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Our current knowledge of the Antikythera Mechanism

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The Antikythera Mechanism is the oldest known mechanical calculator. It was constructed around the second century BCE and lost in a shipwreck very close to the small Greek island of Antikythera. The shipwreck was discovered 2,000 years later, in 1900. The Mechanism was recognized in the spring of 1902 as a geared mechanical device displaying calendars and astronomical information. Application of modern imaging methods to the surviving fragments has led to general agreement on the basic structure of the device and its solar and lunar astronomical functions. The reading of the remains of its extensive inscriptions has shown that it was also intended to display the shifting position of the planets in the zodiac. In this review, we set out our view on what is known about the device, what can reasonably be conjectured and what major uncertainties still remain regarding its origin, context and purpose.

Some twenty or so references to astronomical mechanisms can be found[1,2] in classical literature during the period 50 BCE to AD 500, although a tradition of attributing devices to Archimedes (287–212 BCE) implies an earlier history. The references are of variable content and quality, but they indicate a long tradition of construction, and that such devices were well-known, at least among the intelligentsia. Gears and simple mechanisms incorporating gear-work are discussed in the texts of classical writers such as Hero and Pappus, but there are no known surviving artefacts with small metal gears from before as late as AD 1000, except for the Antikythera Mechanism and an elementary geared Byzantine sundial[3] from around the late fifth or early sixth century BCE. The Antikythera Mechanism was a portable (shoe-box size, approximately 330 mm tall, 180 mm wide and at least 80 mm from front to back; Fig. 1), geared mechanism, made of bronze, and was protected by two bronze covers and a wooden case[4]. There are Greek inscriptions[5] on the covers and on the front and back plates, which also carry dials. A coin-based shipwreck date of within a few years of 60 BCE[6] — consistent with ceramics and other material from the wreck[7–9] — provides a firm latest boundary for the construction of the Mechanism (Box 1), and there is a statement in a philosophical dialogue[2,4,10] by Cicero that may plausibly be interpreted as him recalling an almost-contemporary sighting during the travels of his youth to Rhodes of a mechanism with comparable functions.

From the extent of the shipwreck and particularly from its constructional elements, it has been deduced that it was a very large merchant boat, a *holkas* (length > 40 m, width > 14 m)[9,11,12], probably travelling from the eastern Mediterranean (Pergamum, Ephesus, Rhodes, Kos or Delos) to one of the large Roman ports (Napoli, Ostia or Brundisium). It was loaded (perhaps overloaded) with merchandise in jars and amphorae, as well as precious artefacts, marble and bronze statues, glassware, gold jewellery, silver coins and bowls, and other luxury items acquired by plunder or purchase[6–9,13–15]. Besides the above items, older (1901 and 1976) and recent (2012–2016) dives and marine excavations have brought to the surface coins, cooking utensils, two large anchors, decorative spears, lead items from the hull of the boat (or heavy depth gauges) and at least five well- or less-well preserved skeletons of men, women and children. There is no doubt that the Antikythera Mechanism was being transported on the ship, and was not (despite persistent descriptions in the media) a device for either maritime or space navigation.

The history of the early investigations of the Mechanism is now well documented[1,16–22], and there is a glimpse of the sociology of modern investigators in some of the accounts[19,22].

The dials of the Mechanism

The two concentric dials with scales on the front plate (Fig. 1, left) were used for the display by pointers of the position of the Sun and the Moon and five planets[23,24] on the inner (zodiac) scale. The planetary gearing does not survive (either lost or never fitted), but the actual or intended provision of pointers and a planetary display is clearly inferred[25] from the inscriptions. The scale was fixed and bore the names of the 12 zodiac divisions. The phase of the Moon was shown by a rotating black and white ball, associated with the lunar pointer. The outer (calendar) scale bore the names of the 12 months of the year according to the Egyptian calendar (widely used for astronomy) divided into 365 days, and could be manually rotated to allow correction for the lack of leap years in the Egyptian calendar.

Two plates above and below the circular front dials were inscribed with a parapegma, parts of which survived. This is an almanac[26] of astronomical events — giving the equinoxes and solstices, the Sun entering particular zodiac signs (30 degree divisions of its annual motion through the ecliptic), and characteristic heliacal risings and settings of stars or constellations at dawn or dusk. It was referenced by some 42 index letters inscribed on the zodiac scale. It was divided in four parts, each covering a season and located near to the relevant quadrant of the dial. The content and style of the parapegma[24,26,27] is found to be remarkably similar to that described by the first century BCE writer Geminos[28], which shares both some common elements with older parapegmata[29].

