinguish this type of escapement, I shall use the word 'strob', which is that given to it in the manuscript. In dictionary language, strob is 'etym.dub.' The pallet is simply called a 'semicircle'.

There is no drawing of the strob wheels and verge in the St Albans manuscript, and the reconstruction is one which was achieved by painstakingly piecing together a whole series of measurements of things given in words, many of which were unknown to the dictionaries. Having, after many attempts, arrived at a successful solution, its correctness seemed to be confirmed when I found drawings of the very same escapement in Carlo Pedretti's *Studi Vinciani*,[58] reproduced, need I say, from the work of Leonardo da Vinci. These drawings are from Codex Atlanticus and date from about 1495. There are similar drawings in Codex Madrid. It is not for me to correct here those who have ascribed to Leonardo the invention of this ingenious device, but rather to suggest that if an escapement is known from two places at opposite extremes of Europe and from periods 160 years apart, there is a strong likelihood that the escapement was once widely diffused. There is in fact one other manuscript, of the early fifteenth century, in which the same escapement appears to be the subject of discussion.[59]

The two types of verge and foliot escapement — they may be distinguished as single- and double-wheel types — are obviously functionally related. The double-wheel is mechanically superior and more expensive, and on both scores it might therefore be thought wise to place it historically earlier than the single-wheel. It is the earlier, as far as extant records go, and moreover when Richard of Wallingford gave some numerical data for it, between 1328 and 1336, he wrote as though its construction was generally known. In the customary scholastic manner, he went into minute detail on the astronomical and arithmetical side of his draft treatise, but when he came to the going and striking trains, he took their general construction for granted and contented himself with measurements and gear counts. Some of the most technologically interesting parts of his work are thus the most difficult to disentangle, and this is especially true of the part which concerns the striking mechanism. I hasten to add, however, that I have not the slightest doubt that the clock had hour-striking of the sort men-

tioned earlier, with some sort of locking barrel, even though this directly conflicts with the well-known statement by a certain monk of Malmesbury, who dates the invention to 1373.

On this subject of the oscillatory mechanism for striking the bell, I wish to end. This, in the St Albans clock, works exactly as the main escapement, and it is not inconceivable that such an oscillatory striking device triggered at suitably chosen intervals by a hydraulic clock, pointed the way to the first mechanical escapement proper. (Perhaps my title should have echoed Professor Price's, and read simply 'The escapement before the escapement'.) The bell to be struck in this manner could have been large and the noise impressive, unlike the tintinnabulation to be expected of a water clock of the type illustrated in the thirteenth-century moralized bible. Can it be that the more ponderous tones of a clock sounded in this way were those which, somewhere between 1235 and 1260, it was ordained should be heard at the installation of every new abbot of St Albans? There are water-clocks (*orologia ollarum*, 'clocks of earthernware vessels') briefly mentioned in the St Albans chronicles under the rule of John de Maryns (1302-8), but the earlier reference is more revealing by far. The prior shall enter the church from the chapter house, the rule of John of Hertford tells us, to be presented to God and the Holy Martyr Alban at the high altar, with the striking of a summons, the shawms[60] sounding with the horologe, the tapers lighted round the altar, and the throne uncovered. Very few of those treatises from the centuries following, in which are given precise and complete descriptions of actual clocks, can convey quite as much about medieval humanity as can this passing reference to one way in which a great abbey clock of the thirteenth century was absorbed into the high ritual of the church. Nothing could have been more fitting.

NOTES

1. *Vespae*, 93. 857.

2. *Athen. Polit.*, 67. 2.

3. *Demosthenis Encomium*, 15. The work is probably of the second or third century A.D.

4. *De Oratore*, 3. 34. 138.

5. Aeneas Tacticus (4th cent. B.C.) ed. R. Schone, Leipzig 1911, 22-24.

6. See, for example, Proclus: *Hypotyposis astronomicarum positionum*, ed. C. Manitius, Leipzig 1909, 4-74.

7. This statement is made in the *Enc. Brit.*, 11th edn., art. "Bell", by H.M. Ross, who probably took it from the best-selling book by A[lfred] G[atty]: *The Bell: its Origin, History and Uses* London, 1847, p.16. In neither place is a reference given, but the source was very probably chapter 6 of Hieronumus Magius [or Maggi]: *Anglarensis de tintinnabulis*, many editions; but that of Amsterdam 1689 is illustrated with an imaginary reconstruction, at p.31. A rope from a clepsydra float trips a weight which operates a bell once only (through a crank!). Maggi, writing from prison, gives no precise references, but says that his relative Johannes Nicolaus Justus made him a copy from an old book in which the Lucian clock was delineated.

