The Annual Invitation Lecture

The Scholar, the Mechanic and the Antikythera Mechanism: complementary approaches to the study of an instrument

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Introduction

An ancient shipwreck, discovered in 1900 off the small island of Antikythera, yielded a rich cargo of mixed luxury goods. This 'Antikythera Treasure', preserved within the National Archaeological Museum in Athens, includes fragments of a Mechanism including dials and many small-toothed wheels.[1] The material is dateable to the earlier part of the first century B.C., making the Antikythera Mechanism both the oldest portable elaborate scientific instrument and the earliest known geared mechanism. The largest fragment, in its present state, is shown in Figure 1.

Professor Derek J. de Solla Price published *Gears from the Greeks*, his last word on the Antikythera Mechanism, in 1974.[2] The paper was a revelation and a sensation. Price displayed the depth of understanding and breadth of vision for which he is rightly remembered, writing cogently about the importance of this astonishing artefact to the history of instruments and mechanism. He also offered a solution to the problems of what it was and how it worked. The paper engaged my interests in the ancient world, in mathematics and in mechanism, but I could not follow some of the arguments through which Price developed his reconstruction of the Mechanism. As a young Research Assistant at the Science Museum who had not yet learned the value of scepticism, I supposed that the problem lay in my ignorance.

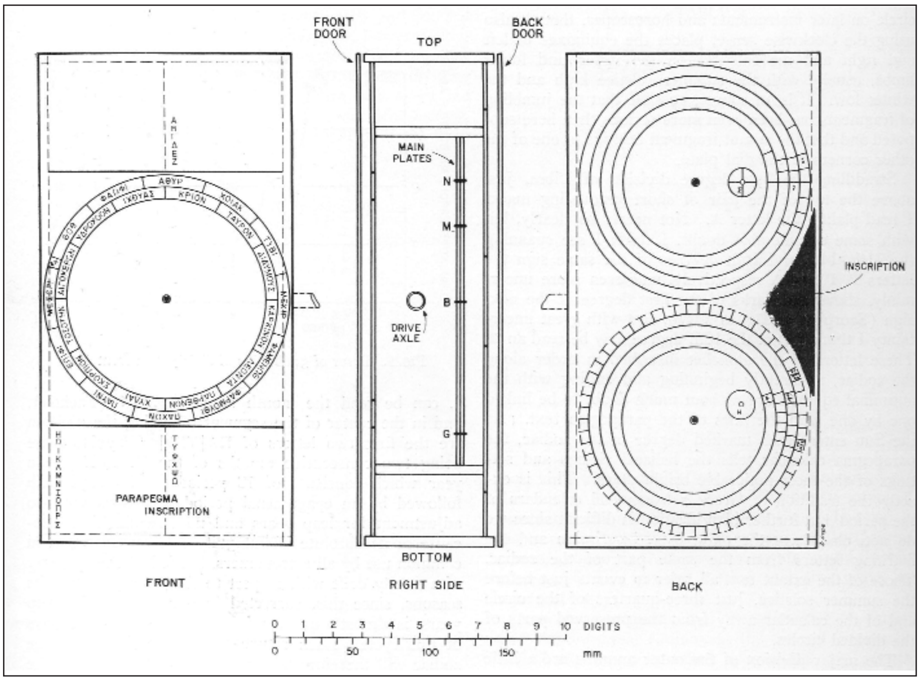

Fig. 2 *Reconstruction according to Price (note 2), general arrangement. Reproduced by kind permission of The American Philosophical Society.*

In 1983 The Science Museum acquired another fragmentary mechanism with Greek inscriptions and gear wheels.[3] My colleague J.V. Field dated it to around 500 A.D., and named it the 'London Byzantine Sundial-Calendar'. I devised a reconstruction, and made several examples at home.[4] This work showed me the value of being a practical man; it taught me a great deal about the instrument that I should probably never have learned in any other way. It convinced me that my true vocation was to combine practical and intellectual activity.

Fig. 1 *Antikythera Mechanism, fragment A (the largest fragment), front face. The spoked wheel, one turn of which represents one year, measures about 130 mm. in diameter.*

I coined the term *minimal reconstruction* to describe the outcome, in which there are no more features than are necessary to account for what is found in the original. Just eight gear wheels, worked by a pointer turned through one revolution in a week, provide approximate displays of the synodic month, the tropical month and the year. More elaborate versions of the gearing are possible, and are interesting, but this minimal reconstruction of the Sundial-Calendar, with its inscriptions in Greek, is important because it corresponds closely to the 'Box of the Moon' described five hundred years later by al-Biruni. It provides artefactual evidence for two points that Price had offered as mere conjectures: there *was* a continuing tradition of the making of geared instruments in the Hellenistic world, and that tradition *was* transmitted to Islamic culture. Moreover, although simpler and later, it makes the Antikythera Mechanism seem less of a freak.

In fact, the closest comparison material to this instrument was the Antikythera Mechanism, so my work drove me back again to *Gears from the Greeks*. Ten years older and more sceptical, I saw that some of Price's arguments were unsound. With this began my compulsion to study the Antikythera Mechanism for myself.

According to Price, the Antikythera Mechanism comprised dials on the opposite faces of a flat box, interconnected by gearing within (Fig. 2). A single input, probably the turning of a hand winch or knob, caused all the indicators to advance together. The 'front' had a dial with two concentric rings: the inner divided into the twelve signs of the Zodiac and subdivided into 360 degrees; the outer divided into the twelve months of the year and subdivided into 365 days. One indicator showed both the mean place of the Sun in the Zodiac and the date, and another showed the mean place of the