The 'Metonic' upper back dial was a spiral (Fig. 1, right and Fig. 2) that showed the location of the current lunar month within the Metonic cycle of 19 tropical years, which is almost exactly (within two hours) equal to 235 synodic (lunar) months (of 29.53 days). The Moon needs 29.53 days to return to the same phase (for example, from full Moon to full Moon). This cycle establishes the days of

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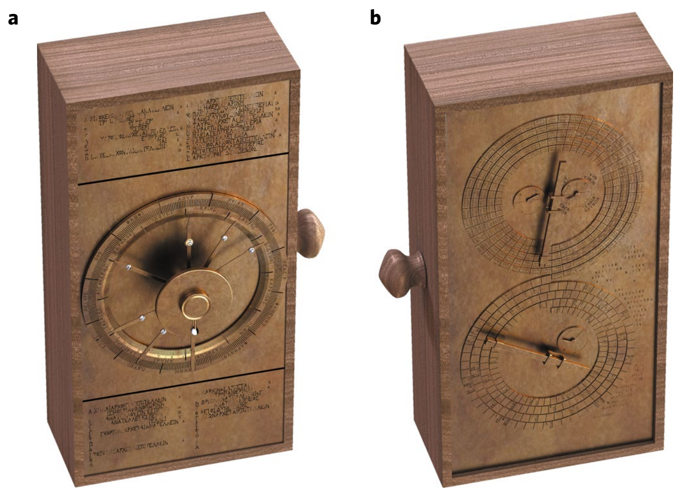

Fig. 1 | A computer visualization of the Antikythera Mechanism. a,b, The front (**a**) and back (**b**) plates, carrying the dials and inscriptions, were protected by removable covers (not shown here), also bearing inscriptions. Credit: Hublot.

full and new Moons — very useful time-reckoning knowledge for agricultural, ritual or nautical activities 2,000 years ago.

The timing of the major Hellenic Crown (Stefanites) Games was set by astronomical tradition. The Olympia (as inscribed on the back plate of the Antikythera Mechanism) competitions began around a full Moon in 'midsummer'— which suggests the first or second month after the solstice[30,31], although there is some uncertainty and it may have been later in the summer. So it is perhaps not surprising that the Antikythera Mechanism should show when the Crown Games were held, as they depended on the phases of the Moon and a lunisolar calendar. The penteteric Olympia Games provided a way of keeping track of years that was independent of the widely varying civil calendars of ancient Greece[32], and it is known that the Olympic Games were used as a stable Panhellenic chronological reference by ancient Greek scholars from at least the fourth century BCE onwards[33]. The four-year games dial inside the Metonic spiral was first recognized by Freeth et al. in 2008[34]. In addition to the Olympic, Pythian, Nemean and Isthmian Games, the dial included the NAIA or NAA Games[34] of the temple of Jupiter at Dodona in northwest Greece and (probably) the Halieia (*ΑΛΙΕΙΑ*) Games[31,35–37] held in Rhodes every four years.

Eclipses repeat in an orderly, periodic manner every 223 synodic lunar months (the Saros cycle). The lower back dial is a spiral displaying this cycle. About 50 or 51 of the 223 lunar month divisions of the lower back dial were inscribed with a 'glyph' of code letters and numbers. 'H' for Helios (the Sun). 'Σ' for Selene (the Moon). The anchor-like symbol (ΩΡ) depicts the first two letters of the word '*ΩΡΑ*' (hour). The rest of the letters represent ancient Greek numbers. When the pointer reached a division with inscriptions (glyphs), the user was warned that, on that month a solar (H) or lunar (Σ) eclipse might take place, reaching its maximum at a particular equinoctial hour[27]. The index letter or letters[27] referred to inscriptions around the dials on the back plate, and gave some further details of the eclipse, with the solar eclipse commentary down the right side and the lunar down the left, and perhaps also at the top of the right side. The eclipses would have to take place at full or new Moon. The Babylonian Saros scheme also prescribes the distribution of eclipses within a Saros cycle. This seems to be well followed by the Antikythera Mechanism for the lunar eclipses. For the solar eclipses, it appears that eclipses occurring too far south of the node were excluded as not visible, in keeping with a practice known in later Greek astronomy.

Box 1 | Place and date of construction of the Antikythera Mechanism

The Mechanism cannot have been built later than the coin-based shipwreck date of within a few years of 60 BCE[57]. The letter style in the inscriptions of the Mechanism initially[42] suggested a construction window of 150–100 BCE, but consideration of the letter style in more complete texts[31] has widened this from slightly before 200 to 50 BCE. An important limit could be set if we knew when the parameters required for the pin-and-slot lunar anomaly mechanism were first deduced. It is known through Ptolemy that Hipparchos did characterize and quantify the anomaly by epicyclic and eccentric models of the lunar orbit, but earlier quantification suitable for mechanical representation is not impossible. This could have been based on Babylonian arithmetic theory — the Babylonians were certainly aware of the anomaly. Requiring that Hipparchos's values be involved must limit manufacture to after he could have begun to be active in astronomy, say at 20 years of age, that is, 170 BCE, but (as mentioned above) the eclipse data on the Mechanism[54,55,78] appears to be fitted best by a Saros cycle that begun in 205 BCE. Aside from the difficulties of dating the eclipse cycles[35], the Mechanism does not have to have been built that early — the data could have been chosen[31] for retrodiction, or simply copied from an earlier model. Unless compared with detailed records, it could be quite a long time before a user would notice any major conflict between eclipse prediction possibilities and the months of actual occurrences. It would be worthwhile to investigate just how long such predictions might actually remain adequate in the context of the possible users. One might have misgivings that the Mechanism could survive usage for more than a few decades — pushing the date of manufacture later, and nearer to the time (sometime during 78–44 BCE) when a similar device was seen in Rhodes[10]. The details of the Metonic calendar[35] and the parapegma[26] very strongly resemble (but are not identical to) those in Geminos's *Introduction to the Phenomena* (ref. [28] and J. Evans, personal communication on the date of its composition), suggesting a close temporal proximity to Geminos's sources. The date of composition of the *Phenomena* is estimated[28] as 90–25 BCE. Overall, we have a preference (echoed by Jones[1] and by Iversen[31]) for a manufacture date within 140–60 BCE, but 205–140 BCE cannot yet be excluded.