8. *De Architectura*, IX. viii. 4-7. Vitruvius was most probably writing a few years before 27 B.C.

9. *Ibid.*, 8-14.

10. Astronomy served not only astrology, a subject to which Islamic scholars added significantly, but among other things it was required by any who would master the lunar calendar adopted by the faith.

11. The Abbot of St Albans, Richard of Wallingford, whose work I shall shortly describe, was the son of a blacksmith.

12. One might imagine that the principle of the water-driven wheel was arrived at by the same sort of accidental discovery of reversibility, in this case of such a water-raising device as, for example that which appears in Vitruvius: X.4 (the *tympanum*).

13. The sources relating to the Salisbury clock are to be found in C.F.C. Beeson: *English Church Clocks, 1280 to 1850*, Antiquarian Horological Society 1971, p.16.

14. Quoted from E. Volkmann by Lynn White Jnr.: *Medieval Technology and Social Change*. Oxford 1962, p.120.

15. *Canterbury Tales*, Fragment VII. lines 2853-4.

16. For the historical controversy see E.A. Belyaev: *Arabs, Islam, and the Arab Caliphate in the Early Middle Ages*, tr. from the Russian, London 1969, p.221. Belyaev is perhaps too extreme in his criticism of the 'traditional opinion inspired by Christian pietism'.

17. A full discussion and translation of the surviving part of the text was given in F. Maddison, B. Scott and A. Kent: 'An early medieval water-clock', *Antiquarian Horology*, 3 (1962), 348-53.

18. I quote from C.B. Drover: 'A medieval monastic water-clock', *Antiquarian Horology*, 1 (1954) 54-8.

19. These earlier references and those next following are given in greater detail in John Beckmann: *A History of Inventions, Discoveries and Origins*, tr. W. Johnston, 4th edn., London 1846, pp.346-9. This is a fundamental source of information on the history of the clock. The section was actually written originally by Hamberger.

20. See 33 below. Dante has something to say on equal and unequal hours, and the difficulty of regulating church services, in *Convivio* IV.23, near the end.

21. *Ibid.*, passim.

22. Mr. Francis Maddison, who is preparing an English translation (with commentary) of the text describing the Alfonsine mercury clock, points out that the inspiration for this clock is stated in the text to be a work by 'Iran el filosofo', namely Hero, more specifically where he explains ways of lifting heavy weights.

23. Bodleian Library, Oxford, MS Bodley 270b, f.183v. For a facsimile of the entire MS and its missing parts (B.N. Lat. MS 11560, and B.M. MS Harley 1527) see A. de Laborde: *La Bible moralisée*, Paris 1911-27, 5 vols.

24. '...ut Sol x gradibus retrorsum in orologio reuerteretur'.

25. *Op.cit.*, pp.120-1.

26. There is no mention of a *horologium*, but the mention of *gradus* prompts the illustrator to paint a flight of 15 or 16 stairs!

27. White, *op.cit.*, p.121.

28. The same convention is to be seen on numerous occasions in the manuscripts (Bodley 270b, ff. 10r, 16r, 34r, 57v etc.), especially in connexion with crucifixion scenes. It was still being followed more than a century later. See, for example, Bodleian Library, MS Ashmole 1522, ff. 27r, 39v, 40r.

29. Drover was puzzled at the cranked form of the arm supporting the wheel, but a comparison with the astronomical instruments of ff.11r, 24r and 27r suggests that this was the standard way of supporting a wheel, resulting in a 'handle' in the plane of the wheel.

30. The antiquary, John Leland. No references to the material on Richard of Wallingford are given here. My complete edition of his writings is awaiting publication at the Clarendon Press, Oxford.

31. The authority is Bernardo Sacco, 1565. A somewhat different report comes from the notoriously unreliable Cardano. For the texts, see S.A. Bedini and F.R. Maddison: 'Mechanical

universe: the astrarium of Giovanni de' Dondi', *Trans. of the American Philosophical Society*, N.S., 66, part 5 (1966), 37-9.

32. The name Robertus Anglicus points to a man of English family, but the commentary was given as a course of lectures at the university of either Paris or Montpellier.

