“Like Opening a Pyramid and Finding an Atomic Bomb”: Derek de Solla Price and the Antikythera Mechanism[1]

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The present article is, in a sense, a review—60 years on—of an American Philosophical Society research grant and its outcomes. In 1958, the Society awarded Derek John de Solla Price (1922–1983) Grant No. 2379, to the amount of $460, for a proposal entitled “Examination of the Fragments of the ‘Antikythera Machine.’”[2] Price’s modest request was to fund his return flight from Copenhagen to Athens and 10–12 days’ living expenses in Athens.[3] The Society’s grant made possible, in the short term, the first substantial breakthroughs in the study of a curious but hitherto rather obscure archaeologically recovered artifact. In the longer term, it set in motion successive trains of research that have led to a detailed and reliable reconstruction of what we now appreciate to be the most complex scientific instrument from the ancient world. More broadly, this research has made, and continues to make, a pronounced impact on the study of Greco-Roman mechanical technology and astronomy, as well as on the calendrical practices of Greek communities, and it has even conferred upon the Antikythera Mechanism an unlikely notoriety in popular culture.

Discovery and Early Research on the Antikythera Mechanism

The extant fragments of the Antikythera Mechanism (National Archaeological Museum, Athens, inv. X 15087) were among the objects

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[1] Read 9 November 2017.

[2] For Price’s report on the grant, see Price, “Grant No. 2379.” The proposal is in the American Philosophical Society’s archives; I am grateful to Charles Greifenstein for providing me with a copy.

[3] Price was probably in Copenhagen that summer for family reasons; his wife was Danish.

recovered in 1900–1901 at the site of a Hellenistic shipwreck off the island of Antikythera, in the straits between the Peloponnese and Crete.[4] This work, the first underwater archaeological salvage of an ancient shipwreck, was carried out by sponge divers from Symi working under the supervision of archaeologists of the Greek Ministry of Education and Religious Affairs. The discoveries from Antikythera aroused intense interest both in Greece and abroad because they included high-quality—albeit fragmentary—bronze statues, marble statues, and other *objets de luxe*.

Reportedly, the mechanical fragments were brought out of the sea late in the campaign, perhaps in June 1901, but they first came to scholarly and public notice nearly a year later.[5] As narrated at the time in several Athenian newspapers, Spyridon Stais (1859–1932)—a former mathematics teacher and politician who, as minister of education, had negotiated and overseen the operations at Antikythera—drew attention, during a visit to the National Archaeological Museum on either May 18 or May 20, 1902, to two "slabs" of corroded metal that were among a number of small, unidentified scraps of bronze from the wreck.[6] Visible on the surfaces of this pair of fragments were mechanical features—toothed gear wheels—and inscribed Greek letters.

From the early newspaper reports we learn that discussions among archaeologists and other historically minded people in Athens during those first days centered on two questions: What was the nature of the

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[4] For the broader story of the Mechanism's discovery and subsequent research up to the present, see Jones, *Portable Cosmos*, 1–46. Documentation is provided there for the present section's narrative.

[5] Dates relating to the discovery and early study of the Mechanism in Greece are given in the Julian calendar, which remained the civil calendar in Greece until 1923. For equivalent Gregorian dates, add 13 days.

[6] Inaccurate information is widespread about the circumstances of the Mechanism's discovery, in particular the claim that it was first noticed in the National Archaeological Museum on May 17 and not by Spyridon Stais, but rather by his cousin Valerios (e.g., in the Wikipedia article "Antikythera Mechanism" as of May 19, 2018, and a Google Doodle issued May 17, 2017). The pre-1920s sources, including many newspaper articles from May 1902 and even an article by Valerios himself (*To Asty*, December 13, 1902, 1–2), unanimously state that it was Spyridon who first noticed the fragments. Only one (*Estia*, May 22, 1902, 4) says that Spyridon made this discovery "with the Ephor of Antiquities of the Museum" (*scil.* Valerios); given the frequent inaccuracies in the newspaper reports, this would be a tenuous basis for assigning Valerios a significant role in the discovery (as does Trimmis in "Forgotten Pioneer," 5). The false May 17 date was derived by Price (*Gears from the Greeks*, 1974, 9) from a report in an Athens newspaper (*To Asty*, May 23, 1902, 1) that the discovery was made "last Saturday," but Price did not realize that the dates were Julian. He does identify the discoverer here as Spyridon Stais (though he wrongly characterizes him on page 8 as a "prominent archaeologist"), but previously he had given Valerios the credit (Price, "Ancient Greek Computer," 61). The first newspaper reports from May 21 and 22, which Price seems not to have seen, imply that Spyridon's visit had taken place on Monday, May 20, so the subsequent specification of the day as Saturday seems likely to be a correction.

device? And could a date be determined for the letter forms in the inscriptions? There was actually wider interest in dating the inscriptions than in reading them, on account of an ongoing controversy between Ioannis Svoronos (1863–1922), the director of the Numismatic Museum, and archaeologists of the Ministry of Education, including the director of the Archaeological Museum, Valerios Stais (1857–1923), who incidentally was Spyridon Stais's cousin. Although the consensus among the archaeologists was, correctly, that the wreck was of Hellenistic or early Roman date, Svoronos maintained that it was from the reign of Constantine (early fourth century AD).

Outside Greece, popular and scholarly publications reported and discussed the statues from the seabed, but there was scarcely any mention of the mechanical object.[7] The first publication providing information about it that was at all likely to be seen by foreign scholars able to read Modern Greek was an anonymous survey of the Antikythera findings in the 1902 volume of the leading Greek archaeological journal, *Efimeris Arheologiki*.[8] This article, the work of a group of ministry archaeologists, describes it merely as a "bronze machine consisting of many gears . . . similar to a modern clock." The inscribed text is said to have provided instructions for use of the machine, "which most probably was astronomical," though a complete interpretation had not yet been obtained. The single photograph (of the fragment subsequently designated "B") shows a face bearing text but no mechanical features.

In 1903, however, Svoronos produced a detailed presentation of the Antikythera finds, in the form of a set of plates accompanied by a book published simultaneously in Greek and German language editions.[9] Embedded within Svoronos's catalog of the objects is a nine-page section headed "The Astrolabe of Antikythera," written by Periklis Rediadis (1875–1938), who was a lieutenant of the Greek navy and professor of geodesy and hydrography at the Royal Naval Academy. Rediadis described four fragments, assigning them the Roman letters A through D by which they are still known, and argued that the original instrument was a kind of astrolabe in which the gearwork served a function similar to the stereographic projection employed by conventional medieval astrolabes. The plates include photographs of both faces of all four fragments (Figure 1).

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[7] The May 1902 discovery was tersely reported in *The Standard* (June 7, 1902, 7). The earliest mention I know of in a scholarly publication outside Greece is Vicars ("Rescued Masterpiece," 562).

[8] Anonymous, Τὰ εὑρήματα.

[9] Svoronos, Ὁ Θησαυρὸς; and Svoronos, *Die Funde*.