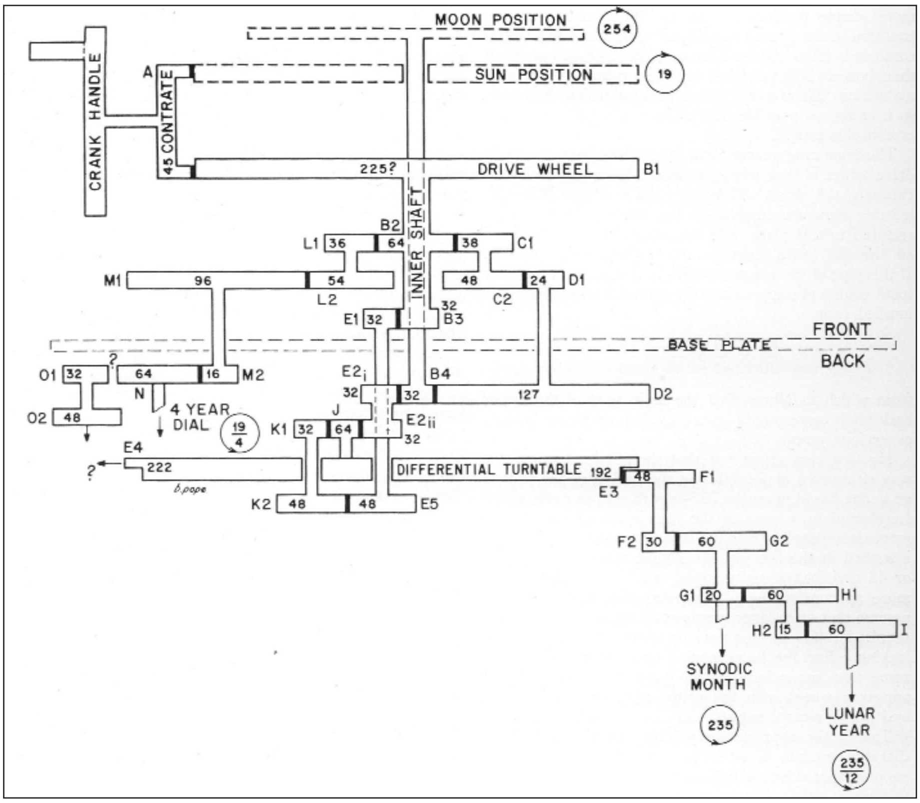

Fig. 3 *Gearing scheme according to Price (note 2). Reproduced by kind permission of The American Philosophical Society.*

Moon; that is, their revolutions represented one year and one mean sidereal month respectively. The 'back' had two dials, one above the other. On the lower dial, driven by a train including an amazing differential gear to combine the two motions from the front, one turn of the pointer represented one synodic month. The rate of rotation of the pointer on the upper dial was less certain: perhaps one turn in four years. Price suggested that this instrument might have been used for demonstrating or predicting celestial or calendrical phenomena, and he called it a 'calendar computer'.

Actually, it is hard to see any real use for Price's reconstruction. Reasonably enough, he had attempted a minimal reconstruction, but his proposed dial indications are banal in relation to the complication of the internal mechanism, and a more elaborate reconstruction might perhaps have made better sense. Others have tried since, but, as will become clear, in elaborating Price's reconstruction they have built on a rotten foundation.

Price's assessment of the importance of the Antikythera Mechanism, as evidence of a previously unexpected level of technical achievement of Hellenistic culture and as a remarkable survival of an early tradition of fine mechanism, is not in doubt. On the other hand, his reconstruction of it is frankly unsatisfactory. In *Gears from the Greeks* he justified his conclusions by the appeal to supposed practical arguments that actually make no sense. The really unfortunate thing is that he seems to have developed so strong an idea of how the instrument must have been arranged that he was tempted to use the evidence selectively, ignoring points that did not fit with his reconstruction.

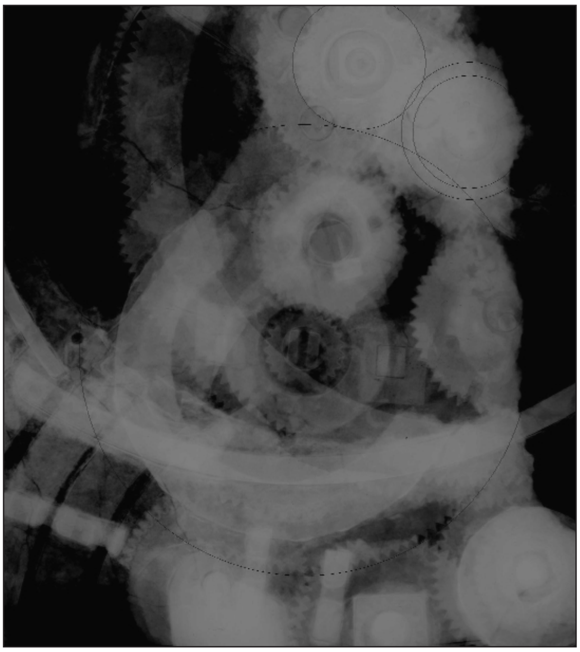

Fig. 4 *Radiograph of part of fragment **A**, showing engagement of wheels on axes B (upper), D (lower)and E (upper right). Circles are drawn around the tips of the teeth of the wheels in question, showing how the large wheel on axis D (wheel D2, Fig. 3) engages a wheel on axis E, not one on axis B.*

I spoke to my late friend Allan Bromley of my determination to examine the Antikythera Mechanism for myself. Together we undertook several campaigns of investigation, including direct visual examination and measurement, photography and radiography. As a mechanic, I also devised and made apparatus for measurement and for the radiographic technique of linear tomography.[5]

Many of our observations ran counter to those of Price, and it became ever clearer that we must reject much of his reconstruction; but we could not immediately make sense of our mass of new information. Bromley took most of our photographs and radiographs to Sydney, which placed me in a twofold difficulty: not only was this work a casual spare-time occupation, but the material that I needed was at the opposite side of the world. In late 2000, as Bromley's health declined, I visited him and recovered most of it. Since then I have made progress in developing a new reconstruction.

Price's Reconstruction as a Point of Departure

Price's reconstruction is still familiar, and I retain (and extend) his nomenclature for the axes and wheels. Therefore his diagram of the gearing (Fig. 3) makes a useful starting point.

The reverted train from wheel B2 to wheel B4, through axes C and D, links two indicators on the front dial in the ratio 19:254, a well-established approximation to the ratio of the lengths of the sidereal or tropical month and the year.[6] The wheel marked 'Sun Position', with the same number of teeth as the 'Drive Wheel', is Price's conjectural addition, providing a reversal to make the Sun and Moon go the same way round the Zodiac.

The engagements B3 – E1 and B4 – E2i transfer the once-a-year and once-a-tropical-month rates of rotation from axis B at the front dial to Price's differential gear on axis E. From here, the train though axis F leads to axis G at the centre of the lower back dial, and thence through H to I, the subsidiary dial.

The other train, from wheel B2, leading through axes L and M to N, the centre of the upper back dial, and probably thence to O, the subsidiary dial, is less complete than Price's diagram suggests. Price himself could not decide just how to restore it or what that dial was for. I ignore these problems on this occasion, to concentrate on the other trains already described.