33. Sometimes called 'equinoctial' and 'canonical' or 'seasonal' respectively. The former are in accordance with our modern convention, each being one twenty-fourth part of a day. The latter are each one twelfth part of day or night. This convention goes back to the ancient world and survived in Japan until the last century at least. A night hour is obviously approximately equal to a day hour only twice a year, near the equinoxes. It should not be thought that the concept of equal hours ('horae de clock', in the late fourteenth century) had to wait for the invention of the mechanical clock, as is sometimes suggested. Astronomers made use of the idea in Antiquity, and it was known in the West in the early Middle Ages from the writings of Martianus Capella, Leontinus, Gerbert and many others. William of Hirsau's *naturale horologium* was probably so called because it showed the equal hours of the 'natural day' (24 hours), rather than of the 'artificial day' (sunrise to sunset).

34. Taken, in a form not significantly altered, from L. Thorndike: *The Sphere of Sacrobosco and Its Commentators*, Chicago 1949, pp.180 (text) and 230 (translation).

35. *English Church Clocks*, Antiquarian Horological Society, 1971, pp.13-14.

36. Mentioned in the Chronicle of Galvano Fiamma. See L.T. Belgrano: *Degli antichi orlogi pubbici d'Italia*, Archivo Storico Italiano, 3rd series, 7, Florence 1868. The clock was restored in 1333 and 1555, and renovated in 1572. See J. Drummond Robertson: *The Evolution of Clockwork*, 1931, p.31.

37. Mr. C.B. Drover kindly provided me with transcripts and photographs of the relevant sections. The Roll for 1323-4 is missing. There are extracts printed in *Archaeological Journal*, 12,1855, and in the Centenary Volume of the Norfolk and Norwich Archaeological Society, 29, 1946.

38. On the nature of the dial, its relation to the portable astrolabe, and the possibility that it was the invention of Hipparchus and came before the astrolabe (which of course is much the better known of the two), see A.G. Drachmann: 'The plane astrolabe and the anaphoric clock', *Centaurus*, 3 (1954), 183-9.

39. For references to the original literature, and for further details, see article by D.J. de S. Price in *A History of Technology*, ed. C. Singer, et al., vol.3, Oxford 1957, pp.604-5.

40. The fundamental studies of Islamic clocks are by E. Wiedemann and F. Hauser. See especially their *Uber die Uhren im Bereich d. islamischen Kultur*, Nova Acta. Abhandl. d. konigliche Leopoldinisch-Carolinsche deutsche Akademie der Naturforscher zu Halle, 100, no. 5, 1914.

41. The multitude of lines on the plate of an ordinary astrolabe (almucantars, etc.) were superfluous on an instrument which was not meant to be matched to observations, while the fine star pointers of an astrolabe rete would have been difficult to identify on a large dial high above the observer's head in a dark church.

42. Gerbert, who was to become Pope Sylvester II, was a highly practical man and it is worth noting that there is mention of a clepsydra in one of his letters (ed. Julien Havet, epist. 153).

Mrs. Harriet Lattin has pointed out to me in a note by Oldoin in Alphonso Ciacconius — Augustinus Aldoinus: *Vitae et resgestae Pontificum Romanorum*, Rome 1677, col. 756 — that Gerbert, as Archbishop of Ravenna, constructed a water-clock there: Horologii aquatilis, seu clepsidrae figura est Ravenna in Herculis regione, quam Gerbertus construxit Archiepiscopus tunc Ravennas. This would have been between April 998 and April 999.

43. Aratus of Soli, of the 3rd century B.C., wrote an astronomical poem based on Eudoxus, which was admired by some Roman writers. Cicero, Caesar, Germanicus and Aviennus translated it, and much still survives. There are at least four English translations. The circles which interest us (galaxy, equator, ecliptic and the tropics) are discussed at p.202 of the Loeb edition. Gaius Julius Hyginus was a prolific Latin author, living in Spain or Alexandria, whose elementary astronomical treatise drew heavily on the poem of Aratus. The commentary by Macrobius on Cicero's *Somnium Scipionis* is, of course, much better known.

44. CLM 210, f.113v. This is reproduced in several places, perhaps the best illustration being that in D. Bullough: *The Age of Charlemagne*, London 1965, plate 50 (in colour).

45. There is a very different diagram, but one based on an astrolabe plate for approximately this latitude, in Bodleian MS F.1.9, f.88r. The latter was drawn at Worcester, lat. 52° 10', in circa 1130.