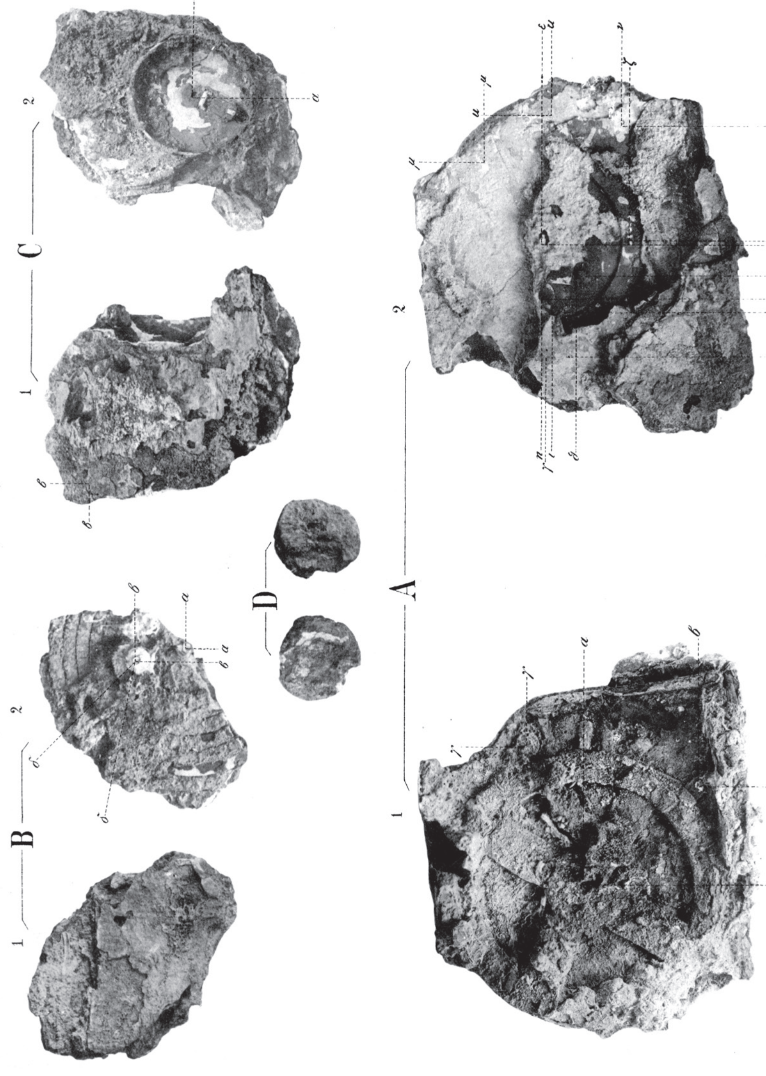

Figure 1. Plate X from Svoronos's *Die Funde von Antikythera*, showing the four fragments of the Antikythera Mechanism known in 1903 before cleaning and removal of accretion layers and bits of the Front and Back Cover plates.

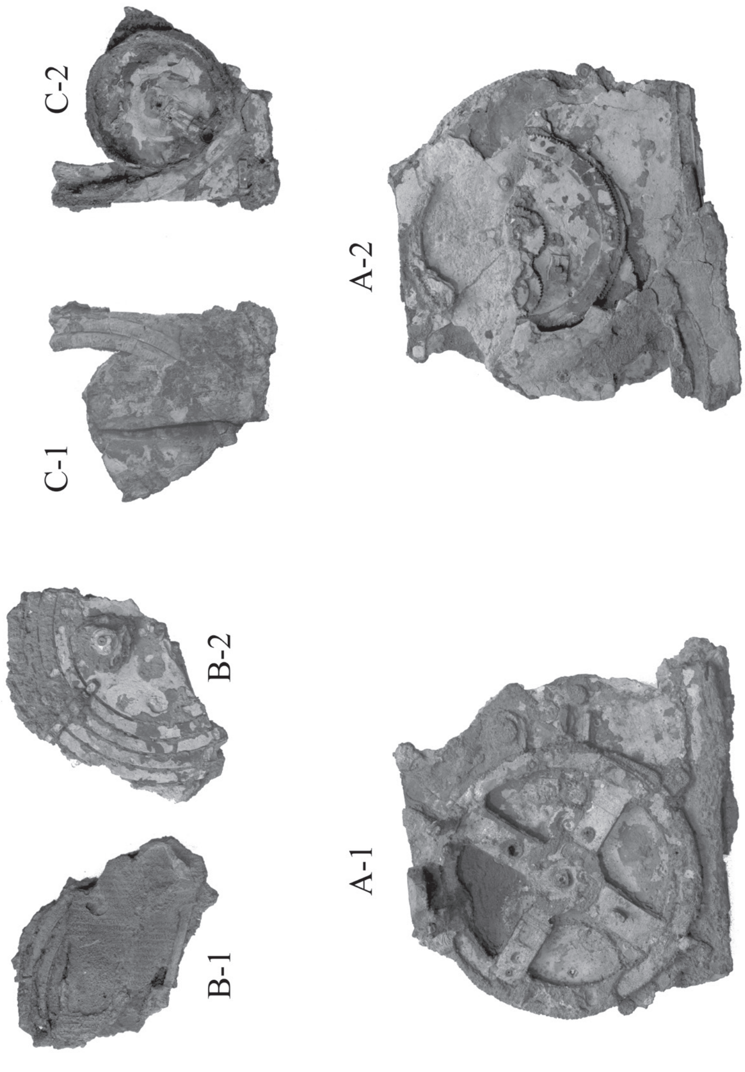

Figure 2. Photographs of Fragments A, B, and C, probably from the 1960s or early 1970s. The fragments are arranged to match the orientations in Figure 1 for convenience of comparison. The labels indicate the original orientations in the Mechanism. Permission from German Archaeological Institute, D-DAI-ATH-Emile 826 and D-DAI-ATH-Emile 827. Photos by Émile Seraf.

Despite the international distribution of Svoronos's monograph, it did not inspire much interest in the mechanical fragments. For the most part, foreign reviews did not even mention Rediadis's excursus.[10] The only account of any significance that I know of—in a language other than Greek—that was based directly on Rediadis's is in Robert Gunther's 1932 *Astrolabes of the World.*

The young philologist and epigrapher Albert Rehm (1871–1949), who had a special interest in Greco-Roman astronomical instrumentation, must have come across Rediadis's description soon after its appearance (there are reprints of both the German and Greek versions in Rehm's *Nachlass*, now in the Bayerische Staatsbibliothek, Munich). Rehm examined the fragments in Athens during two visits in 1905 and 1906, and he argued that the instrument was in fact a planetarium (i.e., a mechanical simulation of the apparent motions of the sun, moon, and planets) in two essays that he never published, though the second was presented on his behalf by Georg Karo at a meeting of the German Archaeological Institute in Athens in 1906.[11] Through private communications, Rehm's planetarium hypothesis got some modest diffusion (in particular in two books by Ernst Zinner) but the often insightful details of his investigations languished in his files.[12]

Even in Greece interest in the fragments lapsed after about 1910, although they (or at least some of them) were put on public display in the rotunda of the Archaeological Museum alongside small bits of bronze statuary, glassware, and fragments of furniture from the Antikythera wreck. The sole person who took a strong interest in them in the 1920s and 1930s was another naval officer, Ioannis Theofanidis (1877–1939), who published new descriptions and speculations concerning them (in Greek and French) and even attempted a physical reconstruction of the Mechanism, as a kind of planetarium that survives in dismantled state.[13] Theofanidis's articles were difficult to follow, and sometimes inaccurate, and they did not bring about any immediate surge of awareness of the fragments among other scholars.

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[10] The conspicuous exception is Rehm, "P. Rediades," which is *specifically* a (rather negative) review of Rediadis's section in its German edition.

[11] Rehm, "Meteorologische Instrumente"; and Rehm, "Athener Vortrag." An account of Rehm's theory, based on Karo's 1906 presentation, appeared in Greek in Rados, Ναυτικαὶ καὶ Ἀρχαιολογικαὶ Σελίδες, 34–36.

[12] Zinner, *Geschichte der Sternkunde*, 111; and Zinner, *Entstehung und Ausbreitung*, 48–49. Rehm also had briefly suggested the planetarium idea in his review of Rediadis (Rehm, "P. Rediades," col. 470), promising a subsequent publication on the topic.

[13] Theofanidis, Ἁγίου Παύλου; Theofanidis, "Sur l'instrument"; and Kaltsas, Vlachogianni, and Bouyia, *Antikythera Shipwreck,* 251, fig. 15.

