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THE ANTIKYTHERA MECHANISM
1. Challenging the Classic Research

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ABSTRACT

The Antikythera Mechanism is an extraordinary 2,000 year-old astronomical calculator, which was recovered 100 years ago by Greek sponge divers. Its true significance was not recognised until the research of Derek de Solla Price from the mid-1950s, which culminated in the classic *Gears from the Greeks* (Price 1974). Price undertook a detailed scientific examination, including x-rays, which showed that it was a complex mechanism with at least thirty gears. He also produced a model of the mechanism, which incorporated a differential - apparently far ahead of its time. This paper challenges some of the key conclusions of this classic research as well as a later revision of Price's model by Allan Bromley. New investigations, using the latest technologies, are advocated in order to settle the many outstanding questions.

KEYWORDS: astronomy, differential, gear, Greek technology, Meton, Saros

STILL A MYSTERY...

The Antikythera Mechanism is one of the most remarkable and mysterious artefacts from classical times. It is an amazing 2,000 year-old astronomical computer, dating from the 1st Century BC. Its discovery 100 years ago by Greek sponge divers is told in fascinating detail in Price (1974) and more recently in Edmunds & Morgan (2000). By the mid-1950s it had been studied for more than half a century, yet its true nature still lay hidden. Then a British physicist, Derek de Solla Price, started a 20-year odyssey of research, which culminated in 1974 with the publication of the groundbreaking paper, *Gears from the Greeks* (Price 1974). He showed that it is a complex, geared mechanism, which is of

central importance to the history of science and technology. Price apparently decoded it and gave us a fascinating model of how it worked. I want to examine the intricate workings of this extraordinary device, but at the same time question some key aspects of Price's conclusions as well as a later revision of Price's model by Allan Bromley. Despite its central importance to the history of technology, the volume of literature is very small and much of the classic research has remained unchallenged for more than a quarter of a century. Recently however there has been a wave of renewed interest in the Antikythera Mechanism, inspired by the work of Mike Edmunds and colleagues (Edmunds & Morgan 2000) on the possible astrological uses of the device.

I am a filmmaker and I am acutely aware that I am not an expert in many of the relevant fields of research - such as astronomy, history and mechanical engineering. I may be treading clumsily into an area where others know much more than I do. So I welcome reactions, corrections and feedback and above all debate.

DEREK DE SOLLA PRICE

Price established that it is the first known calculator, with the first known scientific scale. It has no known antecedents and nothing as complex is known for another 1,000 years. Price's first publication, *Clockwork before the Clock* (Price 1955) locates the mechanism as the precursor of all mechanical clocks. In 1959 he included the mechanism in Price 1959a and wrote an excellent popular account in *Scientific American* (Price 1959b). By this stage, he did not feel that he had solved the gearing of the machine, though he did describe epicyclic gearing (where the axles as well as the gears themselves move). This was a very significant observation. In 1974 he published *Gears from the Greeks* (Price 1974), the classic publication. It is scholarly, brilliant and full of meticulous detail. And it's this detail which I think sometimes means that its conclusions have not been challenged more often – it's easy to skate over the precise measurements of gearwheels and the intricate details of tooth counts and geartrains. What follows has mostly come from my experience building computer models of the device. This forced me to get involved with all these details and led me to ask some awkward questions about the classic research.

The mechanism itself is astonishingly small – only about 33 cms high, 17 cms wide and about 9 cms thick. Price undertook a detailed scientific examination. The gears are made of bronze sheet about 2 mm thick and metallurgical analysis indicated a low tin composition, with about 95% copper – so the gears must have been fairly soft and bendy. The surface showed that it was covered with critical information in the form of dials, scales and inscriptions. On the front dial, there is a Zodiac and a Calendar and Price deduced from the fragmentary inscriptions that they go round clockwise. There are also extensive astronomical inscriptions and a Parapegma plate (a pegboard for marking astronomical events). Edmunds & Morgan 2000 describes the significance of these inscriptions. They include heliacal risings and settings and numbers which appear to refer to the Metonic Cycle – the Moon makes 254 sidereal revolutions of the Earth and 235 synodic revolutions in 19 years – and to the Saros eclipse cycle of 223 synodic months. It was very clear that the device had astronomical functions.

By the 1970s Price was getting excellent co-operation from the Archaeological Museum in Athens and he teamed up with a Greek radiographer, Christos Karakalos, to carry out x-rays and gamma radiographs of the mechanism. This revealed critical evidence and it transformed the understanding of how it worked. The x-rays clearly showed the teeth on the gears inside the fragments. Nearly all the gears were incomplete, but by carefully marking and counting the partial gears, they could make estimates of the crucial tooth counts. After years of painstaking work, they still didn't agree on the tooth counts, and the information about how the gears meshed was also uncertain. Overall the evidence was very incomplete. However Price managed to produce a highly ingenious model of all the extant geartrains (Fig. 1).

