Understanding the Antikythera Mechanism

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The fragmentary Antikythera Mechanism, recovered from a shipwreck that is dateable to the 1st. century B.C., stands alone as evidence of the high level of attainment of the Hellenistic mechanic. A remarkably accomplished instrument of small size, it is justly celebrated as the earliest artefactual evidence for the use of toothed gearing. It is most widely known through the writing of the late Professor Derek Price[1] and through secondary sources based on his work. Yet, as far as the instrument itself was concerned, Price's treatment was inadequate and the Mechanism remained but poorly understood.

A new reconstruction of the Antikythera Mechanism is now presented which, unlike all earlier reconstructions, accords with and accounts for very nearly all of the mechanical detail observed in the original fragments. It is based on a detailed survey of the original fragments carried out by the author at The National Archaeological Museum, Athens, in collaboration with the late Professor Allan Bromley (University of Sydney).

Early results of this survey were presented at the *First International Conference on Ancient Greek Technology* (Thessaloniki, 1997).[2] Price's reconstruction was shown to be fundamentally flawed, but we could not then offer a more satisfactory alternative.

By that time Bromley was suffering from an increasingly incapacitating, and ultimately fatal, illness. The work became delayed because our research material remained in his possession in Australia. Further progress became possible only when most of it was recovered some years later.

Attention then turned to the preparation of our observations for publication, but this was found to be problematic on account of the large volume of material, the intricacy of detail that had been revealed, and the difficulty of printing the radiographic images on which much of its presentation would rely. However, in working through the material the author conceived elements of a new reconstruction, and this offered an alternative way forward: if the reconstruction were developed first, it might then be used to illustrate the evidence on which it was based.

This new reconstruction has been developed step by step and is now complete. A model, built to illustrate it, shows it to be a robust workable instrument. The full detail of what survives of the original instrument can now be described with confidence, and nearly all of it can be explained, by reference to the new reconstruction. The detailed treatment of the material evidence is now in preparation.

We now trace the stages by which the new reconstruction has been developed. Since the task would depend heavily on a careful analysis of X-ray plates, arrangements were made to have nearly 700 plates digitized for computer-aided analysis. When this work became delayed, attention was turned meanwhile to the reconstruction of the front dial display, a part that depended rather little on radiographic evidence.

Price devised the name "calendar computer", which distracted attention from the fact that his reconstruction of the Antikythera Mechanism corresponded to no known instrument and had no discernable purpose commensurate with its elaboration. Moreover, in reconstructing the front dial with indications simply of the places of the Mean Sun and Mean Moon, he overlooked evidence showing that there had been epicyclic gearing mounted on the large wheel that turns with the motion of the Mean Sun. The only possible use of the arrangement was in modelling the motion of the True Sun or of either of the Inferior Planets, Mercury or Venus, according to the prevalent epicyclic theories of Hellenistic astronomy.

It was found possible to combine all three motions, and indeed this combination best fits the material evidence. Previously the size of the "Mean Sun" wheel, much larger than any other in the remaining fragments, was not plausibly explained. Its function as an epicyclic platform supplied a rationale: it conveniently accommodates the necessarily large epicycle for the motion of Venus; and the smaller epicycles for the other two motions and the gearing connecting all three fill most of the remaining space.

Together with the indication of the place of the Moon and a pointer for the date, these indications of the places of Sun, Mercury and Venus make up over half the display indications of a planetarium, a type of instrument which, as literary references show, existed in Hellenistic times and was of widespread interest. It was therefore reasonable to consider whether the Antikythera Mechanism might have been a planetarium, in which case one would expect it also to have included a display of the motions of the Superior Planets, Mars, Jupiter and Saturn.

Mechanism for the Superior Planets was devised by drawing only on the repertoire of mechanical elements found within the original fragments, and was added as a conjectural restoration. Wheel trains which yielded consistently good period relations for all the motions were designed using only wheels within the ranges of pitch and of tooth-count found in the original.[3,4]

The resulting design, in which the Sun and Moon move in accordance with the theories of Hipparchos, and the five known planets move according to the simple epicyclic theory suggested by the theorem of Apollonios, was shown to be practicable through the construction of a working model.[5] It is however important to emphasize that the model is offered only as an illustration. One might as readily model almost any other conceivable epicyclic theory, even adopting the equant of Ptolemaic theory; but while there is growing evidence that variant theories of planetary motion coexisted prior to the time of Klaudios Ptolemaios, the simple planetary theory adopted is the only one that all historians of astronomy will now agree upon as appropriate for the date of the Antikythera Mechanism.