Present Fragments and Current Consensus Reconstruction

At this point it will be helpful to say something about the history of the fragments in the Archaeological Museum from 1902 up to the present, as well as the current broadly accepted reconstruction of the Mechanism's appearance, functions, and workings.[14] Since 2005 the identified remains of the Antikythera Mechanism have comprised 82 fragments: seven "major" pieces designated by Roman letters A through G, and 75 "minor" fragments designated by numbers 1 through 75.[15] Fragments A, B, and C had been on public display in the museum's bronzes galleries since the 1970s, while the then curator of the bronze collection, Mary Zafeiropoulou, found the rest in 2005 collected in a tray in the museum's storage. It is not known who assembled the fragments in the tray, or precisely when, though it must have been since the mid-1970s, and probably after 1994.[16]

The present Fragments A–D are essentially the Fragments A–D of the Svoronos-Rediadis 1903 publication. I say "essentially" because the surfaces of A, B, and C have largely been cleaned of patina, and bits of A and C have been deliberately separated from the main fragments or have broken off. (See Figure 2 for photographs of A, B, and C in their state around the time Price examined them, which is also very nearly their present state.) A, B, and C were the fragments originally noticed in May 1902, while D must have come to light a little later. Fragments E and F were unknown until much more recent times: E seems to have been found somewhere in the museum's storage in 1976, while F first showed up in the mysterious tray in 2005. All six of these major fragments contain mechanical components or parts of display dials and inscribed metal plates, and there is practically no doubt that they all came from the same object.[17]

Fragment G and the minor fragments 19–29, 37–44, and many if not all of the very tiny fragments 45–75 were incorporated in Fragments A and C in their 1902 states; these are all bits either of inscribed plates or of layers of material that accreted against inscribed plates, thus preserving offsets of them. Some were intentionally separated

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[14] For further details on the fragments, see Jones, "Inscriptions of the Antikythera Mechanism," 38–50; and on the reconstruction, see Jones, *Portable Cosmos*, 47–62, 208–223.

[15] For photographs of all 82 fragments, see Freeth et al., "Decoding the Ancient Greek," 587, fig. 1, with key in Supplementary Information 2.

[16] Michael T. Wright and Allan Bromley, who studied the fragments at the museum during a series of years up to 1994, knew nothing of such a tray or some of the fragments it held in 2005.

[17] Physical joins are established for A, B, and E. Wright has suggested that D might have come from a different device (Harris, "Into the Deep," 19).

around 1905 during the first major round of conservation on the Mechanism's fragments, while others seem to have resulted from accidental breakage. Their existence as separate fragments can be verified from photographs taken by Price in 1958.[18] Price refers to a few of these fragments in his publications and unpublished notes, sometimes using nicknames such as "jigsaw" (our Fragment G) and "curled" (Fragment 21), but he produced no comprehensive list or system for identifying them.

Fragments 1–18 and 30–36 were unknown before 2005. Among them, Fragment 9 is a piece of inscribed plate that definitely belonged to the Antikythera Mechanism. None of the others has yet, to my knowledge, been shown to have features confirming that it came from the Mechanism.

Figure 3 shows the reconstruction of the Mechanism's exterior layout that has achieved broad acceptance in recent years. It was box-shaped, with its bronze front and back dial faces about 17 cm wide and 32 cm tall; the front-to-back depth is uncertain but was surely not fewer than 10 cm. The sides, top, and bottom are believed to have been wooden, with the right side perforated so that some sort of drive, probably a knob or crank (*A*), could impart motion to the gearwork. The front face had a single large dial, with two concentric ring-shaped scales respectively divided into the 12 signs and 360 degrees of the zodiac circle (*B*), and into the 12 months and 365 days of the ancient Egyptian calendar (*C*). (The calendar dial could be manually taken off and replaced in any orientation relative to the zodiac since the Egyptian year, lacking leap days, gradually shifted relative to the natural year.) Pointers embellished with small spheres (*D*) indicated the zodiacal longitudes of the sun, moon, and (probably) the five planets known in antiquity, and a small parti-colored ball (*E*) displayed the moon's phases. Above and below the dial was the "Parapegma Inscription" (*F*), a list of annually repeating phenomena relating to the sun, zodiacal signs, fixed stars, and constellations. Turning the input drive clockwise would simulate going forward in time, at a rate of roughly 78 days per turn, and the gearwork would cause the pointers and the lunar phase ball to revolve with motions appropriate for the heavenly bodies that they represented.

The back face had two large dials, in an unusual spiral format, and likely had three small circular dials. Each spiral was formed by a slot composed of semicircles of progressively increasing diameters; a pin

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[18] Photographs in the Price archive at the Adler Planetarium, Chicago. Some of these inscription fragments are identifiable from earlier photographs, Rehm's notes, and Theofanidis's publications. Fragment G was reassembled from many smaller fragments of an inscribed plate that was originally stuck on the front face of Fragment C.

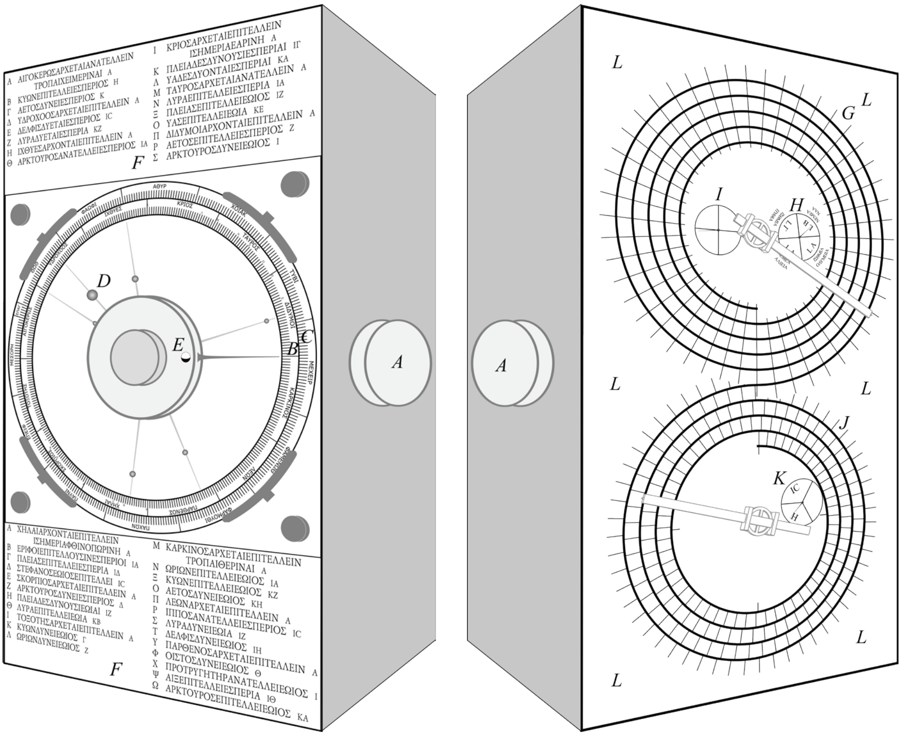

FIGURE 3. Reconstruction of the exterior of the Antikythera Mechanism according to the present state of research.

near the end of a variable-radius pointer slid along the slot, so that the pointer indicated a particular place on the scale that wound along the exterior edge of the slot. (When the pointer had completely traversed the spiral, it would have had to be reset to the beginning manually.) The upper spiral (*G*) had five complete turns, and represented a "Metonic" 19-year lunisolar calendar cycle subdivided into 235 cells inscribed with the names of the lunar months of a Greek regional calendar. Inside this spiral, a subsidiary dial (*H*) represented a four-year cycle inscribed with the names of Greek athletic festivals, such as the Olympic Games, that were held at intervals of two or four years. A second subsidiary dial (*I*) is conjectured that represented a 76-year "Callippic" calendar cycle comprising four 19-year cycles, the minimum multiple that also was an integer number of days (presuming the solar year is 365 1/4 days).