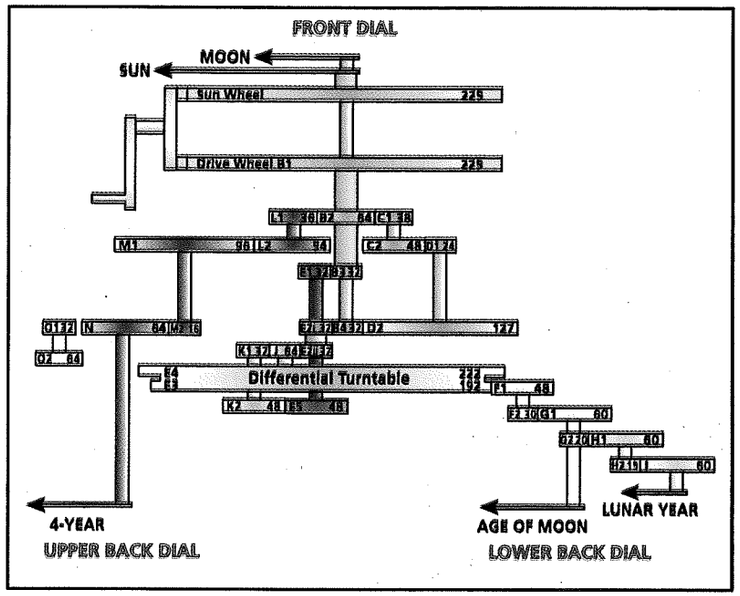

Figure 2. Price's Sectional Diagram (Adapted from Price 1974).

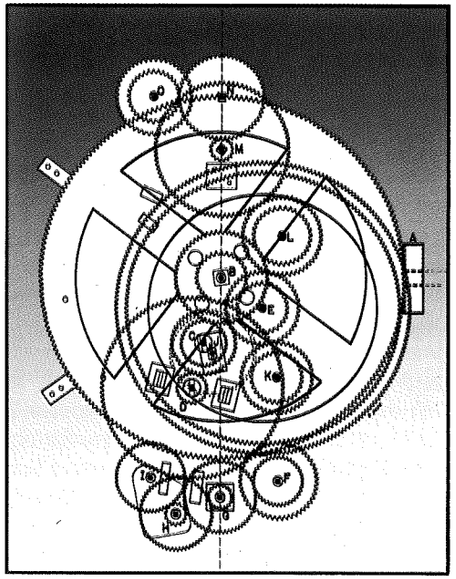

Figure 1. Price's General Plan (Adapted from Price 1974).

He found evidence of 30 gears, but needed to infer the existence of two more to make his model work. He found tooth counts varying from 15 to 225 teeth. It's incredibly complex, particularly given its date of manufacture, and it's really impossible to understand from his General Plan.

In Price's Sectional Diagram, Fig. 2, Sun-related gears are in warm colours, Moon-related in cool colours. Price's viewpoint here is not obvious – we are

looking down on the top of the case from behind at an angle of about 30° from the vertical. This reveals the structure much more clearly than the General Plan and enables us to divide it into sub-systems. A crank handle (in grey) is attached to a contrate gear. This drives two large gears (in yellow) in opposite directions. The top gear, the Sun Wheel (entirely missing from the extant fragments) turns once a year. It is attached to a Sun pointer that goes clockwise round the Zodiac & Calendar Scales on the Front Dial. The second of the two large yellow wheels is the main Drive Wheel for the rest of the mechanism. From this Drive Wheel there is a geartrain (in pale blue) that gives the Moon position in the Zodiac on the Front Dial, using the Metonic ratio of 254/19. Price's *4-Year Dial* geartrain (in red) is also driven from the Drive Wheel and outputs to the Upper Back Dial.

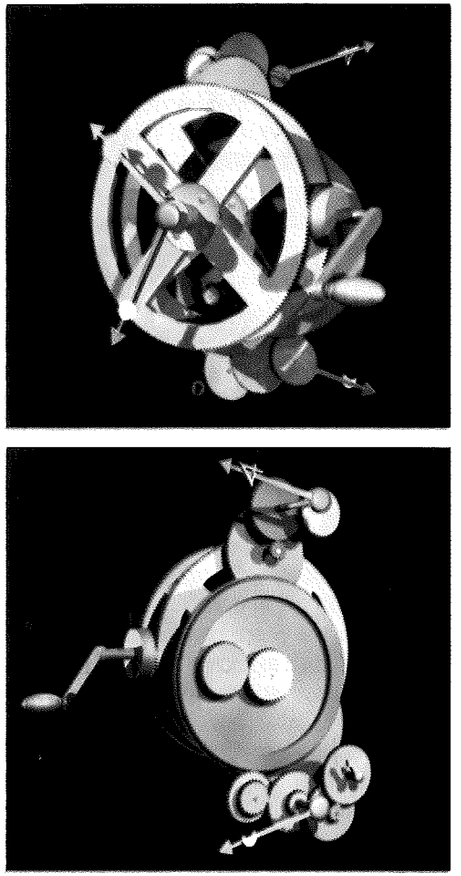

Figure 3. Computer Reconstruction of Price's Model. This shows all the gears, but none of the support structure, case or dials. The colours are co-ordinated with the Sectional Diagram in Fig. 2. On the front is the Sun and the sidereal Moon and on the back the Age of the Moon, the Lunar Year and the 4-Year Dial. It has a rather larger crank handle than other models so that it's easier to turn - and easier to break as well!