However one may choose to interpret the Antikythera Mechanism, there can be no doubt that it exhibits a high level of technical competence. Yet, even after this instrument became widely known, it remained common to suppose that ancient attempts at making planetaria, as described in literature, were probably very naïve. The reconstruction of the front dial of the Antikythera Mechanism as a planetarium, carried out within severe historical and practical constraints, demonstrates that this presumption was ill-founded.

The suggestion that the Antikythera Mechanism was a planetarium is urged as a serious proposal, although the fragmentary nature of the original makes it inevitable that much of the detail of any reconstruction, and still more of any model illustrating it, must be conjectural. It is however a fact that the restored features of the model are compatible with the original fragments in all important particulars, and that every significant mechanical detail in the model is based on precedent found in the original.

The bridge thus built between the artefact and literary references demonstrates both that reports of elaborate planetaria may not lightly be dismissed as writers' fantasies, and that the Antikythera Mechanism may very well have been such an instrument. In support of this as a sober claim, it may be stated that the reconstruction is based on a careful and thorough observation of the artefact, on an awareness of the history of relevant disciplines (principally astronomy and mathematics), and on the close study of the history of tools, techniques and materials and of the history of mechanism.

In contrast to the largely conjectural restoration of planetary motions to the front dial, all the other elements of the new reconstruction were built directly on artefactual evidence, beginning with a detailed examination of the surviving wheelwork. Computer tools of measurement and geometrical analysis were applied to the digitized radiographic images, and the data so collected was subjected to spread-sheet analysis. The ability to manipulate the brightness and contrast of digitized images, and to see them under high magnification, made it possible to find more detail, and with greater certainty, than Price could possibly have done. The radiographs prepared for him by Dr. Ch. Karakalos are excellent, but Price and he were limited to direct visual inspection.

A first, if crude, measure of the success of this procedure may be given in numerical form. Price thought he saw 27 wheels, but his gearing scheme makes use of only 23 of them and he introduced 7 others as conjectural additions to make the scheme work. Some of these were imagined as inserted into the mass of the surviving fragment A, from where the supposed loss of wheels is hard to explain. Even with this degree of artifice, Price's scheme remains incomplete.

In the new survey, the traces of 31 wheels were found. Three of these certainly do not belong within the main body of the wheelwork: two, found as a detached fragment (D), probably formed part of the lost epicyclic gearing below the front dial mentioned above, while the third, in fragment C, is part of a newly-identified Moon-phase assembly which is mentioned below. A new gearing scheme was drawn up which accounts for 27 of the 28 remaining wheels. An explanation for the presence of the unused (28^{th}) wheel is offered later. Leaving aside the lost gearing under the front dial as a set of separate assemblies, the addition of just 5 wheels makes up a scheme directly comparable to Price's. Importantly, however, and unlike Price's, this scheme is complete, and conjectural restorations are made only in places from where one might expect wheels to have been lost, at the edges of the extant fragments.[6]

More significantly still, the new scheme corresponds throughout to the arrangement of wheels actually found in the original fragments, whereas Price's does not. The most striking difference between the two is in the detail of an epicyclic assembly which Price famously identified as a differential gear. A differential gear must have three connections, in this case two inputs and one output; but only one input to the assembly can be traced. In order to develop his idea, Price postulated the existence of a second input, but it has now been shown that this never existed. The central arbor of the assembly was stationary. Besides, the scheme that Price built around the differential gear led him into further difficulties which can, in truth, be solved only by abandoning the differential gear as a central idea.