Although the particular month names used for the Metonic calendar on the Mechanism are characteristic of the Corinthian colonies of northwest Greece[34,35], the optimum latitude for fitting the phenomena listed in the parapegma is much more consistent with the mid-Mediterranean around 35 degrees[27,35]. The fit seems to exclude Egypt (31 degrees) and the northwest above 39 degrees. Rhodes (36 degrees) remains as the most likely candidate, but all of the evidence is circumstantial. The Antikythera ship may have called there before the wreck[7], it was known as a highly technological naval port with a thriving bronze industry, it was home to Hipparchos, it is the place for which we have a record[2,4,10] of a sighting of a mechanism with comparable functions[7], and it might explain the probable presence on the Games dial of the comparatively lesser Halieia Games[31,35,36], held in Rhodes. The apparent discrepancy of Rhodes with the calendrical implication of the month names is not yet resolved, unless[31] it was being shipped (eventually northwards) after being manufactured there, but retaining a mid-Mediterranean parapegma.

In his pioneering studies, de Solla Price[4,38] only mentions in passing the possibility that the Mechanism included some sort of display of the planets. The problem was the absence of any gearing, presumably due to loss in the shipwreck or before, that could conclusively

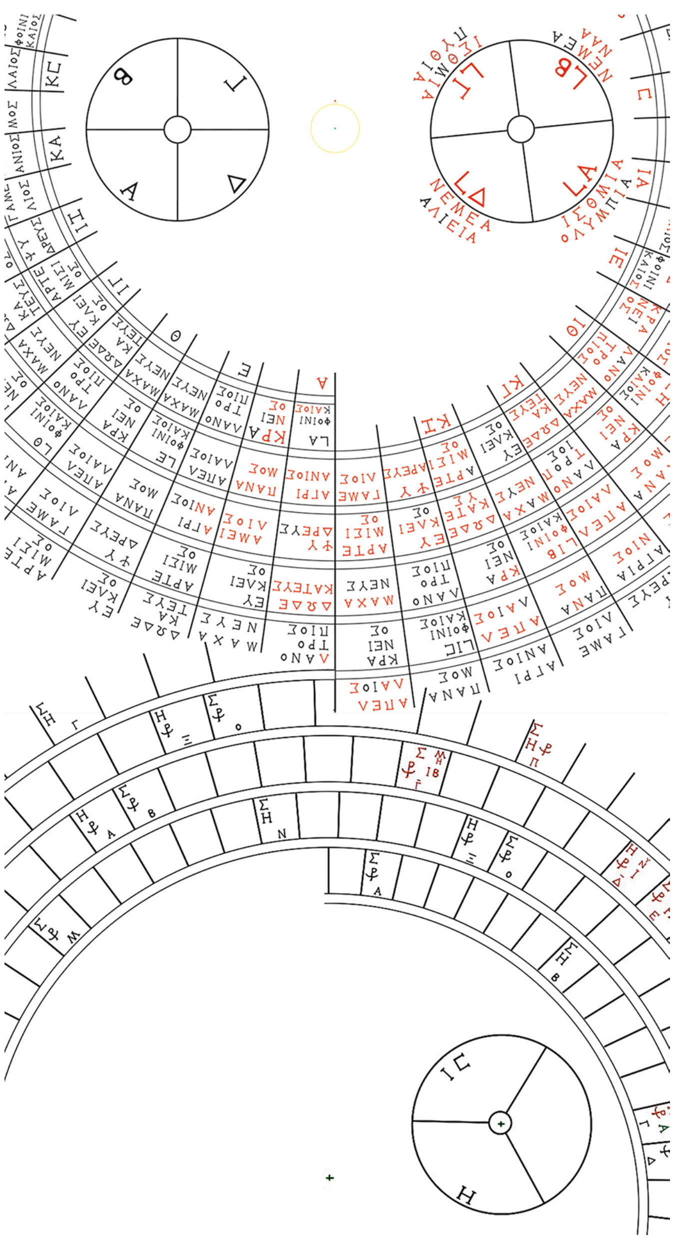

Fig. 2 | Detail of the back plate dials. Part of the Metonic and Saros lunar/solar cycles is displayed. Subsidiary dials showed a four-year Games cycle (upper right), the 3-Saros Exeligmos cycle (lower right) and the 76-year Callippic cycle (upper left), essentially four Metonic cycles. Credit: adapted from ref. [77], Aristotle Univ. Thessaloniki.