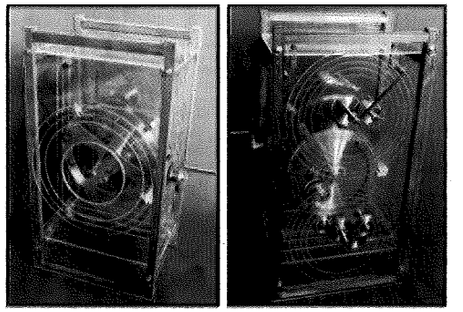

Fig. 4: John Gleave's Reconstruction of Price's Model (Reproduced by permission from John Gleave).

The *Differential* (in lilac) is the heart and soul of Price's model. Unknown in Western technology for another 1,600 years, it is an extraordinary conception. The *Differential* has two inputs: the Sun input (in orange), which turns at the rate of the Sun through the Zodiac; and the Moon input (in blue), which turns at minus the rate of the Moon through the Zodiac. The output of the *Differential* is the average of its two inputs and this is in turn geared to show the *Age of the Moon* and the *Lunar Year*. There is also a pair of gears, O1 + O2, whose function Price couldn't determine.

Fig. 4 shows a beautiful physical reconstruction by the Yorkshire-based orrery maker, John Gleave, based on Price's model. It's extraordinary to see just how small it is at only 33 cms high. It shows the Front and Back Dials with their annular rings.

CHALLENGING THE CLASSIC RESEARCH

The Roman wreck where the sponge divers from Symi found the Antikythera Mechanism lay at 42 metres. My first question about Price's classic research came from a quote in *Gears from the Greeks:* "Only six divers were available, and because of the water depth they could not remain on the bottom for more than five minutes, which together with four minutes for ascent and descent entailed about nine minutes of submersion without air-tanks or tubes to help them..."

Do we have any volunteers to hold their breath for nine minutes?! Research on the Internet found that all the world records for free diving and for breath holding were significantly shorter than nine minutes. "...without air-tanks or tubes to help them..." is surely impossible. More research strengthened my conclusions. When the sponges were fished out in the Mediterranean and the world turned to plastic sponges, the sponge divers of Symi went to Tarpon Springs, Florida. In 1975 they erected a statue of a sponge diver of 1905 – just four years after the Antikythera dive. He has a full diving suit and helmet with a breathing tube. In fact diving suits were introduced into sponge diving in the 1860s. It was terribly hazardous and in the first year more than 20 divers died. On the Antikythera wreck itself one diver died and another was seriously injured. Even though the sponge business in Symi has died out, it is said that in the bars of Symi today, people still do the *Bends Dance* where the performers start dancing normally and end up in paralytic disorder which imitates the 'bends'!

THE 4-YEAR DIAL?

In terms of the mechanism itself, the first thing I questioned was the *4-Year Dial*. Later I found that others too had doubted this part of Price's model and Bromley suggests a fascinating alternative (Bromley 1986, 1990a, 1990b). Apart from anything else, a *4-Year Dial* seems to be a very insignificant parameter to choose. Every geartrain needed an immense amount of work – remember that all the teeth were laboriously cut by hand. It just didn't make sense to do all this work for a 4-year Dial. I want to challenge this geartrain in a precise way. The key question is how fast does M1 + M2 (Axis M) rotate?

We use a modification of Price's notation for geartrains: '□' means that two gears mesh together, '+' means that two gears are fixed to the same axle. Rotations, which are clockwise on the front dial, we define as positive and we measure these in rotations per year. The geartrain leading to Axis M is 64 □ 36 + 54 □ 96. This gives a ratio of - 1 x - 64/36 x -54/96 = - 1! The same rate as the Main Drive (in yellow). 240 teeth just for this? 320 teeth for the total 4-Year Dial and it turns the wrong way - anticlockwise on the Upper Back Dial! The 4-Year gearing spectacularly fails *Occam's Razor*. We do not need to believe that the mechanism was optimised in some way, but the gears leading to Axis M make no sense from any

perspective. And this has direct implications not only for Price's model but also for a later revision by Allan Bromley, which we discuss later. Price did consider an alternative use for these gears, suggesting that they might have produced a ratio of 5/19 with some small alterations in the tooth counts. This would drive a pointer that turns five times in the 19 years of the Metonic cycle around a dial divided into 47 lunar months. So the 235 lunar months of the (synodic) Metonic cycle would be indicated over a period of 19 years. This proposal gets over the anomaly of Axis M but it does seem to me to be an unlikely conjecture.