46. Further notes on the circles will be found with the diagram, in which they are redrawn.

47. *Antike Himmelsbilder*, Berlin, 1898, p.164.

48. The illustration is at f.92v. of an Osma cathedral MS of Ciceronian pieces. It is reproduced in colour in G. de Champeaux and Dom. Sebastian Sterckx, O.S.B., *Le Monde des symboles*, 2nd edn., no place of publication, 1972, p.66.

49. Beckmann, *op.cit.*, p.344, gives as part of the epitaph of this man: 'Horologioque carmen spherae coeli optimum,/ Plura alia graviaque prudens invenit.'

50. I gave the text and translation of the work, with detailed discussion and two potential reconstructions, in 'Opus quarundam rotarum mirabilium', *Physis*, 8 (1966), 337-72.

51. One of my suggested reconstructions required it to have no fewer than ten concentric arbors (tubes). This might seem improbable, and yet we do know that the St. Albans clock used multiple tubes (*caligae*), which were therefore not beyond 14th century technological resources.

52. See the note added in proof, *ibid.*, p.368. Note that on p.362 I was wrong to repeat a claim that the stereographical projection of the Salzburg fragments is from the north pole.

53. A plate in the style of the Munich MS would merely have been required to turn in an anticlockwise sense.

54. The projection may be north or south; the stars may be as seen, or as they would be seen by an observer outside the star sphere, as it were; the rete may be of hours or stars; and it may be fixed or moving.

55. There are actually many late medieval examples of men who were both armourers and clockmakers.

56. Abbot Thomas de la Mare (ruled 1349-96) saw to it that 'the upper dial and the wheel of fortune were perfected' by Laurence Stoke and a monk who was skilled in woodcarving, William Walsham by name. Richard of Wallingford 'first arranged' them, but they were left off the clock on account of his early death. Almost all of the clock was therefore completed before 1336.

57. Laurence was important enough to accompany abbot Thomas to the papal court when he sought confirmation of his election.

58. Geneva 1957, pp.103-4.

59. Cracow, MS 551, ff.44v -49r. There is a further class of Italian double-wheeled escapements used in alarm clocks, as well as cognate devices from later periods. These are cited in my forthcoming edition of the works of Richard of Wallingford.

60. The chronicler adds that they are sometimes called 'mules'!

The Cathedral Clock and the Cosmological Clock Metaphor

F. C. HABER

INTRODUCTION

A new world picture was developed in the seventeenth century around the mechanistic philosophies of leading men of science, particularly those of Galileo, Descartes, Boyle and Newton, but it was a development grounded in religion as well as science. The scientists themselves showed concern with making their picture of the world as a machine harmonize with religion, and some even felt that they were making a contribution to religion by showing the structure of the divine workmanship in the Creation.

It was natural that the new mechanical philosophers would adopt the clock as their favorite explanatory model for the illustration of a world machine. The clock was the most complex and scientific machine at the beginning of the seventeenth century, but more important, the astronomical clock had evolved as a mechanical model to represent the motions of the heavens, as Derek J. de Solla Price has convincingly shown.[1] Furthermore, from the origin of the mechanical clock when the escapement was invented some time around the beginning of the fourteenth century, the astronomical clock had been closely associated with religion.

One of the earliest documented astronomical clocks was that of Richard of Wallingford, Abbot of St. Albans, built between 1327 and 1330, but the construction of clocks in religious buildings was by then already well established.[2] In 1324, for instance, the Treasurer of Lincoln Cathedral offered a donation for a new *horologium* for the Cathedral because, as he said, "the Cathedral was destitute of what other cathedrals, churches and convents almost everywhere in the world are generally known to possess."[3] References to the *horologium* or clock in religious establishments go back much earlier and before 1280 probably indicate water clocks, but that the prototype of the monumental astronomical cathedral clock with its trains of automatons had come into existence early in the fourteenth century seems clear from the records of the Norwich Cathedral Priory which describe a clock built between 1322 and 1325 that had a large astronomical dial and automata with 59 images and a choir or procession of monks.[4]

A clock that was often imitated was the first clock of the Strasbourg Cathedral, begun in 1352 and completed in 1354, almost a century before the last stone of the Cathedral itself was laid in 1439. It had an automated astrolabe, a perpetual calendar, a carillon that played tunes from hymns, a Virgin holding the Christ child before whom the three Magi presented themselves, a magnificent mechanical cock that flapped its wings and crowed, and a tablet showing the body parts and their correlation