At the heart of the gearing is the connection between wheels B4, D2 and E2i. Axes B, D and E actually lie in a triangular pattern and the edges of these wheels all come close to one another: by direct inspection of plain radiographs, the only method open to Price, it is not easy to make out which wheels are engaged, and it is not surprising that he misinterpreted the arrangement. Having first tentatively announced Price's error in 1997, I have since arrived at a firm conclusion both through use of tomographic sequences (resolving the depths at which the several wheels lie) and through detailed analysis of digitised images. One of the latter is reproduced in Figure 4. Circles are drawn around the tips of the teeth of the wheels in question. Wheel B4 does engage an equal wheel on E as Price stated, but D2 engages a further wheel on E, not wheel B4. Since both these wheels on E have 32 teeth the ratios remain unaltered, but we have two reversals: in the nomenclature of Figure 3, B4 runs the same way as D2 and E2i runs the opposite way to D2.

The latter reversal presents a difficulty, to which we will return later. Before that, and following the order in which the work was actually done, I will show how the former reversal makes possible a new reconstruction of the front dial.

Front Dial as Planetarium

Since B4 and D2 run the same way, the central arbor at B and wheel B1 actually rotate in the same direction. Therefore the 'Sun Position' wheel, which Price introduced to make his indicators for the Sun and Moon move the same way through the Zodiac, is not wanted. That wheel was in fact problematic, because wheel B1 still carries the remains of some structure rising higher than the top of wheel A, leaving no room for the upper wheel. Removing the extra wheel leaves scope for developing an interpretation of the structure on wheel B1 (the large wheel seen in Figure 1) that is thereby exposed.

Before announcing my reconstruction of the front dial as a planetarium, in May 2002, I made a working model to illustrate it (see cover).[7] I did so to pre-empt the expected criticism that such a reconstruction would be impracticable. The background to this work is laid out in two conference papers which are now in print.[8] I will not repeat myself at length here, but I take this opportunity to emphasise a few points.

Firstly, this is the only reconstruction based on new observations of the original fragments, and not on those published by Price; I have therefore been able to pay closer attention to the detail of the original than has the author of any other reconstruction. In particular, the interconnection of the wheels on axes B, D and E is now correctly represented for the first time.

Secondly, this reconstruction is not fantastic. Examination of the original convinces me that epicyclic gearing has been lost from the large wheel, B1. One turn of this wheel represents one year, and an epicyclic cluster turning at this rate must have modelled either the Sun or an Inferior Planet – Mercury or Venus – or a combination of these three. I have shown that the evidence is compatible with the modelling of Hipparchus's theory of the Sun and a simple epicyclic theory of both Inferior Planets, all at once.

So far, the reconstruction is to some degree supported by the evidence of the original fragments. My addition of Hipparchus's theory of the Moon, and the simple epicyclic theory of the Superior Planets – Mars, Jupiter and Saturn – is wholly conjectural; but these further features complete a consistent scheme that is still compatible with the physical evidence, and is justified by contemporary literary accounts of planetaria.

I do not claim that the original was just like this, and certainly not in detail; we simply do not have the evidence. But I have explored the principle, and demonstrated the practicability, of reconstruction as a planetarium. In doing so, I have introduced no significant design features that cannot be found in the original fragments in at least some rudimentary form, and I can demonstrate that I have made no demands on materials or skill that could not have been met by the workman of the time.

This reconstruction is not significantly more complicated than the original fragments; it is simply more extensive. In its present form, however, my model contains 41 additional wheels: a degree of conjectural addition that may provoke some discussion. This leads us to questions of accuracy of performance and practicability of the design.

In any astronomical model, the periods to be reproduced are awkward to approximate using gearing. One may accept crude approximations, and so make a simple instrument that will probably work well; but if one wants close approximations then the wheelwork has to be very much more complicated. The labour of making it increases enormously, and so does the difficulty in making it run.

It is unclear what the attitude of the designer of this Mechanism might have been to such questions of accuracy, but one approximation that he did adopt is preserved within the original fragments: the tropical month is 19/254 of the year. This is in close agreement with the ratio of values given by Hipparchus, the best available at the time: it would take over 500 years (turns of the Sun pointer) for the Mean Moon pointer to get out of place by one degree. There is an argument for seeing whether the same level of performance can be built into all the indications of the instrument. In showing that this can be achieved, I have demonstrated that the planetarium scheme is entirely practicable. One may argue that a less accurate performance might have been acceptable, or even – though I do not see why – more appropriate, or that the corresponding simplification of the gear trains is more plausible. In any case, since the complicated model works well enough, one may have confidence that any version with simplified gearing would be wholly practicable. If I had built only a simple version, one could not argue the case in the other direction.

The business of accuracy is not quite straightforward. So far, I have mentioned only approximations to the intended periods, built in to the gear trains. These give rise to errors that go on increasing as long as the trains run; in due course one has to disassemble the mechanism and reset the wheels to correct this *cumulative* or *long-term* error. On the other hand, within the bounds of practicability, the designer is free to refine this aspect of the performance of his instrument through his choice of wheels for the gear trains.

There is another type of error that is outside the designer's control, forced upon him by the limitations of the theory that he models. We do not know what theory of the planets was available to the designer of the Mechanism, but I supposed that he might have modelled the simple epicyclic theory that was investigated well before his time by Apollonius. According to this, the planet's position is defined by a point revolving on an epicycle, the centre of which is carried around a circle – the deferent – that is in turn centred on the Earth. This theory, though easy to mechanise, leads quickly to pretty gross errors; but if the astronomer could give him no better theory, the designer could not have avoided them.

At first sight, therefore, it may seem pointless to have developed elaborate gear trains aimed at reducing the cumulative error; but the second type of error builds to a maximum and then, periodically – at the end of a planet's great cycle – it dies away to nothing of its own accord.[9] For this reason I call it *cyclical*, or *short-term*, error.

The simple epicyclic model is equivalent to the assumption that both the Earth and the planet have circular orbits around the Sun, as in an orrery. The analogy with orrery-making is instructive: the record shows that designers of orreries have striven for ever-better values of the periods, and yet it has always been well understood that the model itself was inexact. Human nature has not changed, and so it is appropriate to have shown that good values for the periods can be built into my reconstruction.