The lower spiral (*J*), with four complete turns, represented a 223-lunar-month Saros eclipse cycle, and some of the 223 cells of its scale were inscribed with abbreviated predictions of solar and lunar eclipses. A subsidiary dial (*K*) displayed a 669-month triple Saros, or

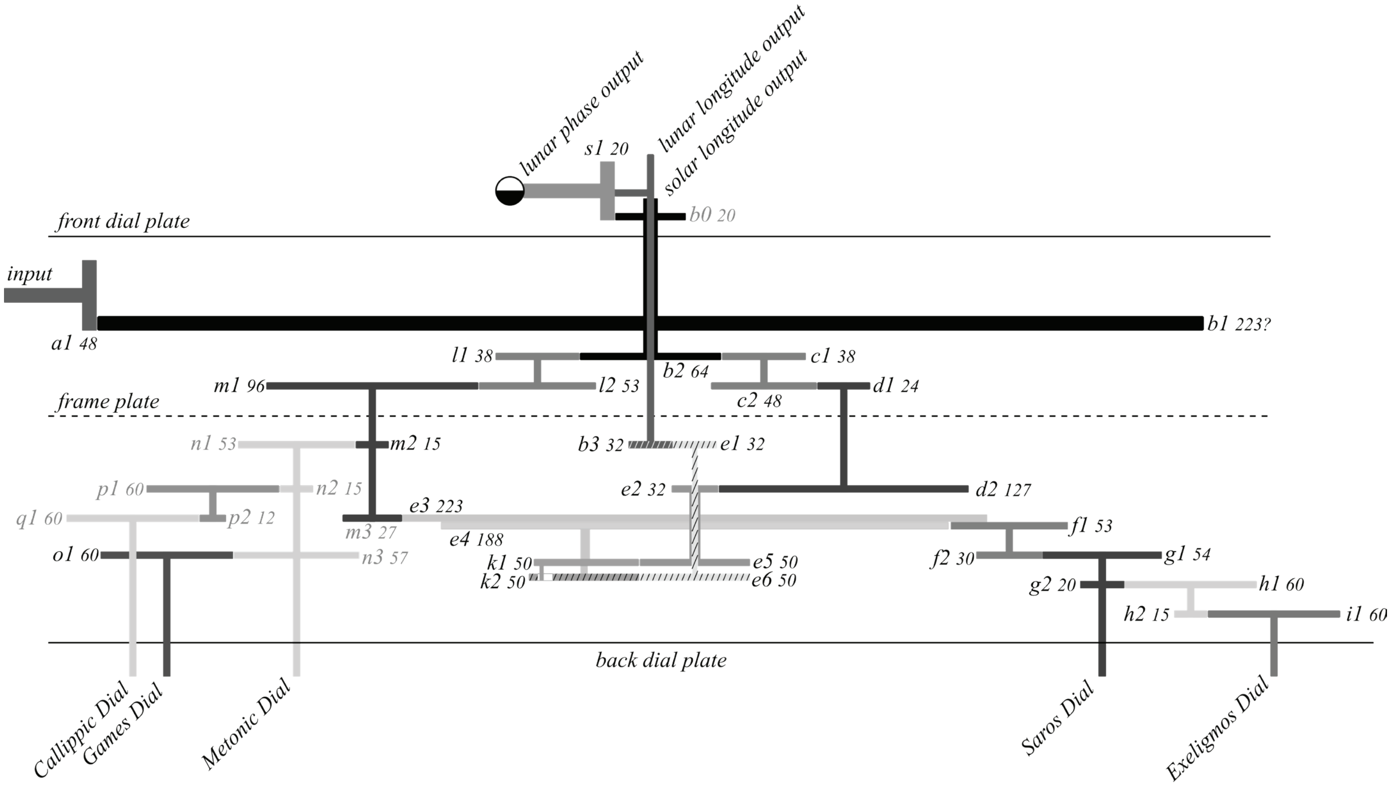

FIGURE 4. Schematic diagram of the reconstructed gearwork of the Antikythera Mechanism. Gear identifiers follow Freeth et al., “Calendars with Olympiad Display,” Supplementary Note 22, Supplementary Fig. 14. Missing gears are indicated by identifiers in gray type. Hatched gears revolve nonuniformly relative to *a1*.

"Exeligmos," period, the minimum multiple that also approximated an integer number of days. Inscribed texts in the spaces around the spirals (*L*), the "Back Plate Inscription," provided additional information relating to the eclipse predictions.

The gearwork that translated the single input motion representing time into the multiple output motions was housed in an inner wooden casing and mostly mounted on a metal frame plate parallel to the front and back faces. Except for two crown gears (*a1* at the input, *s1* driving the lunar phase ball), all extant gears are circular gear wheels with triangular teeth, situated in planes parallel to the faces and frame plate (Figure 4). The securely reconstructable part of the gearwork, which drove all the back dials as well as the solar and lunar longitude pointers and lunar phase ball, accounts for 29 of the surviving 30 gears—the exception is an isolated gear in Fragment D—and requires (at a minimum) eight additional gears that are entirely lost but can be restored with high confidence.[19] In addition to simple gear engagements by means of their teeth, the Mechanism incorporated more sophisticated devices. These included an epicyclically mounted crown gear (*s1*) serving as a differential, to obtain the lunar phase by subtracting the sun's from the moon's motion in longitude, as well as a system of gears epicyclically mounted on the fused pair *e3-e4* and involving another pair, *k1-k2*, whose axes were slightly displaced relative to each other, with *k1* driving *k2* by means of a pin riding in a radial slot, thus introducing a periodic anomaly in the moon's longitudinal motion.

It is very strongly suggested that the Mechanism also had a display of pointers on the front dial to indicate the longitudinal motion of the five planets known in antiquity (Mercury, Venus, Mars, Jupiter, Saturn), in the first instance, by two texts that were inscribed on plates that accompanied the Mechanism, possibly functioning as protective covers. The Back Cover Inscription, in a passage that appears to describe the front displays, names certainly four, perhaps all five, of the planets together with the sun in connection with pointers and little spheres, whereas the Front Cover Inscription contains a detailed description of the periodicities and cycle of synodic phenomena of the planets. Moreover, although with the possible exception of the isolated gear in Fragment D there is no surviving planetary gearwork, physical elements in Fragment A—especially on the large spoked gear *b1*—show that some significant part of the inner workings of the Mechanism that originally

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[19] This minimum assumes that there was no mechanical simulation of solar anomaly and that Wright's reconstruction of the lunar phase gearwork is correct, notwithstanding that it requires that the crown gear in Fragment C was erroneously installed pointing the wrong way.

lay in front of *b1* is missing. References to retrogradations in the Front Cover Inscription imply that the planetary pointers would have moved with varying speeds and reversals of direction, effects that could have been produced using slotted arms or pin-and-slot couplings similar to the preserved lunar anomaly apparatus. The available evidence, however, is not sufficient to establish any specific reconstruction as correct.

Price's Work up to 1958

Writing a quarter century after the event, Price recalled first taking serious notice of the fragments in 1951.[20] This would have been during the first year of Price's second program of doctoral study in Cambridge University's Faculty of History. Previously he had taken a Ph.D. in physics as an external candidate at the University of London, followed by a research fellowship in Princeton and several years as a lecturer in applied mathematics at Raffles College, Singapore; it was while at Raffles College that he came to be attracted to the history of science.[21] Price's initial research topic at Cambridge was "the history of scientific instrument making," and his interests in that direction were quite broad, though most concentrated on astronomical instrumentation such as astrolabes, armillaries, and equatoria—his 1954 Cambridge dissertation was to be an edition of a medieval English text on an equatorium that he identified as an autograph work of Chaucer's. His early awareness of the fragments from Antikythera must have arisen in the context of his research on the topic of early clockwork and gearwork, which also led to an intense collaboration with Joseph Needham and Wang Ling on early Chinese clockwork, beginning in 1954.

At this time Price was familiar with the handful of publications in German, French, and English describing or referring to the fragments (by Svoronos-Rediadis, Theofanidis, Gunther, and Zinner). Svoronos's plates gave the only full set of photographs of the principal fragments, but showed them in their pre-conservation state when they were still covered with layers of rough patina that obscured or concealed the mechanical elements; additionally, Zinner had published photographs of one face each of Fragments A and C, which were of better quality and, in the case of Fragment A, revealed more mechanical detail exposed by chemical cleaning around 1905. Meanwhile the fragments, like all the antiquities in the National Archaeological Museum, had been deposited in safe storage during the Second World War, at which

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[20] Price, *Gears from the Greeks*, 1974, 12.