be identified as having a planetary function. The full reading of the inscriptions on the front[25] and back[39] covers establishes that, in addition to the display of the Sun and Moon, the positions in ecliptic longitude through the zodiac of the five naked-eye planets (Mercury, Venus, Mars, Jupiter and Saturn) were almost certainly displayed on the front plate in appropriate order[23] by concentric pointers bearing small spheres.

Operation of the Mechanism

A generally agreed arrangement of the gearing has been used in recent reconstructions[34,40]. Without taking into account the planetary pointers and with the simplest possible drive for the lunar phase display, this arrangement includes: 39 gears (29 extant, including 2 crown gears, whose teeth project at right angles to the plane of the wheel, allowing transfer of motion between perpendicular shafts, and 10 inferred gears), 17 shafts, a double axle through the double gear that bears two off-centred axes, several spacers and 7 pointers[41]. Descriptions and diagrams of the gearing are covered in refs[1,2,34,42], and a reconstruction and a functional chart are shown here (Figs. 3 and 4). It is generally believed that the Mechanism was driven by hand from a knob on the side of its box, connected to an extant crown gear, which engaged with the large 'chariot wheel' gear prominently visible in images of the largest surviving fragment, known as fragment A. All the known gear trains seem to derive their drive from this gear. However, recent consideration of torques in the gear chains — and experience with replicas — might suggest[43] that driving from the lunar train would take less physical effort, and could be simply accomplished by turning the whole cylindrical Moon-phase device on the front plate. This would probably hide subtleties of the Moon's motion (described below) and be a much slower way of turning the already very long-period back dials — but a user might resort to it instead of turning the side knob. The drive to the lunar position pointer included a pin-and-slot mechanism[42,44] that reproduced the first anomaly of the Moon's motion (known now to be due to its elliptical orbit around the Earth). The pin-and-slot mechanism[45] consisted of an assembly of four gears, one with an off-centre pin, driving a similar gear with a slot and simulating variations in the Moon's orbital velocity, as seen from the Earth. It may be dangerous to draw conclusions about contemporary knowledge of the parameters of the lunar orbit[46,47] based on the supposed very high accuracy in the measurements of this assembly — the true experimental errors, including the effects of spatial distortion, may be significant.

The two main back plate dials, bearing divisions with inscriptions, displaying the Metonic (235 divisions) and the Saros (223 divisions) lunar-solar cycles[42,48], were five- and four-turn spirals. There are three distinct types of spiral carved on tombstones and colonnades in ancient Greece. Archimedean spirals (A-class), centres spirals (C-class) and logarithmic spirals (L-class)[49]. Analysis of the dial spirals[27,48] proves that they were both C-class spirals with two centres (half-circles spirals), confirming Wright's observation[50]. Wright also commented that the pointer could only emerge from one of the two centres, which would introduce an eccentricity problem to the half circle whose centre is not the pointer centre. The graduations are indeed found[48] to compensate for this effect, while in the remaining half circles, the divisions are equal. Unequal divisions of the front dial have also been reported[51], which could be interpreted as an attempt to take account of the solar anomaly causing the seasonal variation in the number of days between the solstices and equinoxes.

From the sequence of inscriptions, it is now evident[48] that both spirals unwind from the inner to the outer divisions. The pointers of the Metonic and Saros dials slid in a physical slot in the spiral, forcing them to follow the spiral pattern and ingeniously indicating the correct turn to be read. The pointer of the Metonic dial has partially survived with a few remains of the mechanism that supported and rotated it. The original arrangement has been reconstructed (Fig. 5). It shows that the whole pointer actually slid in and out at its hub end[48]. It is believed that the pointers could be reset to the beginning of the spirals. The progression of data on the spirals winds clockwise from the inner to the outer ends, and dimensional arguments suggest that the slots of the two spirals probably ran into each other[5,48].

The divisions on the Metonic spiral (Fig. 2) contain month names. Comparing this calendar with the known calendars of ancient Greek cities, it is found[31,34,35] that it coincides with the calendars of Corinthian colonies in northwest Greece or of Corinth itself. No significant coincidence with the surviving calendars of other major Greek cities (for example, Athens, Rhodes and so on) is found. This indicates that the Antikythera Mechanism was intended for use (but not necessarily constructed) in northwest Greece. The