Modifications to the Simple Epicyclic System

In fact, the cyclical errors in a planetarium of the first century B.C. might have been less gross than I have suggested. While some authors suggest that the simple epicyclic planetary theory remained unmodified from the time of Apollonius, through the time at which the Mechanism was designed, until supplanted by Claudius Ptolemy, I have recently become aware of evidence that planetary theory did indeed evolve during that time.

Pliny the elder, writing a century before Ptolemy, gives a garbled account of planetary astronomy in which he seems to list the apogees of the planets. Actually, he gives two lists, end to end, in which the parameters are quite different, but the point is this: he had an informant – or, probably, at least two – who thought of the planets' deferent circles as eccentric.

Pliny's account post-dates the loss of the Antikythera Ship by a good hundred years, but the concept may be older. Simplicius quotes from a lost work by Geminus, commenting in turn on a lost work by Posidonius; and again there is reference to the eccentricity of the planets' paths. Posidonius lived in the first century B.C., and the Antikythera Ship was probably lost in his lifetime; and so, although we do not know whether this idea was present in what he actually wrote, we must consider its implications for the Antikythera Mechanism.[10]

This single addition to planetary theory can yield a great improvement. Its mechanical realisation is in principle simple, at least for the Superior Planets, but to include it will entail some rebuilding of my model. Each epicyclic mechanism must be placed off-centre under the dial by a specific amount. Such an eccentric stage must have a larger central boss, so that the central hole can be set to one side (and if there is a further eccentric stage below it the pipe coming through will be larger, and so the hole must be larger too). The sizes of the gears must be adjusted accordingly, and that may mean, for convenience, changing the numbers of teeth. It may also be expedient to alter the order of the stages, perhaps bringing that for Mars, with its large eccentricity, to the top.

The Inferior Planets now ride, with the Sun, on a single wheel as a common platform. Therefore setting their stages eccentric would entail a greater complication, and the gain would be more questionable. Moreover, the wheel that serves as their common platform in my reconstruction is one that survives in the original, and I am not yet satisfied that such a modification could be made compatible with the evidence.

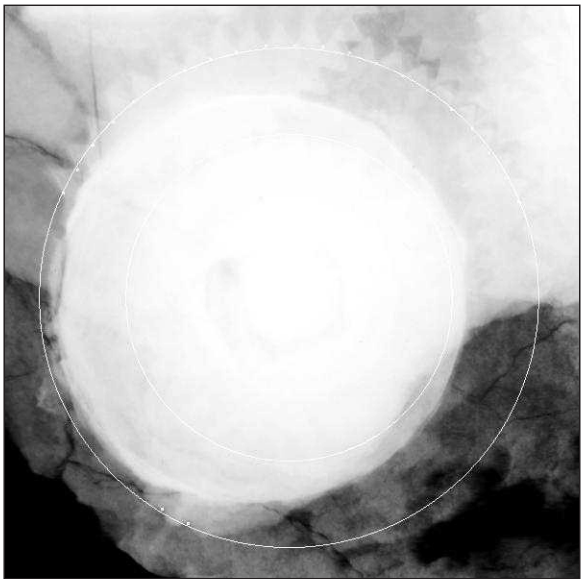

Fig. 5 *Radiograph of part of fragment A, showing axis F, with circles drawn around the roots of the teeth of the two wheels on it. The larger wheel is F1. Data points, representing the apices of the spaces between teeth, have been marked in.*

The Train to the Lower Back Dial

Retracing my steps to the important error that I found in Price's gear scheme, I pointed out that his wheels E2i and D2 (Fig. 3) turn in opposite directions, not in the same sense as Price supposed. If we were to assume that the connection B3 – E1 remained as Price shows, then we would have a very serious problem: reversing just one of the inputs to the differential gear would make its output not the difference, but the sum, of the two rotational velocities of E1 and E2i: the *difference* between the rates (one turn in a year) and (one turn in a tropical month) is (one turn in a synodic month), but their *sum* means nothing and this arrangement would make no sense.

A resolution to the impasse offers itself if we look for wheels B3 and E1; they cannot be found. While it is conceivable that wheel E1 might have broken away and dropped out as the instrument decayed, one cannot say the same of wheel B3. The most probable explanation is that they never did exist: in that case, the central arbor on axis E must have been fixed.[11]

Accordingly, instead of a differential gear with three connections, we have an epicyclic gear – with just one input and one output – followed by a fixed-axis train. This arrangement was often used much later in astronomical dial work to yield a ratio that is not easily got by a fixed-axis train alone, and this is also the most plausible explanation for its use here. Our task is to recognise what ratio, difficult enough to achieve that it would justify the designer's use of this elaborate arrangement, might have been intended. The problem is not easily or unambiguously solved, because the tooth-counts of most of the wheels are uncertain.

In Price's differential gear, the numbers of teeth of the several small wheels were unimportant, so long as the ratios K1:E2ii and K2:E5 were equal. If, however, this were an epicyclic cluster, yielding a non-trivial

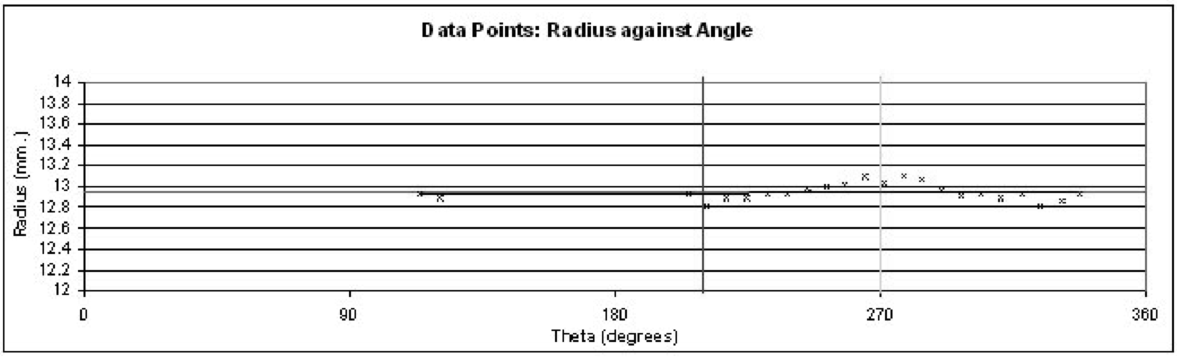

Fig. 6 *Analysis of wheel F1. A centre has been chosen and the points (x) represent the radii from it to the data points (Fig. 6). The centre has been adjusted to make the graph as nearly horizontal as possible.*