The numbers of teeth in all the wheels have been estimated anew. Naturally, many of the new estimates agree with those of Karakalos.[7] In some cases the new analysis shows a more secure result than his, but in others there is a wider margin of uncertainty. Typically, this occurs where much of a wheel is lost and detailed analysis shows that the remaining teeth are far less uniformly spaced than Karakalos tacitly assumed. In the few cases in which the new result differs markedly from that of Karakalos, clear reasons for the disagreement can be found. The freedom with which Price adjusted some of the numbers given by Karakalos is shown to be unsupportable, as is that of other writers who have followed his lead.

The crucial velocity ratio of the reverted train underlying the front dial, 19 : 254, corresponding to the relation 19 years = 254 tropical months (the mechanical evidence that there were indications of the places of the Sun and Moon on that dial), was confirmed. Many wheels are so wrecked, however, that direct counts of their numbers of teeth will always remain uncertain. Analysis of the wheels alone does not lead to unique solutions for the function of the trains to the upper and lower back dials.

Solutions to these problems were however found by using the tools of computer-aided analysis in other ways. Applied to the geometry of the fragments of the back dial, they led to a new understanding of its design, giving insight into the functions displayed on it. Applied to the layout of the arbors in fragments A and B, they led to a better estimate of the correct juxtaposition of these fragments and so to a good estimate of the size and number of teeth of the driven wheel lost from the centre of the upper back dial.

These two steps led at last to the discovery of the function of the upper back dial. One revolution of the main pointer represented 47 synodic months. The scale was laid out as a five-turn spiral containing 47 divisions in each turn. It therefore presented a visual display of the 235 months of the "Metonic" period relation (19 years = 235 synodic months), exactly consistent with the period relation built into the gearing under the front dial as mentioned above.

Fragmentary inscriptions suggest that the pointer on the subsidiary dial showed a count of four cycles of the 19-year period, equal to the 76-year Callippic period. This is achieved by adding a further wheel to the arbor at the centre of the main upper back dial and two more on an arbor that lies beyond the edge of the surviving fragments, in an arrangement that follows closely the surviving gearing to the lower back dial.

The main significance of this display seems to be its use, in conjunction with the front dial, in counting long intervals of time between events displayed on the front: the day and month indication of the Egyptian calendar, read on the front, are combined with the year of the Callippic cycle displayed on the back. Ptolemy uses just such a divided system of time-reckoning in the *Almagest*. The display might also be used in comparing calendars such as the Egyptian solar calendar (used by astronomers) and any of the various local civil lunar calendars.[8]

When Price's false assumptions about the supposed differential gear were swept away, the reconstruction of the train that includes the epicyclic assembly, and the function of the lower back dial that it served, remained problematic. Apart from uncertainty as to how many epicyclic arbors, if any, there might have been on the lost half of the epicyclic platform, the layout of the wheelwork is complete; but many of the wheels in this train are so severely mutilated that one cannot establish with certainty how many teeth each had and thence the velocity ratio at each stage. Analysis of the wheels alone leads to a wildly uncertain estimate of the train's output period at the lower back dial. However, its combination with mathematical analysis, astronomical and mechanical considerations, and the observable detail of the dial itself, leads to just one probable solution for the function displayed: the period of rotation of the main pointer was intended to be one draconitic month. This leads to the conclusion that the lower back dial was used in the attempt to predict eclipses. Curiously, though, several different combinations of the numbers of teeth for the ruined wheels, all within the bounds of possibility indicated by the analysis, achieve the same result to acceptable approximations.[9]

The use of the epicyclic gear implies that the designer attempted to realize a period-relation that he supposed could not conveniently be achieved by using a fixed-axis train alone; but several satisfactory approximations that could have been realized more simply do in fact exist. These include a well known period-relation yielding an eclipse cycle of 223 synodic months, something which the designer certainly knew about since a fragmentary inscription on the instrument alludes to it. So, while admiring the designer's ingenuity in introducing epicyclic gearing, one might be tempted to suggest that his powers of numerical analysis were limited. Such a judgment would however beg the question as to the precise period-relation on which the design was based, and this we can probably never know.