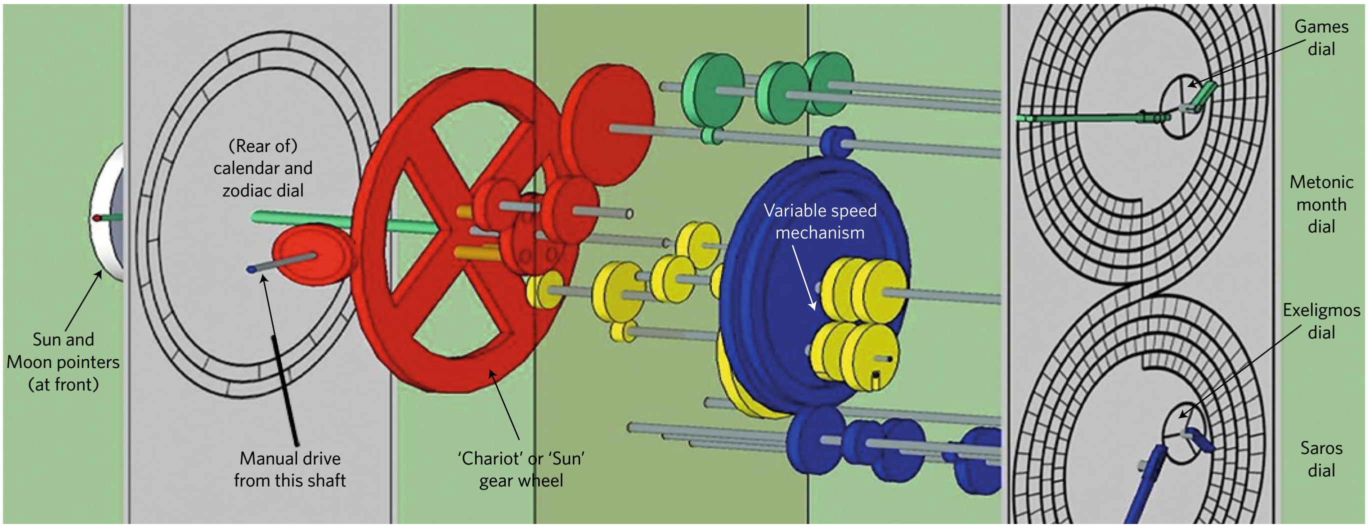

Fig. 3 | An exploded schematic of the known gear trains of the Antikythera Mechanism viewed from the rear. From the side shaft at left, the red gears drive the Sun pointer on the front dial and the other trains. The green and blue gears drive the back dial spiral displays of the Metonic lunar/solar calendar (upper) and the Saros eclipse cycle (lower), respectively. The yellow gears, incorporating a variable speed device, drive the Moon pointer on the front dial. Credit: Antikythera Mechanism Research Project.