Data point	X	Y	θ	dθ	Mean teeth in interval	Suggested no. of teeth	Tooth count
23	9.6	27	113.9489949	136.3677032	20.48	20	**20**
22	8.25	26.25	120.803649	6.854654067	1.03	1	**21**
1	3.1	9.8	204.6017333	83.79808436	12.58	13	**34**
2	3.85	8.6	210.8870965	6.285363105	0.94	1	**35**
3	4.65	7.3	217.6878451	6.800748685	1.02	1	**36**
4	5.7	6.1	224.7799953	7.092150211	1.07	1	**37**
5	6.8	5.05	231.5269124	6.746917049	1.01	1	**38**
6	8.1	4.15	238.5347282	7.007815839	1.05	1	**39**
7	9.4	3.4	245.1724472	6.637719017	1.00	1	**40**
8	10.75	2.85	251.6068831	6.434435835	0.97	1	**41**
9	12.1	2.45	257.8099907	6.203107652	0.93	1	**42**
10	13.65	2.15	264.7381783	6.928187579	1.04	1	**43**
11	15.15	2.15	271.318933	6.580754731	0.99	1	**44**
12	16.6	2.2	277.6784767	6.359543643	0.96	1	**45**
13	18	2.5	283.9511561	6.272679364	0.94	1	**46**
14	19.4	3.05	290.5612215	6.610065404	0.99	1	**47**
15	20.75	3.7	297.2003214	6.639099925	1.00	1	**48**
16	22.05	4.45	303.8622372	6.661915815	1.00	1	**49**
17	23.3	5.45	310.9726197	7.110382526	1.07	1	**50**
18	24.4	6.45	317.568439	6.595819234	0.99	1	**51**
19	25.25	7.7	324.2751497	6.706710771	1.01	1	**52**
20	26.15	9.05	331.5211482	7.245998509	1.09	1	**53**
21	26.8	10.25	337.5812917	6.06014344	0.91	1	**54**

Centre	X	Y
Centre	14.15	15.18

Fig. 7 *Analysis of wheel F1. The angular separation of the radii from the chosen centre to all the data points is given in terms of numbers of mean tooth-spaces, and from this a tooth-count is derived.*

velocity ratio, the numbers would matter. In the fixed-axis train that follows it, Price was obliged to adopt numbers for the wheels that would give a ratio of 2:1 between axis E and axis G, because the output of his differential gear could *only* be one turn in two synodic months; but here the evidence just will not support his figures.

I have started again from scratch, working from my own radiographs to prepare new estimates of the numbers of teeth in all the wheels. This is not straightforward: very few of the wheels are complete, and very large parts of some are missing. Moreover, it is often impossible to see the full extent of what does survive in any single view because the density of the image, corresponding to the radio-opacity of the object, differs greatly from one point to another.

The task has however been eased by the availability of high-resolution digitised images of these radiographs. The brightness and contrast can be varied at will, and any part can be inspected at high magnification. The coordinates of a set of selected points, typically either the tips of teeth or the bottoms of the spaces between them, are recorded using a 'point and click' tool. A circle can be overlaid on the image, and occasionally this is helpful when searching for teeth in difficult areas of an image. An image of wheel F1 is shown as an example (Fig. 5).

The data set obtained in this way is then copied to a spreadsheet program for analysis. The data points, together with a first approximation to their centre, are presented as a plot of radius against angle (Fig. 6). The centre is shifted iteratively to make the plot approach a horizontal line. The new centre and any marked departure from roundness are checked back against the original image.

The angular separation of the teeth is then analysed. Working from the mean pitch of data points accepted as representing adjacent teeth, the table presents suggestions for the numbers of teeth to be interpolated into the lacunae (Fig. 7).

The data points and centre are also presented as a plot, over which a 'model', a circle of equidistant points, is superimposed. The number of points in the model, and their angular relationship to the data points, can be adjusted to explore the match. I begin with a model having the number of teeth suggested by the previous routine, but visual inspection sometimes persuades me that an adjacent number offers a more convincing fit; that is to say, in deciding what will make a workable toothed wheel, the experienced eye is at least as good a guide as mindless averaging (Fig. 8).

This procedures offer an easier and more objective method for estimating numbers of teeth in wheels than that of inspecting radiographs with a magnifier; moreover, it can generate a permanent record. On the other hand, the analysis shows very clearly that there are wild variations in the pitch of the teeth of many of the wheels, seeming to result from their manufacture and not from damage.[12] Consequently, where there is a large lacuna between preserved wheel teeth, we have to admit considerable uncertainty in deciding how many teeth it contained. The problem is especially acute for the wheels in the epicyclic gear, because each of these is broken away roughly across a diameter, and the remaining halves are not all very well preserved.

It follows that further analysis cannot offer certainty in reconstructing the gear train. Rather, it confirms what I have stated before: the condition of the fragments is such that, without further evidence from elsewhere, we can probably never be certain just how the Mechanism was arranged or just what it did.

Nevertheless, pro-gress may be made. We

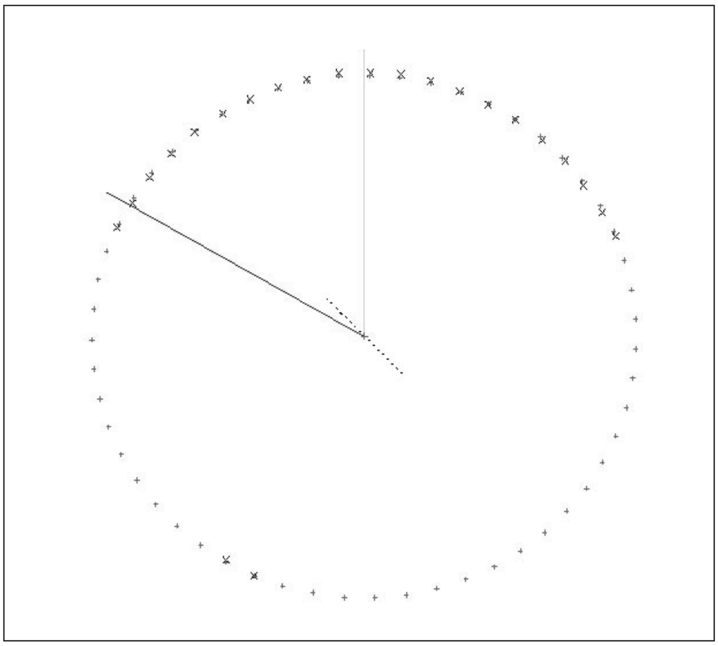

Fig. 8 *Analysis of wheel F1. The data points (x) are plotted against a set of 'model points' (+) equally spaced about the same centre. In this case a model of 55 points arguably gives a better match than one of 54 as suggested by the table (Fig. 7).*