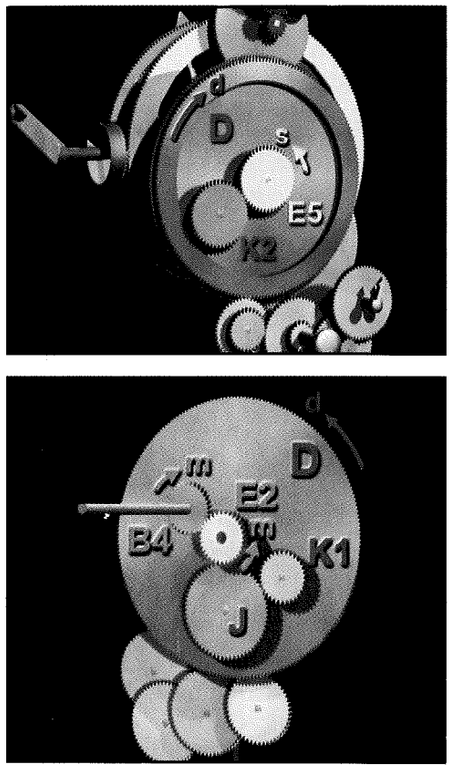

Figure 5. Price's Differential.

QUESTIONING THE DIFFERENTIAL

The *Differential* is a subtle and extraordinary conception that defies easy understanding. The point of the *Differential* is to produce a synodic Moon (*Age of Moon*) output from the sidereal Moon output by subtracting the Sun output. If we only use gears with fixed axles, then we are limited to multiplication by rational numbers. To do addition or subtraction with gears, we need to use moving axles. In Price's model of the Antikythera Mechanism, the *Differential* has two inputs and one output – so it's working like a car differential in reverse. An additional feature is that the inputs are geared together, so they can't move independently. The inputs are E5 – the Sun rotation, s; and E2 – the Moon rotation in reverse, - m.

I find that the easiest way to work out the rotations is to imagine that you are riding on the *Differential*, D. From the point of view of this frame of reference, D, all the gears have fixed axes. So we can use the simple properties of meshing gears with fixed axes to establish how the gears turn. On the back of the Differential, E5 is the Sun Input and it rotates at the Sun's rate of 1. We shall use the notation Rot (X|D) to mean the rotation of Gear X relative to the epicyclic table, D. Since E5 and K2 have the same number of teeth we get:

$$\text{Rot}(K2 \mid D) = -\text{Rot}(E5 \mid D) \quad (1)$$

On the front of the *Differential* B4 turns at the rate, m, of the Moon in the Zodiac and this drives E2 in the opposite direction, at the rate - m. Notice that E2 must be a double wheel since, otherwise, gear J would crash into B4 as the *Differential* turns. In an earlier reconstruction, Price assumed that this was a single wheel. Gear J is an idler gear in the system and K1 and E2 have the same number of teeth, so:

$$\text{Rot}(K1 \mid D) = \text{Rot}(E2 \mid D) \quad (2)$$

However, K1 and K2 are fixed on the same axle, so:

$$\text{Rot}(K1 \mid D) = \text{Rot}(K2 \mid D) \quad (3)$$

From these two equations we get:

$$\text{Rot}(E2 \mid D) + \text{Rot}(E5 \mid D) = 0 \quad (4)$$

Now, if we go back into the 'real world', the actual rotation of E2 is given by:

$$\text{Rot}(E2) = \text{Rot}(E2 \mid D) + \text{RoT}(D) \quad (5)$$

So:

$$\text{Rot}(E2 \mid D) = -m - d \quad (6)$$

Similarly:

$$\text{Rot}(E5) = \text{Rot}(E5 \mid D) + \text{Rot}(D) \quad (7)$$

$$\text{Rot}(E5 \mid D) = s - d \quad (8)$$

Hence:

$$-m - d + s - d = 0 \quad (9)$$

$$d = 1/2(-m + s) = 1/2(-254/19 + 1) = -235/38 \quad (10)$$

This is half the speed we want for the Age of the Moon.

If Price's *Differential* is correct, it's the first known use in history of a differential gear, which Price aptly describes as one of the greatest inventions of all time. Though the differential is rumoured to have been developed by the Chinese in 1,000 BC, or even earlier, in the form of the *Constant-pointing Chariot*, there is apparently no direct evidence before 300 AD (Temple 1986). It may be heretical to throw a spanner in the works by challenging Price's *Differential*, but there are some questions that I think are hard to answer.

- **Why is the *Differential* so big?**

It doesn't need to be this big to carry the epicyclic gears, K1, K2 and J. They could clearly be carried by a differential table that is much smaller. Why does E3 need 192 teeth? It's a lot of work to cut all those teeth by hand – a gear of 128 teeth for example would be ample and very easy to divide. Another failure of *Occam's Razor*. The *Age of the Moon* could then be achieved with an idler gear at Axis F and a gear of 64 teeth at Axis G. (Though the epicyclic gears on the differential would then project marginally beyond the edge of the differential table, there is ample space for them to clear the axle of Gear F.)

- **Why quadruple the rotation and then half it again?**

To get from the *Differential* to the *Age of the Moon*, Price quadruples the rotation and then halves it again – presumably because E3 is so large that you'd need a gear of 96 teeth to just double the rotation. But, as already discussed, E3 doesn't need this number of teeth – with 128 teeth, it could yield a synodic moon output with much fewer gears.

- **What is E4 for?**

Price found no explanation, yet it is one of the largest gears in the system. Price described the *Differential* as 'elegant' but is there an easier way to get the synodic moon ratio of 235/19?