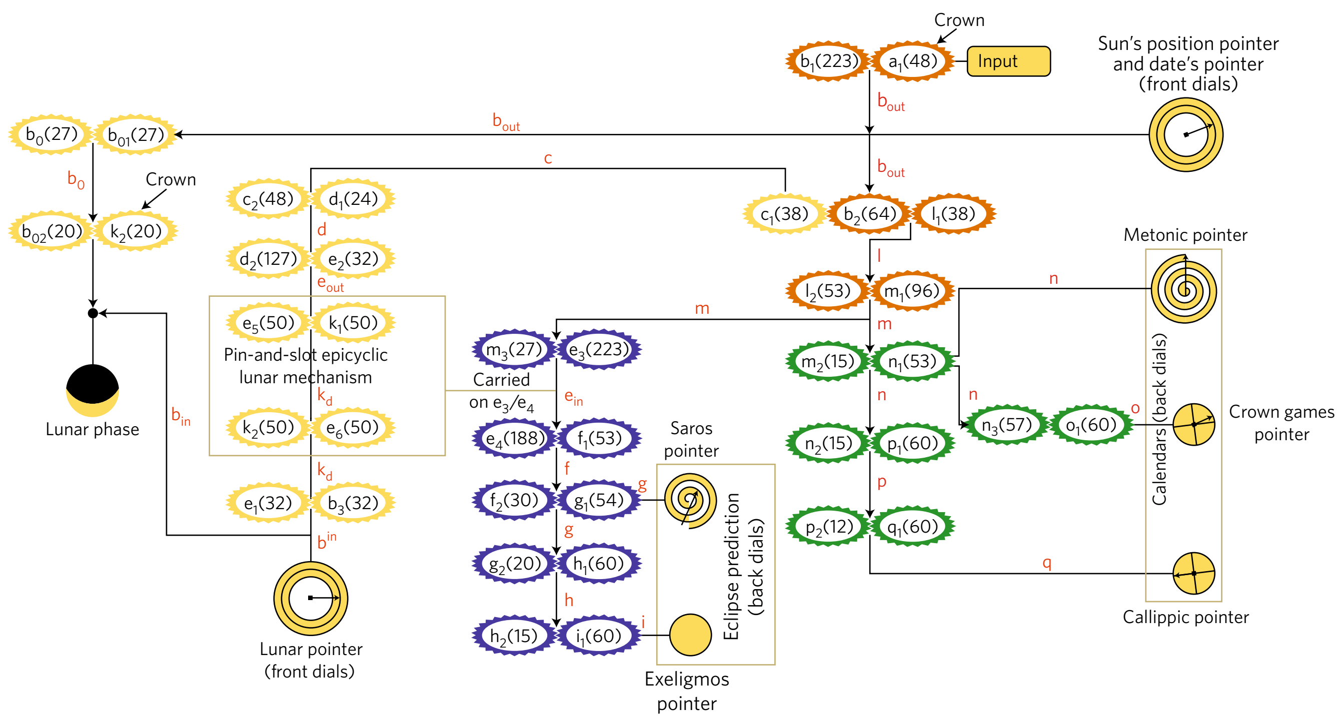

Fig. 4 | A functional diagram of the calendrical, solar and lunar gear trains. There is general agreement on these trains, but the actual form of any trains to represent planetary motion in the original Mechanism remains speculative. The seven pointers as well as the Moon phase sphere are schematically depicted (taken from ref. [41]). The colours match those in Fig. 3. The name of each shaft or axle (a to r) are taken from ref. [42]. The gear pairs are shown with the driving gear first (to the left), then the driven gear, except for the top pair where a_1 drives b_1 and the triple below this where b_2 drives both c_1 and l_1. The front dial double shaft is depicted as b_{in} (lunar) and b_{out} (solar). The tooth count of each gear is shown in parenthesis. The tooth counts, the dimensions and the arrangement of gears b_0, b_{01} and b_{02} are conjectural. They were chosen to provide the correct function, that is, the 29.5-day lunar phase. It should be noted that the pin-and-slot epicyclic lunar mechanism is mounted on gears e3/e4 to reproduce the correct period for the lunar anomaly. [1,42].

closest integer to the 29.53 days of the synodic month would imply a calendar of 12 (civil) months of 30 days each. But, the period of 19 × 12 = 228 months is short by 7 months of the 235-month Metonic cycle. To compensate, 7 of the 19 years should have 13 months (228 + 7 months = 235 months). The 7 'intercalated months' were evenly interspersed among the 235 months of the Metonic period. The intercalated month in the Metonic spiral was chosen to be the month *Machaneus*. But, 19 years × 365.25 days equals 6,939.75 days, whereas 235 months × 30 days equals 7,050 days, longer by 110 days. These days should be evenly (every 64 days =

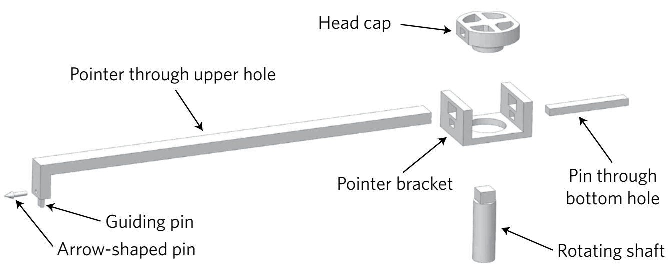

Fig. 5 | Exploded view of the reconstruction of the pointer mechanism. The pointer slid through the upper (larger) holes of a bracket. The whole structure was secured to the rotating shaft with a head cap and a pin through the bottom (smaller) holes of the bracket. The quadrant cavities of the head cup were probably used to smooth the motion of the pointer with a lubricant (perhaps animal grease) or they may have had a decorative role. Credit: adapted from ref. [48], SAGE.

7,050 / 110) excluded from the Metonic period. Both the intercalated months and the excluded days at 64- or 65-day intervals are represented on the Metonic dial[27] in a manner that is extremely close to that described by Geminos[28].

A subsidiary 76-year Callippic dial, with four divisions, was probably located within the Metonic spiral (Fig. 2). Its driving gears have not survived, but their reconstruction is straightforward, and there is good evidence[27] for its existence in the inscriptions of the back cover. The Callippic cycle is four times the period of the Metonic minus one day[39].

The calculation of the positions of the Sun and Moon allowed the Mechanism to be used to demonstrate the phase of the Moon. As mentioned above, the phase was displayed by a device[24] using what appears to have been a half-black, half-white ball in the central hub of the front dial, although there remains considerable uncertainty about its actual gearing and structure[52], since the configuration as it stands in the surviving fragment would not function[24]. But the co-planar lunar and solar position display would not be able to accurately predict eclipses, which of course occur only during times when the Sun and Moon are near the nodes where their mutually inclined orbits cross. There exists an incomplete and rather vague description[53] of a demonstration device attributed to Archimedes that may have shown physical shadowing of one body by another, but the prediction/retrodiction of eclipses in the Antikythera Mechanism relied on the tabulation of known cycles. While it would be possible to turn the drives until the Sun and the Moon pointers were either opposite each other (full Moon) or in-line (new Moon), errors in the gearing (described below) would often cause an error of a day or two in the indicated date. An additional cause of uncertainty in reading a date from the front dial might be caused if the solar anomaly (described above) were not compensated by the form of the dial division spacing[51], or perhaps there was a (now lost) correction mechanism for the solar pointer and a separate date pointer. But again, we have no evidence for the latter. Such uncertainties may not have been too serious for the user, since they would at least be made aware of an eclipse possibility at the new or full Moon. A subsidiary Exeligmos dial within the Saros dial extended the eclipse sequence to three Saros cycles, indicating the 8 and 16 equinoctial hours to be added in the second and third Saros cycles to the eclipse times indicated in the glyphs.