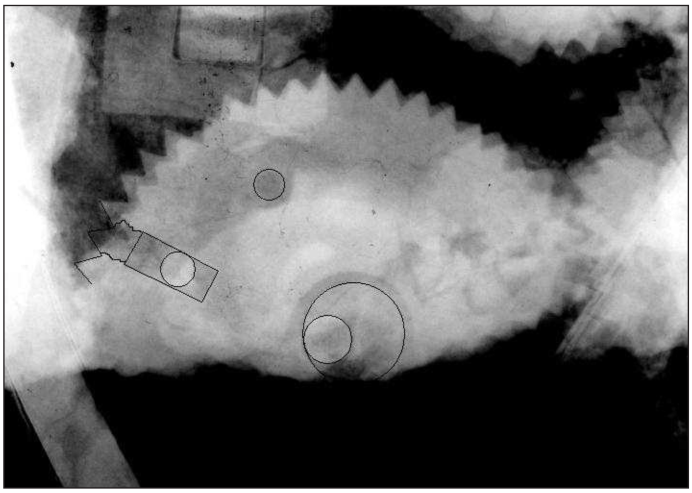

Fig. 9 *Radiograph of part of fragment* ***A****, showing axis K. The slot in the upper wheel, the hole for the pin in the lower wheel, and the central stepped arbor, are overdrawn. The portion of the upper wheel lost through the breaking out of the end of the slot is also indicated.*

have an input – one turn in a tropical month – leading, through an epicyclic assembly and then fixed-axis gearing, to the lower back dial. Multiplying together the possible range of tooth-counts for all the wheels, we have some 2 million permutations. This must be doubled to take account of two possibilities: there may or may not have been an idler gear – Price's wheel J (Fig. 3) – on the epicyclic platform.

It is straightforward to set up a 'spreadsheet' program to calculate the ratio of the gearing, running through all the possible numbers. One must be a little circumspect, because it is easy to start a computation that would take days to complete, overloading the system with data to be sorted. Before beginning the number-crunching, some general points can be made to help us to see what sort of result we may be seeking.

With no idler gear – no wheel J – the platform of the epicyclic assembly would run rather fast, and the function at the lower back dial would have a short period. About a day or half a day is possible, and we might think in terms of the culmination of stars, timekeeping, hours of daylight, tides, and so on. On the other hand, I dislike the prospect of such a fast-moving train. I judge that, with the rather crude teeth, and the consequent poor engagements, it would be very hard indeed to drive the device from where it seems to have been driven: the slow end. The step-up ratio from the large wheel B1 (Fig. 3) to a pointer making one turn a day would be an impracticable 365:1. It is worth remembering, however, that there are teeth around the edge of the epicyclic platform – Price's E4 – for which we have no purpose. Bromley chose to drive his conjectural reconstruction at this point, which is why it works better than any other variant on Price's reconstruction. Provisionally, we cannot rule out the no-idler option, perhaps with the train driven from here, yielding a short-period display at the lower back dial.[13]

With an idler gear in the epicyclic assembly, the overall ratio of the whole train would be rather close to unity. In other words, the indicator at the lower back dial would have rotated roughly once a month. The synodic month of Price's reconstruction is unconvincing because it could so easily have been got by a short fixed-axis train without the use of his differential gear. By the same argument, this output does not justify the use of our epicyclic train, so we should look at other types of month. The draconitic month, affording a means of predicting eclipses, is an interesting possibility: there are several possible trains that yield quite good approximations, but unfortunately – from the point of view of trying to offer a clear rationale for the epicyclic assembly – it is again easy to find several compact fixed-axis trains that yield an even better performance.

Fig. 10 *Antikythera Mechanism, fragments* ***B*** *and* ***E*** *assembled on the back face of fragment* ***A****, showing the visible remains of the back dial system. The dial is partially overlaid by the remnant of a 'cover plate', and some further details can be made out only through radiography.*

Beyond these options, one may consider the possibility that the lost half of the epicyclic assembly carried not just an idler gear, but a compound train. The size of the platform limits what wheels might be fitted, but even so the range of possible output periods is widened appreciably.

A New Feature

Possibly the key to the use of the epicyclic gear may be found in another curious feature. Price noted a one-tooth gap in one of the wheels in the epicyclic train, which shows in radiographs as a well-defined radial slot with a square inner end. He interpreted it as evidence of a repair.

On closer examination, I find that the slot was once closed, but that a piece has broken out at the end, taking away the lost tooth, Figure 10. The circular image in the slot is the hole in the wheel beneath for a pin to engage the slot in the upper wheel. At the centre we see two circles, one within the other but offset so that the peripheries of the two touch. This is a stepped arbor, allowing the two wheels to turn about different centres.[14]

The pin-and-slot arrangement allows one wheel to drive the other, even though they are not concentric, introducing a roughly sinusoidal wave into the velocity ratio of the train. Its amplitude is fixed by the ratio between the radius at which the pin is set and the offset between the axes of the two wheels, and its frequency depends on the rate of rotation of the two coupled wheels with respect to the platform. Here are further factors to juggle.

At present, this feature remains unexplained. Even so, the use of a crank pin embraced by a slotted follower provides a good precedent for the use of similar ensembles in my reconstruction of the front dial display to connect the epicyclic trains to the hands.

The Casing and the Back Dial

Comparison of Figures 2 and cover illustration shows that the shape of the case of my partial reconstruction is very different from that of Price's.

Firstly, my case is deeper. I have raised the front dial above the frame plate on which the surviving wheels are mounted to make room for the stages for the Superior Planets. This is acceptable because there is no evidence of a direct connection between original fragments **A**, with all the gearing, and **C**, with the remains of the dial.

Secondly, while the two are much the same width, my box is more nearly square than Price's, which is elongated to suit the apparent geometry of the back dial. Therefore the shape of my box, which is certainly shorter than the back dial, calls for an explanation.