A SLEDGEHAMMER TO CRACK A NUT?

The *Differential* could easily be

replaced with much simpler gearing that does exactly the same thing (Fig. 6). First let us strip away the *Differential* as well as the *Age of the Moon* and *Lunar* geartrains (compaire Fig. 2 & Fig. 6). Then flip and shift the gears M1 + M2 and alter all the tooth counts somewhat: change L1 from 36 to 38; L2 from 54 to 47; M1 from 96 to 90 and M2 from 16 to 18 – not large changes and well within their margins of error. Commandeer the unknown gear O1 with 32 teeth and we get the geartrain: 64 □ 38 + 47 □ 18 + 96 □ 64 □ 32, which gives a ratio of - 235/19 – exactly what we want for the *Age of the Moon*. Notice the 'elegant' symmetry we now have between the sidereal and synodic Moon geartrains. Price did consider that the Metonic ratio could have been obtained by direct gearing but ruled it out on the grounds that it involved dividing gears with awkward numbers of teeth. The same though is true of his sidereal Moon geartrain, which contains gears of 38 and 127 teeth – also not easy to divide. So I don't think this is a very strong argument. In addition Allan Bromley has shown that there are simple techniques for dividing gears with awkward tooth counts (Bromley 1985/86). Our new simple *Age of Moon* uses 6 gears with 289 teeth, whereas Price's *Age of Moon* with the *Differential* (excluding E4) used 11 gears with 618 teeth. William of Occam would have turned in his grave. Just think of how much more work it was filing all those teeth individually by hand. Think of all the extra friction on those soft and bendy (95% copper) teeth.

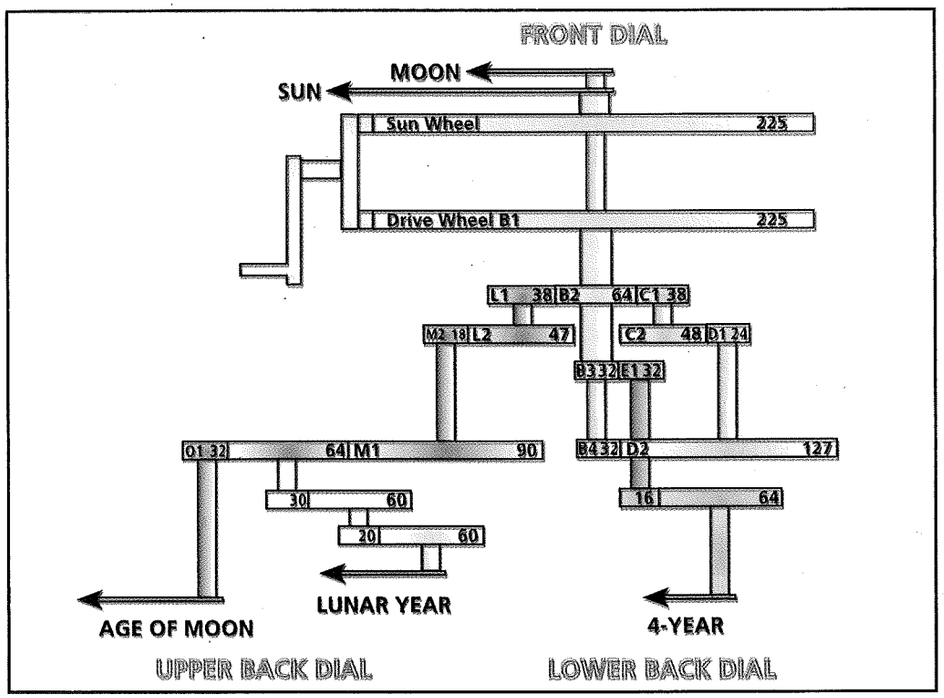

Figure 6. The Minikythera Mechanism.

If we now add gearing for a *Lunar Year Dial* (as in Price's model) and a simple *4-Year Dial*, then we have a much simpler mechanism that does exactly the same as Price's model. Let us call it the *Minikythera Mechanism*. Price's Model has 32 gears with 2,201 teeth; The *Minikythera Mechanism* has 24 gears with 1,431 teeth. Not only is it much easier to turn but the *4-Year pointer* now rotates the right way! It may be excluded by the x-rays but it forces us to think about why they would have incorporated a differential in the mechanism. And yet Price's *Differential* is such a beautiful conception that it is hard to abandon. Why did Price think that there was a differential? I think that the answer must lie in the gears K1 and K2. If the x-rays show that these are above and below gear E4 and are fixed to the same axle going through E4, then they must be epicyclic gears. If E2 is also a double wheel, then the evidence is strong (though this cannot be obvious from the x-rays since Price got it wrong in an early reconstruction). Only a new detailed x-ray examination of the mechanism itself can settle this crucial question. In another publication we explore the intriguing idea that Price's *Differential* might in fact be a *Jupiter Mechanism* (Freeth 2002).

INTERPRETING THE EVIDENCE

Price and Karakalos both studied the x-rays independently and made different estimates of the crucial tooth counts. There are many examples and we give just three.