Detailed studies of the origin of the particular eclipse glyph sequence used on the Saros dial were published in 2014[54,55] and 2016[35]. It appears that the theoretical models used by the makers may have included arithmetic progressions (such as Babylonian calculations), and included both lunar and solar anomalies. The conclusion is that the Saros cycle represented is best fitted by an epoch starting with the new Moon of 29 April 205 BCE. A small surviving part of the solar eclipse inscriptions from the right-hand side of the back plate shows four eclipses directions (initial and final), a magnitude and a colour. The direction may be the expected wind direction[35] at the time of the eclipse or, less likely, a direction in which the eclipse occurs[54]. The magnitude is probably the extent of the eclipse, but the colour is not a property previously known to be discussed in Greco–Roman astronomy. It might suggest[35] a link with astrological omens.

The exact form of the gearing for the planetary display is not known, although many ingenious suggestions have been made (see, for example, refs [23,44,56–60]). The complexity of the extant lunar gear train shows that the Mechanism's maker would certainly have had the ability to construct planetary gear trains, and the fragmentary data in the inscriptions[25] includes just enough information to show planetary period relations that are suitable for representation by gearing. The accurate and long-term relations for Venus and Saturn in the front cover inscriptions were not previously known from literary sources. The front cover inscriptions also contain reference to planetary elongation, retrogradation and Venus's variable speed relative to the Sun, implying[25] that the motions were almost certainly represented by simple epicyclic or eccentric models rather than the simplest possible mean-period circular orbits. It remains to be seen whether the interesting but sparse numerical data from the inscriptions will be sufficient to place significant constraints on the actual form of the original planetary gearing.

Performance of the Mechanism

Several physical reconstructions[61–63] of the Mechanism have been made, some including speculative planetary displays, illustrations of which can easily be found in an Internet search. They do function, although mechanical aspects such as the triangular profiles of the gears, copied in some models, can make the motions rather 'jerky', and, additionally, give rise to considerable 'backlash' — annoying slack in the gear trains that can be overcome by driving consistently in a single direction. It is interesting that the introduction of spacers (as observed in the original between some gears) was found to be necessary to render some of the recent reconstructions viable[37,64]. We do not know how long an original Mechanism could function before breakage and probable recycling for its metal. Obviously this would depend on care and usage, but the average lifetime of a mechanism must have been long enough to satisfy customers — otherwise the making of devices could not have persisted over centuries (see below).

In addition to uncertainties in the marking of dial divisions, at least two sources of error will influence the accuracy of the displays. The first source of error we call representational, arising because the design and gear trains are not a perfect model, either because the underlying theory employed is not accurate, or because the theory cannot be accurately modelled at this level of mechanization. Representational errors are likely to have been present in any planetary display. A simple epicyclic model may demonstrate retrograde motion and good long-term representation of planetary periods, but (for example) could be off on any given date by over 30 degrees[23] in positional prediction for Mars — a planet whose large eccentricity and nearness to Earth prevents mechanical simulation that is both simple and always accurate. The second source of error is unintended systematic and random errors during construction, particularly associated with the manufacture and positioning of the gear teeth. An elementary study of the gear trains[65], based on the statistical properties of surviving gears, suggests that (i) the eclipse and Metonic dial indications would have been on average satisfactory enough to identify a month, and hence not to miss (except occasionally) an eclipse given the obvious knowledge that it will occur at full or new Moon; (ii) the lunar drive suffers from bigger errors and could be 20 degrees away from its intended position at some times during the year. This is considerably greater than the