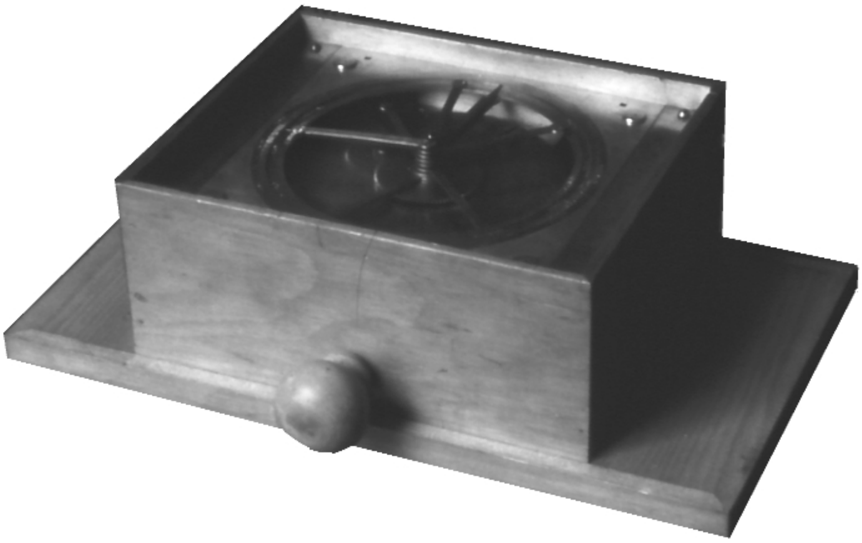

Fig. 11 *Author's reconstruction, showing how the case containing the mechanism for the front dial must be stepped out to accommodate the back dial.*

In the original fragment **A** there are clear traces of woodwork. A piece runs down one side, and a second piece runs at right-angles, across the back dial plate. Price took the cross-piece to be internal framing, but he missed the fact that the two pieces meet at a mitred joint, which makes sense only as the external corner of a box. This joint is aligned over the corner of the internal frame plate, suggesting a box fitting closely around the frame plate. If this is a correct interpretation, then the case has to be stepped out to accommodate the longer back dial as shown in Fig. 11..

The detail of the back dial plate itself is interesting. Segments of both the upper and lower dial systems survive (Fig. 11), each showing what Price interpreted as a set of concentric rings. I have previously drawn attention to the fact that these rings were not moveable, as some have supposed: they were joined by bridge-pieces into a rigid structure, with gaps between them. The object of the arrangement was to leave slots, and the bridges were designed to leave the margins of the slots clear on the back of the dial, so that moveable pieces should be free to run in the slots, like the beads of an abacus.

Recently I have examined these dial fragments more carefully, using the tools devised for analysis of the gear wheels. Each has its own oddity. The slots of the upper back dial are indeed circular and concentric with the arbor that carried the hand, but radiographs show that the innermost slot comes to a neat, abrupt end, apparently on the vertical midline of the dial plate. This part of the lower dial is not preserved, but here the circular slots, though probably concentric with one another, are certainly not concentric with the arbor. They appear to have a common centre displaced from that of the arbor by about half the width of the distance between slots.

Comparing the two fragments, the innermost and outermost slots of each have about the same radii, but the separation between adjacent slots differs so that there are different numbers of slots in the two cases. Nevertheless, on the assumption that the upper and lower dial systems were designed in similar ways, the observed features can be accounted for by supposing that each was made with a single slot forming a crude spiral, drawn as a set of arcs struck alternately from two centres. Figure 12 is a rough sketch of this arrangement.

A further oddity is apparent. The subsidiary dial in the upper system seems to be neatly placed on the horizontal line through the centre of the system, 'at 3 o'clock', while that of the lower system is not. The surviving gearing connecting the latter subsidiary dial to the centre offers no obvious explanation: these wheels might just as well have been planted to achieve the neater layout of the upper system. The explanation might have lain in some detail of the lost part of the dial surface, that called for the larger space made available by moving the subsidiary upwards.

Understanding the significance of these bizarre features might help greatly in the reconstruction of the instrument as a whole, in view of the considerable uncertainty in the gearing leading to each of the back dials.

Tailpiece: Displaying the Synodic Month

I have shown that we can no longer accept Price's train – including his differential gear – leading to his proposed display of the synodic month on the lower back dial. The same value for the synodic month, perfectly consistent with the value for the tropical month shown on the front dial, could in any case have been derived from the once-a-year rotation using only a short fixed-axis train. Accordingly, while it remains possible that the designer of the mechanism did not spot this possibility, or that he preferred a more complicated solution for some reason that escapes me, the display of this period does not offer a very satisfactory explanation for my revised arrangement using an epicyclic train. Nevertheless, it seems quite likely that the synodic month, expressed as the age of the Moon in days or as a representation of the Moon's phase, is a function that the designer would have wished to display somewhere. I will close by pointing out that such a display can be added to the front dial using no additional gearing whatever.

We already have on the front dial two indicators showing the positions of the Sun and the Moon in the Zodiac. While, relative to the dial, the Moon hand turns once in a *tropical* month, relative to the Sun hand it turns once in a *synodic* month. The synodic month can therefore be indicated by the motion of one of the hands over a circular scale fitted to the other. The earliest known application of this economical idea is in a so-called geared astrolabe of about 1300.[15] The same idea was widely used soon after that in the dial work of monumental clocks, in which it was common to use the differential movement to provide some sort of visual representation of the phase of the Moon.

There remains in the original fragment **C** of the Antikythera Mechanism a curious circular component, cemented by corrosion

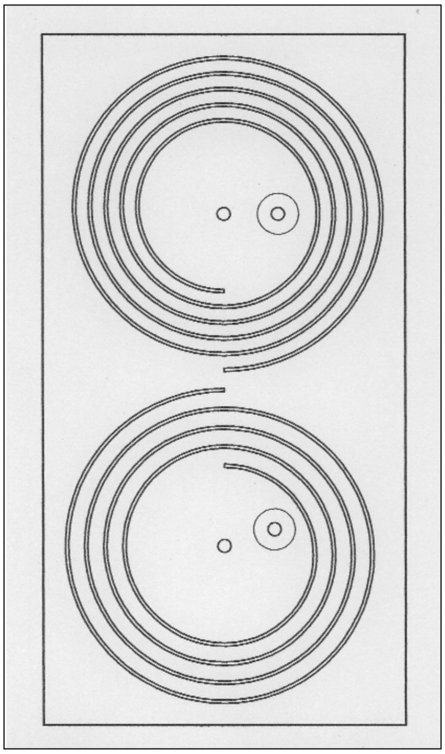

Fig. 12 *A rough sketch of the author's reconstruction of the back dial system.*

Fig. 13 *Antikythera Mechanism, fragment **C**, inside face. The circular component measures approximately 62.5 mm. in diameter.*

products to the back of the preserved corner of the front dial (Fig. 13). Its relationship to the front dial is certainly suggestive, and the component is of a suitable size and weight to make plausible the tentative assumption that it may be the wreck of such an arrangement. It has an offset circular opening, which might just have been a 'window' displaying some representation of the Moon's phase, even a rotating Moon globe. I am happy to record that Price also hinted tentatively at this interpretation. His alternative, that it might have been a driving knob with a folding winch handle, has been widely accepted; but this suggestion was certainly wrong.