Gear D1: "Karakalos counts 128... I suggest that the actual number should be 127..." Price wants the number to be 127 because it is a prime factor in the Metonic geartrain that leads to the sidereal Moon output. Tooth counts are absolutely critical in terms of the functions of the mechanism: if the count really is 128, then this gearing does not calculate the Metonic Ratio. A difference of one tooth makes a dramatic difference in possible function.

Gears F1 and F2: "Karakalos counts the wheel pair as 54 and 30 teeth... but I view the former number as an overestimate in view of the fact that a simple ratio with the 192 teeth of E3 seems to be intended..." Price needs F1 to have 48 teeth, a big difference from 54, to produce the Age of the Moon output. The phrase "...seems to be intended..." is telling.

Gears L1 and L2: "...Karakalos finds 36+ and 52. From the trains I find 36 to be acceptable for the smaller but suggest the rounder number 54 for the larger..." Price wants 54 to make the highly dubious *4-year Dial* work. Is 54 really a 'rounder' number than 52?

What this calls into question is the whole scientific process by which we infer structure from incomplete evidence and theory from contradictory information. An interesting analogy comes from Millikan's famous *Oil-Drop Experiment*, which established the charge on the electron (Holton 1978). Robert Millikan needed to carry out his experiment many times: sometimes it went 'well' and sometimes 'badly'. As his own laboratory notes read: "This is almost exactly right & the best one I ever had!!!" [20 December 1911]; "Exactly right" [3 February 1912]; "*Error high will not use*" [15 March 1912, #2]; "Perfect Publish" [11 April 1912]; "Won't work" [16 April 1912, #2]; "Too high by 1%" [16 April 1912, #3]; "1% low"; "Too high e by 1%." So Millikan was highly selective about what data he published. It is said that he was more successful than his rival Ehrenhaft because his 'intuition' was better. And of course he turned out to be right and was awarded the Nobel Prize in 1922. A similar process apparently hap-

pened with Mendel's sweet peas, where his published results are too statistically good to be true. Price publishes the tooth counts that don't agree with his theory, but then abandons them to suit his ideas when he constructs his model. But is there anything wrong with this? For example, the reassessment of the tooth count of Gear D1 from 128 to 127 seems to be right because of the contingent evidence from the inscriptions that the device calculated the Metonic ratio. Perhaps we need to be more careful and explicit about the uncertainties and their implications. Some more hard evidence from new x-rays would also be useful!

PLANETARY INSCRIPTIONS

What mentions are there of the planets in the inscriptions on the mechanism? This is a very important question in terms of what mechanisms might have been incorporated into the machine. It is also critical in terms of the machine's intended functions as discussed in Edmunds & Morgan (2000). In An Ancient Greek Computer, Price (1959b), he writes: "On the upper dial the inscriptions are much more crowded and might well present information on the risings and settings, stations and retrogradations of the planets known to the Greeks (Mercury, Venus, Mars, Jupiter and Saturn.)"

Yet in the more scholarly *Gears from the Greeks*, Price (1974), based on much more detailed examination of the mechanism, the only reference I can find is: "Line 18 [Venus]" ("The readings in lines 18 and 42 are uncertain and conjectural.")

So what evidence was there for the first statement in *An Ancient Greek Computer?* If it is true, it would put the whole mechanism in a different light - it would almost certainly have contained planetary mechanisms.

FIDUCIAL MARK

When was the Antikythera Mechanism made? Price finds a mark on the front calendar dial, which he identifies as a *Fiducial Mark*, inscribed at the time of manufacture to indicate the position of the month circle at the time. From this he gives a sophisticated astronomical argument that leads to the conclusion that the mechanism must have been made in c. 87 BC – a brilliant deduction in the great tradition of Sherlock Holmes. Yet just how secure is the evidence for this mark? Price says: "*I feel sure it is no accidental crack.*" However the published photograph is much too small to make any judgement. Since it has such great significance, a microphotograph of the mark would have been helpful. Allan Bromley's direct observations of the fragments, Bromley (1990d), confirm my scepticism: "Price's fiducial mark near the outer dial ring is certainly now a crack. I have not been able to persuade myself that it was originally a deliberate engraving mark from which a crack subsequently developed."

If this is indeed correct, then Price's tenuous dating argument - concluding that the mechanism was made c. 87 BC - completely falls apart.