The model that was originally built to illustrate only the reconstruction of the front dial as a planetarium was extended to include all these features of the back dial and the wheelwork serving it. In addition, a Moon-phase display was restored to the centre of the front dial, following a new, correct identification of the circular component found in fragment C which Price interpreted as a “crank handle” for working the instrument. The device depends simply on the differential movement of the Sun and Moon pointers, and so its restoration to the centre of the dial is independent of the conjectural planetary indications of this dial.[10]

No workmanship and no materials have been introduced into the model that are superior to those found in the original, but the outcome should still be seen only as a first trial attempt, made at home of materials that lay to hand. It must also be said that in making a physical model one has to decide on many details for which there may be no supporting evidence; but in this case all such details are unimportant, in that they may be changed without altering the function or working of the instrument in any significant way. The relation between the model and the reconstruction might be expressed loosely by the Platonic distinction between “what is seen” and “what is understood”.

The new reconstruction is presented with confidence because it explains nearly all of the artefactual evidence. Yet there remain some details of the instrument that are hard to explain, seeming oddly designed for the apparent purpose, or having no identifiable purpose, or seeming – bizarrely – to have a purpose that makes no sense in the present context.

One might emphasize that no further survey of the original fragments can solve these problems. Even in its wrecked state, the mechanical arrangement of the instrument as a whole is now quite clear, and the puzzling details mentioned above simply do not fit in. Instead, the researcher needs to envisage detail that no longer exists, for which he must exercise an informed imagination. What then emerges is that, rather than casting doubt on the soundness of the reconstruction, these problems point to the interesting probability that the instrument was altered.

The most striking of these features is the form of the wooden case. The design of its front part is based on evidence from fragment A that is seen most obviously in early photographs. Two pieces of wood, one along the side of the frame plate and the other running across its lower edge, met at a mitred joint. The detail of the joint indicates that they formed the external corner of a case, not internal framing; but the lower end of the back dial overhangs this corner. The newly-discovered fragment F (which the author identifies as a corner of the back dial plate with traces of woodwork including a similar mitred joint) confirms that further casework enclosed the elongated back dial too. The case must therefore have been stepped, a design that has the air of being improvised. It suggests that the front part of the instrument, comprising the front dial, the frame plate of fragment

A and the mechanism between them, was designed and built without the present back dial and was neatly contained in the smaller part of the case; and that the back dial was a later addition. In designing a new dial to be fitted to an existing instrument one would surely make it to suit the dimensions of the case; and so it seems probable that the present back dial already existed as part of another instrument. According to this argument, at the time of its loss the Antikythera Mechanism was composite, the result of a combination of components originally built as parts of separate instruments.

This hypothesis can explain some odd internal features. The unused gear teeth mentioned above are cut on the edge of the epicyclic platform; the next wheel in the train engages not these teeth but those of a gear ring fastened to the platform. Certainly some alteration has taken place here. Analysis indicates that there were probably 223 teeth in the unused set. The count, a prime number, is compatible with the suggestion that large wheels, with high numbers of teeth, were usually resorted to only when the required ratio contained a high prime factor, and it suggests a connection with the 223-month eclipse period-relation. Thus this wheel, perhaps as a wheel-pair together with the gear-ring attached to it, may once have formed part of a fixed-axis gear train which would have served a function analogous to that served by the epicyclic train in which it is now found; but the wheel of 223 teeth cannot possibly have had any such direct significance in the present gear train. Instead, it seems that, as a large wheel, it was reused merely as a convenient disc to be made into the epicyclic platform, the teeth on its rim being ignored. It appears that we have here the relic of an alternative earlier train serving a similar purpose, which may very well have belonged to the gearing previously fitted behind the back dial if that dial did indeed once exist as a separate instrument.[11]

Another feature, correctly identified only recently, is the arrangement of the two epicyclic wheels planted on the large wheel that has just been discussed. They lie one directly above the other but they turned about separate axes on a stepped stud, coupled by a pin that projected from the face of the lower wheel into a radial slot in the upper one. The slot now appears open-ended due to damage, and it was wrongly identified by Price as evidence of a repair.

Previously, the stepped stud was thought to be first found in much later mechanical models illustrating Ptolemaic planetary theory, where its use allowed mobiles to rotate about closely-spaced but distinct points (the centre of the deferent and equant). Yet the consensus of opinion in the history of astronomy opposes this interpretation in an instrument of the first century B.C. Besides, in that application the ensemble would be found at the fixed centre of a dial system, not on an epicyclic axis.