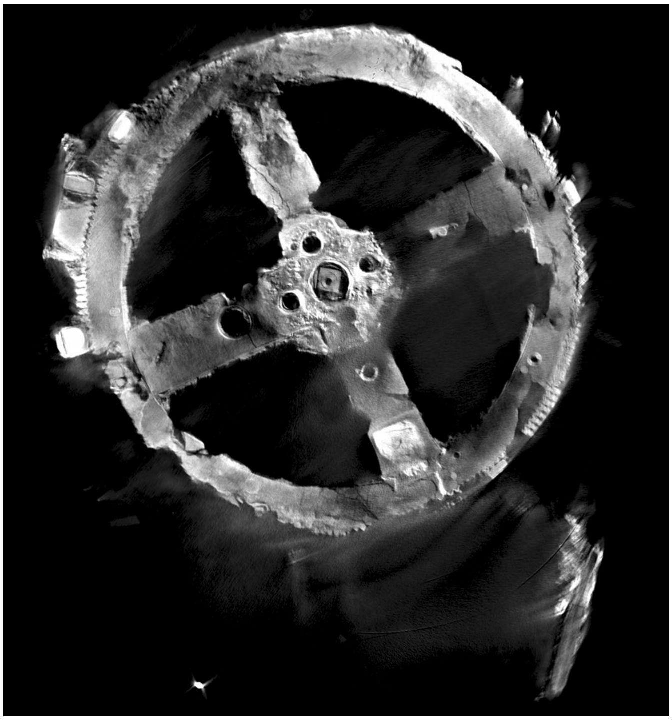

Fig. 6 | X-ray computed tomography slice from the largest remaining fragment (fragment A) of the Mechanism. It shows the 'chariot wheel' gear (b_1), also seen diagrammatically in Figs. 3 and 4. Credit: Antikythera Mechanism Research Project.

amplitude of the lunar anomaly included in the mechanical calculations, and also implies that about half of the predictions of new or full Moon that could be made by requiring that the lunar and solar pointers align would be out by a day or more. These errors should perhaps not be over-emphasized. It remains uncertain what 'accuracy' of the device would actually have been important to its user and potential audience. Perhaps the incorporation of every known astronomical phenomenon[23,52] would have seemed more important than whether it was swamped by errors, particularly if the device was intended as an educational display. However, it does imply that it was not primarily a calculating device for a working astronomer.

The purpose of the Mechanism

We do not know the specific purpose for which the Mechanism was made. The identity of the maker is unknown, but the variety of skills and knowledge required suggests a collaboration between an astronomer/mathematician and a mechanic. The inscription on the back cover is in a different hand to the rest[17], showing that at least two people worked on the machine. The content and language of the inscriptions[25,26,39,48] suggest the intended audience was sophisticated, but neither exclusively nor necessarily specialist astronomers. As speculated above, its intrinsic errors probably rule out its use for detailed calculations. Its use as a display for educational or cultural purposes seems more likely[27]. An attractive suggestion[17,66] is that it represented a 'statement' of contemporary knowledge of the astronomy that would be an impressive and marketable status object, a view that might be re-enforced by a (particularly Pythagorean and Platonic, but probably fairy general) belief that contemplating the immortal Universe gave one a sort of immortality.

A lack of apparent decoration on the Mechanism may be noteworthy, but some symbolism or design convention could be present. The form of the main 'chariot wheel' gear (Fig. 6), whose turn represents one year and has a Saros number of teeth (223 — although 224 cannot be ruled out), may be significant. There is no obvious functional reason for this numerical choice. It can be objected that the form of the wheel would have been hidden from view, and may simply have been dictated by a need for strength to carry other structures (for example, to carry planetary gearing[23]), but the Sun Chariot was a common classical symbol, even appearing on the Parthenon East pediment[67].

Recently it has been shown[68,69] that it is possible to make a conjectural reconstruction of a mechanical display of the planets attributed to Archimedes (287–212 BCE). The existence of geared mechanisms may have acted as a stimulus for planetary theory and mathematics[60], and mechanistic philosophy[2] in the classical World. The extent of the concurrent application of geared technology in other areas deserves further investigation[70]. Application of gears to astronomical mechanisms survived into the Byzantine[3] and Islamic[71] traditions, but the wider fate of the technology is uncertain until the explosion in technical advance with the era of the medieval clocks around AD 1300. That explosion can currently be interpreted either as a re-invention[1] or the continuation of an almost-hidden tradition[2,72], although there is epistolary evidence that later astronomers, such as Kepler[73], were well aware of the Greeks' mechanical astronomical displays.

Future work

A particular fragment of the Mechanism (fragment D)[42] remains a mystery. It contains a well-preserved gear with 63 teeth — perhaps suitable for a Mercury[74] or other planetary mechanism — and a strange, bean-shaped bronze piece. No reconstruction has included this in a satisfactory way, although remarkably the bronze piece has a shape that would enable it to act as a cam in a mechanical arrangement[75] that would display the effects of 'the equation of time' — the difference between time as measured by a sundial and a mean solar time, essentially the solar anomaly recognized by Ptolemy.

Based on existing modern X-ray imaging, a full set of dimensioned mechanical drawings or three-dimensional computer-aided design (3D CAD) files of what survives would be valuable, to check the veracity of the reconstructed gear trains, and reveal more of the detail of the engineering. We already know there are spacers and complex shafts, one with a pentagonal section. More work on the actual accuracy of the device could be pursued with faithful reconstructions. Detailed metallurgy of the fragments would be interesting, perhaps by non-invasive multi-energy X-ray or neutron[76] tomography.

The new dives on the shipwreck[19] may provide fresh material, and there is always hope that some unrecognized geared device (or part of one) might be lying in a museum store or private collection. For context and development, literature sources can be pursued, particularly later Arabic translations or accounts.

The Antikythera Mechanism is a unique testament to the astronomical and technical ability of the ancient Greeks. It has become much better-known to the public in recent years, and they have responded with interest and fascination. It no longer seems anachronistic, and continues to enrich our view of classical culture.

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