[21] Beaver, "Price, Derek John deSolla."

time they appear to have undergone the accidental damage mentioned above (especially severe in the case of Fragment C). In 1953 Ioannis Bakoulis, a highly regarded archaeological conservator, carried out a fresh round of cleaning.[22] Hence a new set of photographs of Fragments A, B, and C that Price obtained from the museum exhibited them in a considerably different state and revealing new detail, including a pair of concentric dial scales graduated into degrees and into the months and days of the ancient Egyptian calendar.[23]

In several surveys of the early history of gearwork devices that he wrote in the 1950s, similar in content but for a different kind of audience, Price presented the Mechanism as an exciting, unexpected, and inadequately studied artifact that nevertheless proved—presuming it was genuine!—that the Western tradition of clockwork originated in classical antiquity.[24] While emphasizing the complexity and apparent sophistication of the mechanical elements visible in the photographs, and the refinement of the graduated scales, he was cautious with respect to the purpose of the Mechanism, beyond saying that the inscribed texts established that it was "concerned with the motion of the planets and the rising and setting of the stars."[25]

Price's first attempt to study the Mechanism firsthand took the form of an application to have the fragments brought to London for the sake of conservation and research in the British Museum's Research Laboratory, then headed by Harold Plenderleith.[26] The request was refused by the Greek government, an outcome that Price blamed on counterproductive regulations in combination with the current tensions between the Greek and British governments connected with the status of Cyprus. With hindsight one might be relieved that the extremely fragile fragments, consisting almost entirely of corrosion products with little free metal remaining, were not subjected to the long journey and possibly destructive treatment.[27]

The next developments in Price's career took him still further from Athens and, for a while, from the prospect of examining the

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[22] Ἐλευθερία, January 11, 1959, 11.

[23] Price, "Ancient Greek Computer," 63; and Price, *Gears from the Greeks*, 1974, 12. The former gives 1955 as the date when the museum provided the photographs, whereas according to the latter it was in 1953.

[24] Price, "Clockwork before the Clock," 1955–1956, 32–34; Price, "Prehistory of the Clock," 157; Price, "Precision Instruments," 618; and Price, "On the Origin of Clockwork."

[25] Price, "Clockwork before the Clock," 1955–1956, 33.

[26] Price, "Clockwork before the Clock," 1955–1956, 33, note 18.

[27] Plenderleith, *Conservation of Antiquities*, 232–55, might offer some clues to how he would have handled the Antikythera Mechanism. The best course, in retrospect, would have been to aim for stabilization without attempting further removal of material, and this was evidently accomplished by the National Archaeological Museum's technicians.

Mechanism. In 1957 he came to the United States as a consultant for the planning of the hall of physical sciences for the Smithsonian's new Museum of History and Technology (the present National Museum of American History). This was followed by two successive appointments as a member of the School of Historical Studies at the Institute for Advanced Study (IAS) in 1957–1959. Otto Neugebauer (1899–1990), the preeminent historian of ancient astronomy and a long-term member of the IAS, seems to have been instrumental in bringing Price to Princeton, and he was also in support of Price's application for the American Philosophical Society grant to travel to Athens during August 1958.

In contrast to his noncommittal published remarks, Price gave a surprisingly definite view of the nature of the Mechanism in his application statement: "I have been able to determine that it was a planetarium, perhaps similar to that said to have been made by Archimedes." During the 10–12 days that he would be in Athens, Price proposed to examine the fragments directly, make photographs and X-ray radiographs, and, if possible, arrange for "partial cleaning and restoration of the fragments." He had secured an offer of the museum's cooperation from its director, Hristos Karouzos, and (probably through Benjamin Dean Meritt of the IAS's faculty) could count on assistance, if needed, from the American School of Classical Studies at Athens.

In the end he spent 10 days in the museum. At this time the fragments, as they were then known, were not on public display but stored in shallow boxes, some of which can be identified as cigar boxes from Price's photographs. Price was provided with work space where he could examine, handle, measure, and photograph them. He was unable to obtain X-ray images because of the lack of equipment (or indeed sufficient electricity to operate such equipment); however, in all other respects he accomplished almost everything that he had hoped for. In fact the great part of the detailed materials on the Mechanism that he eventually published in the 1970s and that did not depend on radiography resulted from this visit or from a follow-up visit in June 1961.[28]

Price was the fourth scholar, after Rediadis, Rehm, and Theofanidis, to make a close inspection of the Mechanism's fragments, but he had considerably more experience with early scientific instrumentation than his predecessors, and this helped him know what to look for and how to interpret what he saw. But the chief reasons that he was able to advance the study of the Mechanism far beyond anything achieved up to then were two crucial insights. Firstly, he realized that earlier investigators had been much too pessimistic about the relation between what

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[28] The 1961 visit was assisted by a grant-in-aid from the American Council of Learned Societies under the project title "Examination of Ancient and Medieval Scientific Instruments."

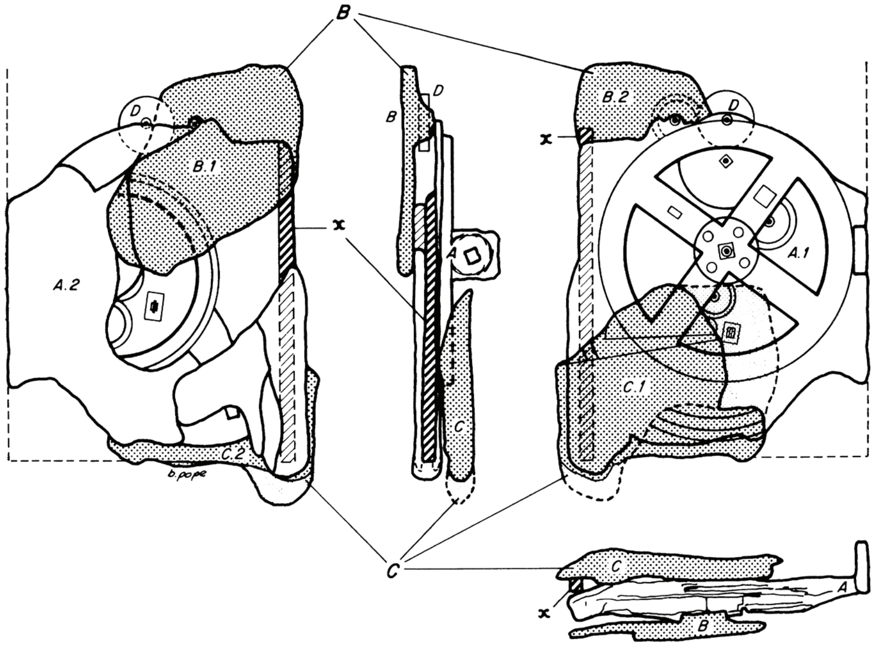

FIGURE 5. Price's diagram showing how he believed that Fragments A, B, C, and D were originally situated in the Mechanism. His placement of D is mistaken, but the other placements have been verified as correct. From Price's 1974 *Gears from the Greeks*, American Philosophical Society.

was preserved of the Mechanism and what it had originally been. Rediadis, for example, had written that the ancient instrument was "almost completely destroyed through the millennia-long contact with the seawater under many atmospheres' pressure," while Rehm thought that "the disturbance [of the remains] is even more serious than had been apparent at first examination; in particular, the parts lying on the upper side of 1 [i.e., Fragment A], the numerous gears and the remains of plates situated above them, are almost entirely disturbed in their position. . . ."[29] Price, on the contrary, observed "that most of the pieces are very nearly in their original places, and that we have a much larger fraction of the complete device than had been thought."[30]

Secondly, Price solved the problem of where the three main fragments—A, B, and C—were originally situated (Figure 5). His predecessors had tried to do this, but were thrown off by mistaken assumptions. Thus Rediadis relied primarily on the texts visible in 1902–1903 on all three fragments. The key fact for him was that the face of Fragment B

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[29] Rediadis in Svoronos, *Die Funde*, 43; and Rehm, "Athener Vortrag," 1–2.

[30] Price, "Ancient Greek Computer," 64.