Conclusion

In a sense I can offer no conclusion, because I continue to extract new information from the material collected by Bromley and myself, and I have to go on working through its consequences. The notes given here include reference to material already in print, and I plan to continue publishing further material, including those topics that I have merely touched upon.

I believe, however, that I may claim that a new reconstruction of the Antikythera Mechanism is emerging, one which is more firmly based on the detailed appraisal of the original. It makes better sense than any previously offered: as a mechanism; as a scientific instrument; and as an artefact of its time.

Even without Price's differential gear – which, I suggest, was a mistaken interpretation – it is clear that the designer of the Antikythera Mechanism could draw on a yet wider range of mechanical ensembles than has previously been realised. We must accept that as early as the first century B.C. the arts of the mechanician and the instrument-maker were already well developed.

Acknowledgements

I take pleasure in recording my thanks to the Committee of the Scientific Instrument Society for having honoured me with their invitation to give the Society's Annual Lecture and, in particular, my thanks to the Chairman and the Meetings Secretary for their particular help with the arrangements; and my further thanks to the Editor for his patience while I have prepared this version for publication.

I am indebted to my sons, who have helped by setting up the computer tools that I have used, and my wife, who has put up with all this activity and who has read this paper in draft and made many valuable suggestions.

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Notes and References

1.The Mechanism bears inventory number X.15087.

2.D.J. de S. Price, 'Gears from the Greeks', *Transactions of the American Philosophical Society*, **64**, No.7, 1974; also issued as an independent monograph, Science History Publications, New York 1975.

3. Inventory number 1983-1393.

4.The first account of this artefact is: J.V. Field & M.T. Wright, 'Gears from the Byzantines: a Portable Sundial with Calendrical Gearing', *Annals of Science*, **42** (1985), pp.87-138, reprinted in J.V. Field, D.R. Hill & M.T. Wright, *Byzantine and Arabic Mathematical Gearing* (London: The Science Museum, 1985). Some technical considerations are treated more extensively in: M.T. Wright, 'Rational and Irrational Reconstruction: the London Sundial-Calendar and the Early History of Geared Mechanisms', *History of Technology*, **12** (1990), pp.65-102.

5. M.T. Wright, A.G. Bromley & H. Magou, 'Simple X-ray Tomography and the Antikythera Mechanism', ***PACT*** 45 (1995) (proceedings of conference 'Archaeometry in South-Eastern Europe', April 1991), pp.531 – 543.

6. Price refers to the sidereal month; but the dial is marked with the names of the conventional constellations of the Zodiac and with the degrees of the ecliptic, not with a star map, so strictly the tropical month is indicated. The numerical difference between the two is, of course, very small.

7. M.T. Wright, 'A Planetarium Display for the Antikythera Mechanism', *Horological Journal*, **144**, No. 5 (May 2002), pp. 169 – 173, and **144**, No.6 (June 2002), p. 193.

8. M.T. Wright & A.G. Bromley, 'Towards a New Reconstruction of the Antikythera Mechanism', S.A. Paipetis, ed., *Extraordinary Machines and Structures in Antiquity*, (proceedings of a conference of that name, Ancient Olympia, August 2001), Peri Technon, Patras 2003, pp. 81 – 94; and M.T. Wright, 'In the Steps of the Master Mechanic', *Η Αρχαία Ελλάδα και ο Σύγχρονος Κόσμος* (*Ancient Greece and the Modern World*), (proceedings of a conference of that name, Ancient Olympia, July 2002), University of Patras 2003, pp. 86 – 97.

9. The concept of the *great cycle*, a period after which the observed behaviour of the planet recurs, was developed within the predictive Babylonian astronomy that was absorbed into Hellenistic astronomy. The actual lengths of Babylonian great cycles range from 8 years (Venus) to 83 years (the longer of two cycles for Jupiter). The system is explained clearly in J. Evans, *The History and Practice of Ancient Astronomy* Oxford: O.U.P., 1998).

10. The relevant passages in Pliny and in Simplicius are given in translation by J. Evans (note 9), who also gives a clear demonstration of the considerable value of this addition to planetary theory.

11. Illustrate this new interpretation in a revised version of Price's gearing diagram in: M.T. Wright, 'Epicyclic Gearing and the Antikythera Mechanism, part 1', *Antiquarian Horology,* **27**, 3 (March 2003), pp. 270 – 279. Part 2 is in preparation.

12. The local variations in pitch, and the equally striking variations in tooth profile, seem random. The tooth profiles suggest that they were cut freehand, using a file, and the variations in pitch suggest that their positions were laid out using simple methods, and pretty roughly too; the work can easily be matched using a few hand tools.

13. Any such arrangement would, however, leave us with no purpose for the contrate wheel A (Fig. 3).

14. The stepped arbor was commonly used, much later, in modelling the Ptolemaic system, allowing several mobiles to be superimposed while turning about different centres. It seems far-fetched to suggest a connection, but it is curious that, although this represents a different use of it, the ensemble should in both cases occur in the context of mechanical models of astronomical phenomena.

15. The Science Museum, London, inventory number 1880-32. The instrument is now in a garbled state. A reconstruction is offered in J.D. North, 'Opus quorundam rotarum mirabilium', *Physis*, **8** (1966), pp. 337 – 371. A clearer illustration, but with the unfortunate misprinting of 47 for 45 (for the number of teeth of one of the wheels) is given in J.V. Field & M.T. Wright, *Early Gearing* (London: The Science Museum, 1985). A central dial is fixed to the (broken) Sun hand. The tail of the (missing) Moon hand should pass over this to indicate the age of the Moon in days, beginning when the two hands are aligned.

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