OVERLAPPING GEARS

Nearly all of Price's measurements are given to the fine accuracy of a tenth of a millimetre. Yet if we look at Price's positions for the gears, D2, B4 and E2i, there is a puzzle. In his Sectional Diagram (Fig. 2), these gears are all in the same plane. Yet in his General Plan (Fig. 1), D2 overlaps E2i by more than 4 mm, which is clearly impossible if they are in the same plane. It's easy to fix by moving the axis of D2 or of the Differential. However it's such an elementary mistake that it leaves

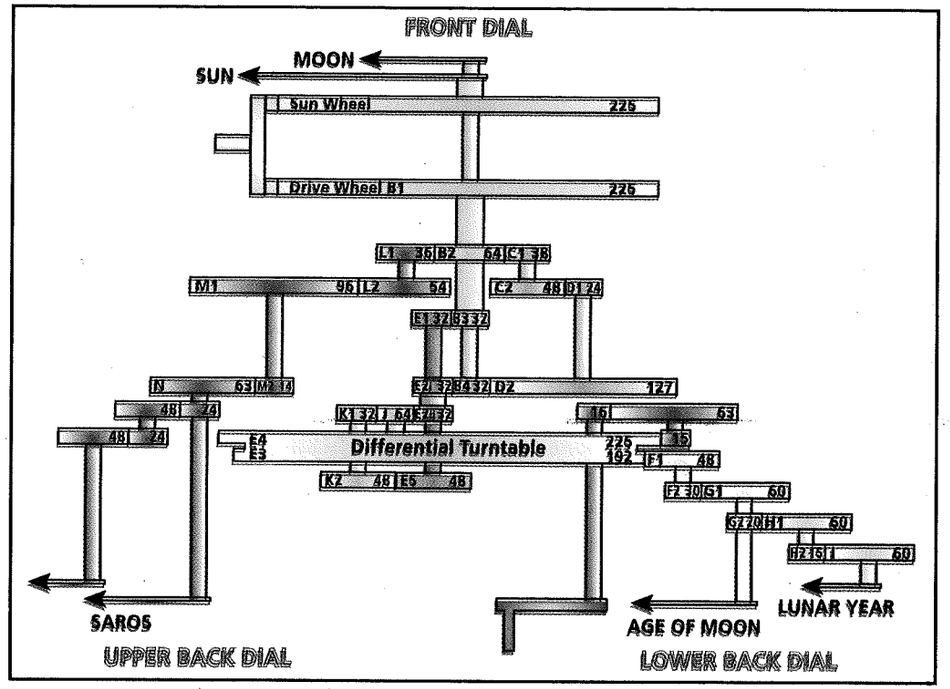

Figure 7. Allan Bromley's Model (Adapted from Bromley 1990a).

further doubts. John Gleave, who made the superb reconstruction of Price's model in Fig. 4, tells me that he solved this problem in a different way by making B4 into a double wheel. This problem is also addressed in a similar way in Bromley (1990d).

METONIC GEARTRAIN

Allan Bromley has made some very interesting modifications to Price's model, which we shall look at later. At the end of Bromley (1990b) he wrote: "Since writing the above I have been able to examine the original fragments of the Antikythera Mechanism... They differ in important ways from Price's descriptions from which I worked. Even the embodiment of the Metonic Cycle now seems in doubt. Instead of being at the end I now find myself at the beginning of the whole project."

I had thought that the Metonic Cycle, as it applied to the sidereal Moon geartrain, was the most secure part of Price's reconstruction. But this gives pause for thought. In Bromley (1990d) Allan Bromley amplifies his reservations about Price's descriptions of the physical layout of the gears. However he does not appear to question that this geartrain calculates the Metonic ratio.

If we add up the doubts about Price's classic research, we find a significant list: "...without air-tanks or tubes to help them..."; 4-Year Dial; Differential; Tooth Counts; Planetary Inscriptions; Fiducial Mark; Overlapping Gears; Metonic

Geartrain. Price's work was extraordinary, but some doubts are surely justified - like the dive "...without air tanks or tubes...", *4-Year Dial and Overlapping Gears.* Others, such as the *Differential*, ask questions that I can't answer. In some ways Price seems to me to have been like a magician, pulling rabbits out of hats.

ALLAN BROMLEY'S MODEL

In Bromley (1986, 1990a, 1990b), Allan Bromley writes with great enthusiasm about his ideas and the techniques of constructing a physical model. He has proposed an alternative model with some very persuasive features. He makes two significant changes to Price's model: it is driven from the *Differential* and it incorporates the *Saros Cycle.*

In Fig. 7, Bromley's new drive from the *Differential* end of the gearing is coloured pink. This change was a response to a criticism of Price's model by the mathematician, Christopher Zeeman. In Price's Model the step up ratio between the main drive and the fastest-moving axle, F1 + F2, is nearly 25 : 1 – this would make the mechanism very hard to turn. John Gleave, the orrery maker who has made a superb reconstruction of Price's Model (Fig. 4, Gleave 2000) says that it will turn but only just – you certainly couldn't mechanise it because it would seize up. Bromley's model introduces a new geartrain that drives the system from its high-speed end, so reducing mechanical stress. A crank handle drives the gear E4 on the *Differential*, via an ingenious geartrain, which means that the crank turns exactly once per day. At last E4 has a function, the mechanical design is much better and the 'day' becomes a natural part of the mechanism. I have reservations about Bromley's model. The first is that it limits the possible functions of the machine because of the *Resetting Problem.* One of the likely uses for the mechanism was to predict the future or reconstruct the past. However, if you want to wind Bromley's model forwards or backwards for a number of years, it means turning the crank handle a large number of times. For example, an astrologer who wants to wind the machine back to the date of my birth would need to turn the handle 20,000 times (and counting)! It would also be hard to implement the interesting suggestion in Economou (2000) that it was used to predict the dates of moveable public holidays such as the Olympiad, which were determined by astronomical criteria. This is not a terminal criticism. It may be that the mechanism – just like many mediaeval astronomical clocks – simply indicated current positions of the heavenly bodies. Or the movable annuli on the dials could have been used to set known past positions and the mechanism used to interpolate between them. (This wouldn't work if the device contained planetary mechanisms because of the retrograde motions). Another reservation is that his model makes the front structure of the machine difficult to explain. In Price's model the two largest gears, B1 and the Sun Wheel, provide leverage to overcome the high step-up ratio observed by Zeeman. In Bromley's model they could easily be replaced by much smaller gears (unless again, planetary gearing was included). Also it is much harder to conceive, at the design stage, of driving the mechanism from the *Differential.* And there is no physical evidence for Bromley's new drive.