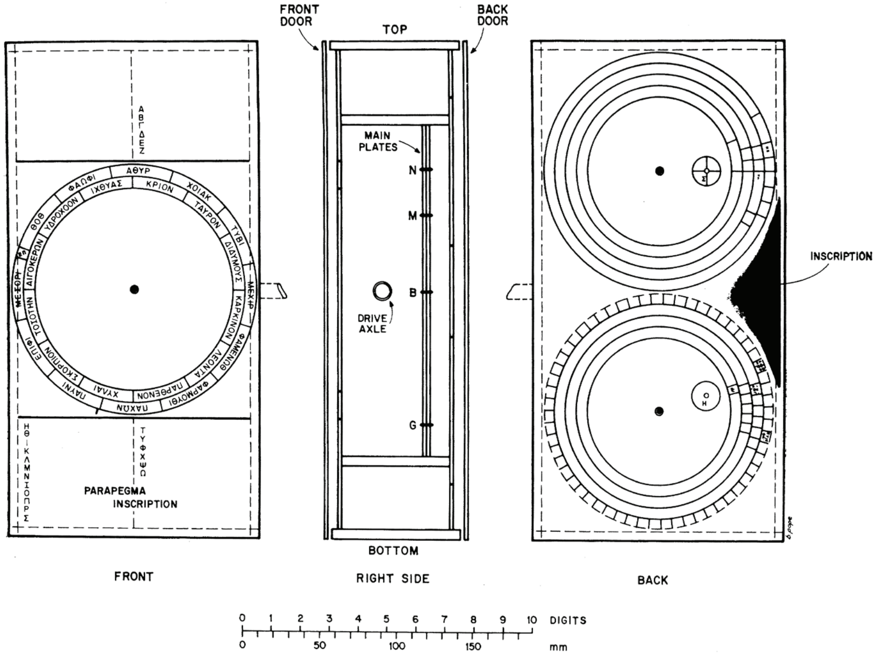

FIGURE 6. Price's reconstruction of the Mechanism's exterior. From Price's 1974 *Gears from the Greeks*, American Philosophical Society.

designated B-1 bore mirror-reversed lettering, the strokes of which were raised above the background surface, whereas both A and C had lettering in the normal orientation, and indented in the surface. Rediadis therefore supposed that there had originally been a single inscribed plate, bits of which were stuck on A and C with the inscribed face outward, and other bits on B with the inscribed face inward, resulting in a configuration of the three fragments that, as we now know, is hopelessly scrambled, with the Mechanism's gearwork on the exterior and the dial faces on the interior.

Just how Price arrived at what he called the "joins" is not clear from his later accounts.[31] His fitting together of Fragments A and B, such that face B-2 originally lay snugly against the upper part of A-2, is exactly right, as more recent research has abundantly verified, but this would not have been straightforwardly deduced from closely matching contact surfaces, since by 1958 there had been extensive cleaning away of patina on both fragments.[32] His realization that C was originally on

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[31] Price, "Ancient Greek Computer," 63–64; and Price, *Gears from the Greeks*, 1974, 12, and 14, where he states that the joins were confirmed by physical fit, matching colors, and the structure of the dials.

[32] Around 1990 Allan Bromley and Michael Wright photographed temporary

the *other* side of A, with C-2 facing A-1, was equally unobvious, and over the years he changed his mind about C's original orientation, ending up however with an arrangement that has recently been confirmed to be correct.[33]

The first and most important corollary of establishing how A, B, and C were originally situated was that Price was able, for the first time, to visualize the exterior layout of the Mechanism (Figure 6).[34] In general outline his reconstruction was remarkably close to the present consensus described above. The most important difference is that Price believed that the large dials on the back face were *circular*, each consisting (as Price believed) of three or four concentric mobile rings surrounding a fixed central plate bearing a small, subsidiary circular dial.

Also for the first time it became possible to sort out the inscribed texts. In addition to short inscriptions visible on the dial scales, patches of more extensive texts were preserved on Fragments A, B, and C as well as on many of the "minor" fragments. In some instances what one saw was part of an original inscribed plate, with the lettering engraved and in the normal ("direct") orientation, while elsewhere the lettering was mirror-reversed and raised—offsets, as Price realized, of the original plates on detached layers of accreted corrosion products. Portions of these texts had been transcribed before, with variable accuracy, but it was not at all clear which bits belonged with which. With the aid of the new positional information as well as variations in letter sizes and line spacing, Price identified the four major inscriptions of the Mechanism:[35]

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reassemblages of Fragments A, B, and C from the front-face side, and Fragments A, B, and E (discovered in 1976) from the rear-face side. The photographs appear as the front and back cover images of the June 1990 issue of *Horological Journal* (which contained an article on the Mechanism by Bromley). For the rear-face photograph see also Wright, "Scholar, the Mechanic," 9, fig. 10; and Wright, "Counting Months and Years," 10, fig. 5. Price may have tested the fit of B against A during his 1961 visit to the museum.

[33] Compare Price, "Ancient Greek Computer," diagram on 62–63, with Price, *Gears from the Greeks*, 1974, 14, fig. 6. Wright, "Antikythera Mechanism and Early History," 323 asserts that (even in their present state) Fragments A, B, and E share common fracture surfaces, but that A and C do not. For the confirmation of Price's final placement of C, using evidence inaccessible to him, see Bitsakis and Jones, "Inscriptions of the Antikythera Mechanism," 103–105.

[34] At first Price believed that the frame and the front face were only about 21 cm tall, with the back face projecting about 6 cm above and below; see his diagram in Price, "Ancient Greek Computer," 62. Michael Wright's reconstructions are somewhat similar to this design; for his reasoning, see Wright, "Reconstruction as a Medium," 11–12.

[35] For the present state of knowledge of these texts, see Allen et al., "Inscriptions of the Antikythera Mechanism," 20–23, and the series of editions and studies in the special issue (7.1) of the journal *Almagest*.

- Parapegma Inscription, on plates above and below the front dial, preserved in direct lettering on Fragment C and three small fragments (the present 20, 22, and 28).[36]
- Back Cover Inscription (Price's "Back Door Plate Inscription"), on a plate that lay against the Mechanism's back face, preserved in mirror-reversed lettering on Fragments A and B and in direct lettering on one small fragment (the present 19).
- Back Plate Inscription (Price's "Lower Back Dial Inscription"), around the large dials of the Mechanism's back face, preserved in direct lettering on Fragment A.[37]
- Front Cover Inscription (Price's "Front Door Plate Inscription"), on a plate that lay against the Mechanism's front face, preserved in direct lettering on the present Fragment G.

When it came to transcribing these texts, Price faced serious obstacles. The lettering is tiny by the standards of typical Greek inscriptions on stone, ranging from about 2.5 mm letter-height in the Parapegma Inscription down to about 2 mm in the other major inscriptions (and some of the dial scale inscriptions are still smaller). None of the major inscriptions is even close to being entirely preserved, and in the case of the Back Cover and Front Cover Inscriptions even the lines of text are always incomplete so that no continuity subsists from one line to the next. While some of the inscribed and offset surfaces are in fairly good condition so that the outlines of the letters are clear, other surfaces were badly damaged by corrosion, trauma, or chemical treatment—in particular, the Front Cover Inscription on Fragment G is almost entirely unreadable by direct inspection. Add to this that Price had limited knowledge of Greek and no experience in epigraphy.

Fortunately Price was able to call on the assistance of a competent Greek epigrapher, George Stamires (1914–1996), a protégé of Meritt who had held memberships and research assistantships at the Institute for Advanced Study since 1948 and who happened to be in Athens in the summer of 1958. The precise extent of Stamires's contribution to the transcriptions that Price eventually published is not certain; there are occasional mistakes that could scarcely have been made by someone conversant with ancient Greek.[38] Moreover, Price lost contact with

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[36] I list in this summary only the pertinent fragments identified by Price.

[37] Price, *Gears from the Greeks*, 1974, 48, fig. 37, associates the mirror-reversed text on Fragment 21 (his "curled fragment") with this inscription, though in reality it belongs to the Front Cover Inscription.

[38] Notably, Price's drawings of the zodiac scale on Fragment C consistently gave the impossible spelling "ΧΥΛΑΙ" for χηλαί, "Claws" (the Greek name for Libra). The file of Price's manuscript notes on the Mechanism's inscriptions at the Adler Planetarium does not appear

Stamires after Stamires abruptly left academic life in 1961, but on the other hand he subsequently revised and augmented the texts to take account of Rehm's unpublished transcriptions, to which he gained access at some time in the 1960s.[39] In any case, the texts that Price finally published in 1974 represented a substantial advance on anything hitherto available, though only the Parapegma and some numbers in the Front Cover Inscription contributed to Price's efforts to reconstruct the Mechanism's functions.