The device introduces a fluctuation in velocity ratio that may represent an astronomical anomaly in a less directly geometrical way. Its application to the solar and lunar theories of Hipparchos and to later astronomical theories is simple, and for this purpose it might in principle be mounted anywhere in the train; but – as is the case with the large wheel on which this ensemble is mounted – the context in which we find it is clear, and in that context it serves no useful purpose.

Its redundancy suggests that here is yet another mechanical element that was reused in a way that was not originally intended. The question arises as to whether the epicyclic platform, together with the paired wheels planted on it, formed an ensemble in some other design, or whether we have here elements taken from two separate designs, brought together in the realization of a third.

The identification in so early an instrument of the kinematic ensemble of driving pin and slotted follower, not otherwise attested until the early thirteenth century A.D., is an important addition to our understanding of the history of mechanism in general. In the context of this instrument in particular, it provides the necessary precedent for the use of the device with each of the epicyclic motions under the front dial, as a way of transferring the angular motion of a pin on the epicycle to the corresponding hand moving over the dial.

If in reconstructing the Antikythera Mechanism no single, unified solution to these and other oddities is possible, that is a measure of our new awareness of the richness of our legacy. Where before we saw simply the wreck of one instrument, now we see evidence that the instrument was altered, that parts were added, and that what survives is probably the marriage of parts of two or more pre-existing instruments. Where before we spoke of an unique artefact, now we may discuss growing evidence for a tradition of this class of intricate mechanism. It becomes easier to believe that other geared mechanisms, the baroulkos, the dioptra, the hodometer that we find in Hellenistic technical books, and other more shadowy designs incorporating gearing, were not simply armchair inventions but really were made and used. Other such instruments may wait to be found, but the majority, made of valuable bronze, were probably returned to the furnace in antiquity. We owe the survival of the Antikythera Mechanism to chance: it was lost beyond the reach of the scrap-metal man. So we have just this one precious artefact to open our eyes to see that intricate mechanism using gears and other advanced kinematic devices was an accepted element of Hellenistic technology.

Many details remain still to be considered as publication of the author's research material proceeds. Every new examination of the fragments of the Antikythera Mechanism will furnish yet more detail, and may bring forth surprises, but repeated observations can only confirm the correctness of the important elements of the reconstruction presented here. In all essentials, the Antikythera Mechanism is now understood.

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[5] M.T. Wright, "A Planetarium Display for the Antikythera Mechanism", *Horological Journal*, vol. 144 no. 5 (May 2002), pp. 169 – 173, and vol. 144 no.6 (June 2002), p. 193.

[6] M.T. Wright, "The Antikythera Mechanism: a New Gearing Scheme", *Bulletin of the Scientific Instrument Society*, no. 85 (June 2005), pp. 2 – 7.

[7] The procedure is outlined in: M.T. Wright, "The Scholar, the Mechanic and the Antikythera Mechanism", *Bulletin of the Scientific Instrument Society*, no. 80 (March 2004), pp. 4 – 11. A more detailed account is in preparation: M.T. Wright & G.J.T. Wright, *Computer-Aided Analysis of Radiographic Images, applied to the Antikythera Mechanism*.

[8] M.T. Wright, "Counting Months and Years: the Upper Back Dial of the Antikythera Mechanism", *Bulletin of the Scientific Instrument Society*, no. 87 (December 2005), pp. 8 – 13.

[9] M.T. Wright, " Epicyclic Gearing and the Antikythera Mechanism", *Antiquarian Horology*: vol. 27 no. 3 (March 2003), pp. 270 – 279, and vol. 29 no. 1 (September 2005), pp. 51 – 63.

[10] M.T. Wright, "The Antikythera Mechanism and the Early History of the Moon-Phase Display", *Antiquarian Horology* vol. 29 no. 3 (March 2006), pp. 319 – 329.

[11] This idea is explored further in a paper now in preparation: M.T. Wright, *The Second Antikythera Mechanism: an Hypothetical Reconstruction*.