Bromley's other major change is to abandon the 4-Year Dial and replace it with the *Saros Cycle* – see the gears coloured red in Fig. 7. The *Saros* is a cycle of 223 lunar months (just over 18 years),

which can be used to predict eclipses. It was known to Babylonian astronomy and used in a famous eclipse prediction by the Greek astronomer, Thales, in 585 BC. This is the '223' that Price tentatively identifies in one of the inscriptions on the mechanism itself. Price showed that the Upper Back Dial has four annuli. By a small change in the tooth counts in Price's *4-Year Dial* geartrain, Bromley drives a pointer on this Upper Back Dial, which turns once in 4.5 years. He also introduces a subsidiary pointer that turns at a quarter of this speed - in other words once every 18 years - around a dial divided into quadrants. This subsidiary pointer tells you which of the four annuli should be read by the large pointer. His suggestion apparently fits very well with the x-ray evidence, even restoring Gear N, which Price had changed to 64 teeth, to Karakalos' original 63 teeth. My primary criticism is that in Bromley's model, as in Price's, Axis M still turns at rate - 1, with all the problems that has for William of Occam's peaceful rest. It's an odd decision also to get the ratio 2:9 by multiplying by 7 to yield the gears 14 □ 63 and this ratio does not in any case give a true Saros Cycle of 223 lunar months, despite Price's assertion that this number is inscribed on the case. In addition the Age of the Moon and the Saros Cycle in Bromley's model could be replaced with much simpler gearing, which would have the additional benefit of giving a true *Saros Cycle* (though this would not accord with the x-rays). Since building his model, Bromley has studied the fragments directly, Bromley (1990d). Not only does this fascinating study cast doubt on many of Price's observations of the fragments, but appears to overturn his own idea about the Saros cycle: "I see faintly but certainly, seven sets of radial division lines crossing all three visible dial rings... Certainly the observations do not seem compatible with my previous suggestion, that the upper back dial represented a Saros cycle..."

So, from the archaeological viewpoint as well as the theoretical viewpoint, Bromley's idea of a Saros Dial appears to be unlikely. Overall Bromley's suggestions are very ingenious but I still don't find them convincing.

THE WAY FORWARD

In another paper (Freeth 2002), I have built on the work in Edmunds & Morgan (2000) to explore the possibility that planetary mechanisms were also included in the Antikythera Mechanism. Taken together with the ideas in this paper, we now have a wide variety of possible structures – without any hard evidence to decide between them.

In 1990 Allan Bromley and Michael Wright (from the London Science Museum) obtained permission to take new x-rays of the mechanism, in association with Helen Magou from the Archaeological Museum in Athens. They used a method called Linear Tomography (Wright 1990; Wright, Bromley and Magou 1995). It appears from accounts of the x-rays that the results were disappointing. A student of Allan Bromley, Bernard Gardner, wrote a thesis (Gardner 2000) on the interpretation of the x-rays of the main surviving fragment: "Linear motion tomography suffers however from the presence of all planes of the object outside the plane of focus in the image, they are just blurred by the motion, and so appear as streaks, confusing the desired image."

From reading reports of these x-rays (Magou 1990; Wright, Bromley and Magou 1991) it seems that not a great deal has been added to our knowledge. The x-rays appear to be unavailable. However

the latest 'microfocus' x-ray technology promises a much better chance of success. Microfocus x-ray is a cutting-edge technology that gives extremely fine resolution digital pictures in real time and can be programmed to provide 3-D images of unprecedented clarity. It has the potential to give us remarkable new insights into the structure of the Antikythera Mechanism. There are also recent digital techniques for reading inscriptions (Brooks 2001) that could give critical new information. We would advocate the use of these new technologies as soon as possible.

When Allan Bromley found his ingenious alternative use of Price's *4-Year Dial* for the *Saros Cycle*, he wrote: "...when I found an answer it had a simplicity and elegance that is hard to deny... I mentally wrote 'Q.E.D.' at the bottom of my work and started to sleep at night."

I understand this feeling and I'm sure that Price had it in spades when he thought of the *Differential*. My own view is that we should be more cautious. The uncertainties in the evidence are so great that we may never get a definitive answer. We need to take a highly critical view of all the classic research and rethink the structure from scratch.

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