The Parapegma Inscription comprises a list of statements about stars and constellations on the pattern, "Hyades rise in the morning," "Arcturus sets in the evening." These phenomena recur at fixed stages of the solar year, and in Greek astronomy, calendar-like texts specifying the solar dates of stellar risings and settings were called *parapegmata*.[40] The Mechanism's parapegma does not directly specify the dates, but each event is indexed with a Greek letter in alphabetic order, and corresponding letters are inscribed at irregular intervals along the zodiac scale of the front dial. Price inferred that the front dial must have had a pointer indicating the sun's annual motion around the zodiac, so that when it aligned with an index letter, the indexed stellar event was predicted. Moreover, since the front-most surviving gearwheel in Fragment A—the one closest to the front dial—is a large spoked gear that was driven by a crown gear whose axis passed through the right side of the Mechanism's frame, Price conjectured that one revolution of the spoked gear represented a solar year and that this gear in turn imparted motion to other gears that led to outputs representing other temporal cycles on the various dials.

What these temporal cycles were and what they signified was, in principle, something that might be deduced from the gears and the dial scales. Price succinctly described the strategy of investigation that has been pursued from his time to ours:

> There are four ways of getting at the answer. First, if we knew the details of the mechanism, we should know what it did. Second, if we could read the dials, we could tell what they showed. Third, if we could understand the inscriptions, they might tell us about the mechanism. Fourth, if we knew of any similar mechanism,

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to contain anything in Stamires's hand.

[39] Meritt's letters to Stamires, now at the American Philosophical Society, witness Meritt's increasing dissatisfaction with Stamires's work. In 1961, when his final appointment as research assistant (for just one year) ended, Stamires returned to Greece, bitter that after so many years in the United States he no longer had a prospect of an academic career in Greece (personal communication of Harry Avery to Paul Iversen). He cut off all communication with Meritt and, it seems, also with Price.

[40] Lehoux, *Astronomy, Weather, and Calendars*.

> analogies might be helpful. All these approaches must be used, for none of them is complete.[41]

With the exception of the crown gear, all the gears appeared to have been mounted, in tightly spaced layers, in planes parallel to the front and back faces. Motion would have been transmitted from one layer to another by means of gears sharing a common axle, a connection that preserves the rate of rotation. Within a layer, gears drove other gears by means of engaged teeth, resulting in new rates and senses of rotation according to the ratio of their tooth counts. (Note that Price did not recognize the pin-and-slot lunar anomaly coupling for what it was—he thought that the slot was evidence of an ancient repair.) With complete knowledge of a train of gears and their tooth counts, one could obtain the sense and period of rotation of any dial pointer in proportion to the solar year. Hopefully, inscriptions on the dial's scale would confirm and give meaning to this period as well.

In reality, however, Price was unable to trace any of the gear trains from beginning to end: some gears were evidently lost, while others were extant but concealed behind other components. Obstructions and breakages also impeded accurate counting of teeth, and in fact all Price's tooth counts were incorrect, sometimes by as much as 25 percent.[42] The scale inscriptions of the main upper back dial were illegible, and those of the main lower back dial were too abbreviated to be fully interpreted. And as we have seen, Price's reconstruction of the geometry of these back dials was itself mistaken; a correct understanding could have provided him with crucial clues to their functions.

To obtain a sense of when the Mechanism was made, Price consulted Meritt, in whose opinion the letter forms of the inscriptions "could hardly be older than 100 B.C. nor younger than the time of Christ."[43] But he also found what he thought was a much more precise basis for a dating: a rectilinear groove just outside the Egyptian Calendar scale that he hypothesized was a "fiducial mark" indicating how the scale ring should be aligned with the zodiac scale at the Mechanism's epoch or zero date.[44] By an indirect argument, he initially found 82 BC as the epoch, though subsequently he pushed it back to 87 BC.[45] Price's dating continues to be frequently cited, though there

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[41] Price, "Ancient Greek Computer," 64.

[42] Price, "Ancient Greek Computer," diagram on 56–57.

[43] Price, "Ancient Greek Computer," 61. It is not clear whether Meritt expressed his paleographical dating in precisely these words. In Price, *Gears from the Greeks*, 1974, 48, Meritt's opinion is given as "characteristic of the first century B.C., or more loosely, of Augustan times."

[44] Price, "Ancient Greek Computer," 65.

[45] Price, *Gears from the Greeks*, 1974, 19.

are serious problems with the reasoning behind it (and indeed doubts have been raised about whether the supposed fiducial mark is more than just an accidental crack).[46]

Gears from the Greeks

At the annual meeting of the American Association for the Advancement of Science in Washington DC on December 30, 1958, just four months after his return from Athens, Price delivered a paper on the Mechanism that received press coverage in several newspapers including the *New York Times* and the *Washington Post*. At this stage he does not seem to have revealed many details of his research, but he portrayed the Mechanism as an artifact spectacularly advanced in comparison to common perceptions of Greco-Roman technology and civilization, using phrases such as "like finding a jet plane in the tomb of King Tut" and "like opening a pyramid and finding an atomic bomb."[47]

While planning a monograph on the Mechanism, which he intended to submit to the APS, Price was persuaded by Arthur C. Clarke, the science and science fiction author, to write an article on the subject for *Scientific American*.[48] Allowing for its brevity and popular character, "An Ancient Greek Computer" contains a surprising amount of detail on the fragments, derived from his sojourn in Athens. It also offers a new conception of the Mechanism's purpose, significantly different from the Archimedean planetarium idea in his APS grant application. A device whose gear trains could only scale up or down an ostensibly uniform input rotation according to the fixed ratios determined by the tooth counts could not adequately reproduce the apparent course of the planets through the zodiac, with their varying speeds and alternation of direct and retrograde motion. What it *could* do was display the passage of time in terms of diverse astronomical cycles having at least approximately constant periods, such as the moon's various kinds of month (synodic, sidereal, draconitic, anomalistic) and the synodic cycles of the planets. Price saw this as a mechanical representation of the ancient Babylonian arithmetical approach to mathematical astronomy—which he knew from Neugebauer to have been partly

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[46] Jones, *Portable Cosmos*, 76–77.

[47] *New York Times*, December 31, 1958, 4; and *Science News-Letter*, January 17, 1959, 36.

[48] Price, "Ancient Greek Computer." See Clarke, "Arthur C. Clarke Comments"; and Price "Grant No. 2379," 620. The publication must have been arranged at short notice, since the April 1959 issue's "Science and the Citizen" section (page 62) had just carried an item on Price's work.

transmitted to the Hellenistic world—rather than the more familiar Greek geometrical approach employing combinations of circular motions. The Mechanism was thus not so much a simulator of appearances as a calculator of data: a computer, in other words.

The frequent application of the term "computer" to the Mechanism, which began with the title of Price's 1959 *Scientific American* article and was renewed in his 1974 monograph's subtitle ("a Calendar Computer from ca. 80 BC"), is sometimes criticized as puffery. Today, when it has become rare for the word to refer to any device that is not electronic, digital, and programmable, calling the Antikythera Mechanism "the world's first computer" admittedly raises misleading expectations. Price, however, meant that the Mechanism was an *analog* computer, using continuous motion of revolving parts to model the relations of specific astronomical and calendrical time-cycles, a precursor of the many analog devices that still coexisted with early electronic computers in the mid-20th century. Nor did he claim that the Mechanism was a direct ancestor of modern computers.

Price did believe that there was a continuity between the Mechanism and modern technology, but the pathway that he conjectured led to modern mechanical clockwork.[49] His starting point was Archimedes's reported invention of mechanical planetaria in the third century BC. The Mechanism, a product of the early first century BC, was in part a response to the progress of Greek planetary theory since Archimedes's time, which rendered the project of translating the more complex contemporary astronomical theories into gearwork impracticable, so that innovation was redirected to the goal of more and more sophisticated mechanization of time relations and periodicities. Price identified the later heritage of the Mechanism in a few Islamic instruments and texts (around AD 1000 and later) describing instruments, where gearwork performed calendrical functions at a rather simpler and cruder level, and ultimately in the much more sophisticated European astronomical clocks from the 14th century onward.

Having put so much of his research on the Mechanism into his popular article, Price—now on the faculty of the Department of History of Science at Yale University—found it difficult to complete the promised monograph to his satisfaction.[50] He had entertained the possibility of publishing in conjunction with other archeologists' investigations of the materials recovered from the Antikythera wreck. However, the symposium volume on this topic that came out in 1965 in the

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[49] His fullest narrative is *Gears from the Greeks* (1974, 51–53), but the elements are already there in "Ancient Greek Computer" (67).

[50] Price, *Gears from the* Greeks, 1974, 12.

American Philosophical Society's *Transactions* had to go without a contribution by him, though it makes reference to his dating the Mechanism to the 80s, which was conveniently close to the 80–50 BC window that the symposium's participants arrived at for the shipwreck.[51]

Price was unable to have X-rays taken of the Mechanism's fragments in 1958. The idea that radiography might reveal new details also occurred soon afterward to another historian of technology, Edwin A. Battison, who was a curator at the National Museum of History and Technology. In 1964, Battison applied to the National Archaeological Museum and to the Greek government to have X-rays made, but for some reason not evident from the surviving documents, this effort (which seems to have been independent of Price) also came to nothing.[52] Meanwhile, believing that the main obstacle to obtaining X-rays was still the lack of an adequate electric supply in the museum, Price was excited to learn of the successful application of gamma rays in imaging the interior of bronze artifacts.[53] Through American contacts and the Greek Atomic Energy Commission he gained the collaboration of a radiographer, Haralambos Karakalos, who undertook an extensive campaign of radiography of the fragments in 1971.

Karakalos began with gamma rays, but soon realized that portable X-ray equipment was now available that could produce sharper and clearer images of the fragments. Many radiographs were made at various focal distances and with various exposures. Karakalos also experimented with double images made with the X-ray source in different positions in the hope of establishing the relative depth of components, but the resulting images were too complicated to interpret. The analysis of the radiographs, primarily consisting of determining the gears' tooth counts and which gears meshed with which, was carried out by Karakalos, his wife Emilia, and (during another visit to Athens in 1972) Price himself. Simply in terms of the number of gears revealed through the radiographs, the advance was substantial: in 1959 Price was only able to state that the Mechanism had at least 20 gears, but now Karakalos and Price believed that they could see 29 or 30.[54]

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[51] Price, "Grant No. 2379," 620; and Weinberg et al., *Antikythera Shipwreck Reconsidered*, 4.

[52] Smithsonian Institution Archives Collection 397, Box 20, Folder "Misc., Computer, Astronomical, Antikythera"; and Tsipopoulou, Antoniou, and Massouridi, "1900–1901 Investigations," 31, note 92.

[53] Price, *Gears from the Greeks*, 1974, 12–13.

[54] Price, "Ancient Greek Computer," 60; and Price, *Gears from the Greeks*, 1974, 27–40. Two gears reported in 1974 by Price in *Gears from the Greeks* are spurious.

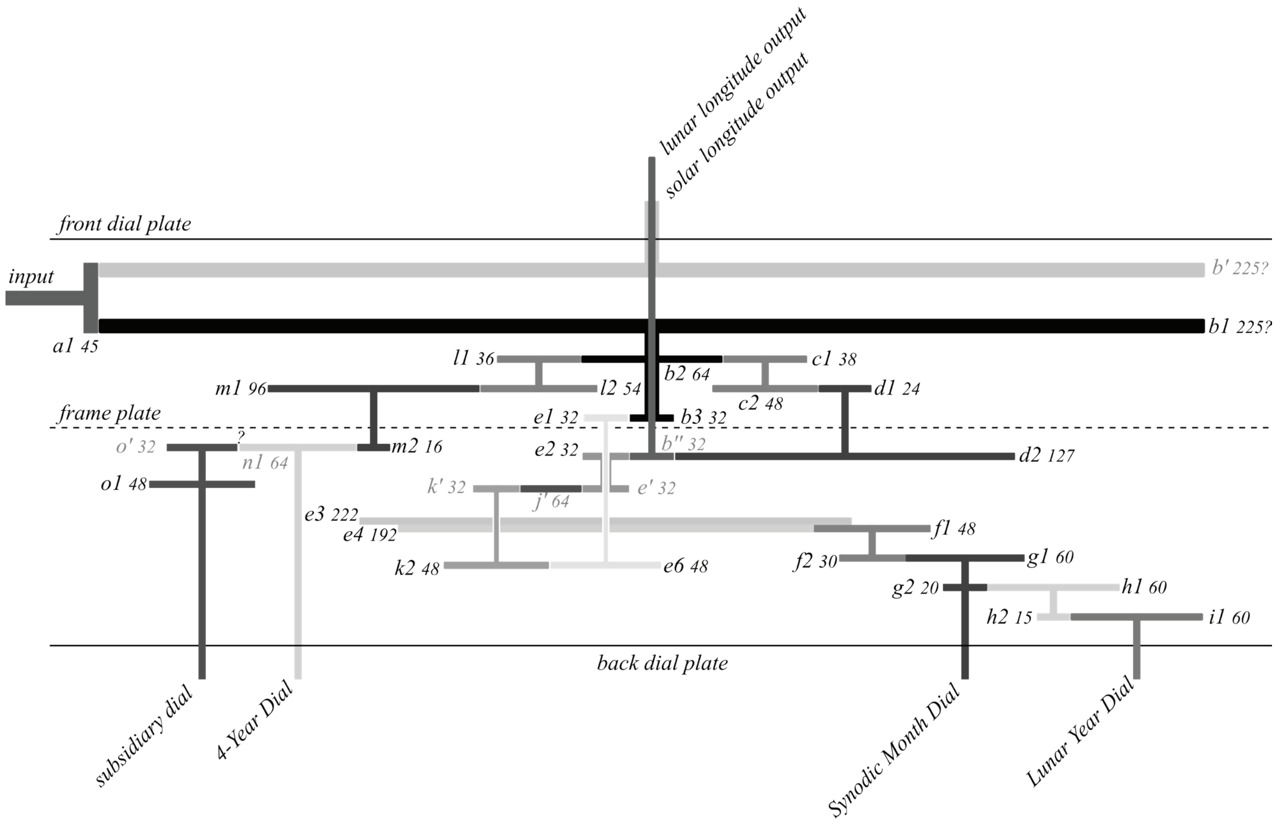

FIGURE 7. Price's 1974 gearing scheme, adapted from *Gears from the Greeks*, with gear identifiers as in Figure 4. Gears having no counterpart in Figure 4 are designated by primed letters.

This collaborative analysis of the gears, and the reconstruction of the gearing scheme that Price deduced on its basis (Figure 7), provided the additional material that he needed to finish his monograph, *Gears from the Greeks*, which appeared in the APS *Transactions* in 1974 and, unaltered, as a separately published book in 1975.[55] The gearing scheme was not completely determined by the data from the radiographs. The Karakalos' estimates of the tooth counts were sometimes specific numbers, but sometimes ranges. To arrive at definitive numbers, Price took into account what he considered to be plausible outputs in terms of ancient astronomy and calendrics, as well as a few hints from the Mechanism's inscriptions, in several instances diverging from the numbers or ranges obtained from the radiographs. Where more than one resolution offered itself, he discussed the possibilities evenhandedly in his text, picking the one he thought most likely for the scheme. When summarizing his results elsewhere, however, he could be categorical about the validity of the reconstructed scheme, passing over the uncertainties.[56]

In comparison with the present consensus reconstruction (Figure 4), with its eight conjecturally restored gears, Price's was conservative, at least in intention. Of the seven gears indicated as "missing" in Figure 7, Price believed he could see *b''*, *k'*, and *o'*, though in fact they are spurious. His *n1* is the isolated gear (with correct tooth count of 63) in Fragment D, which he mistakenly supposed was lodged between A and B. The only gears that Price included in his scheme as pure conjecture were *e'* (a doublet of *e2* presumed necessary to avoid collisions of *j'* and *k'* with *b''* and *d2*), the idler *j'*, and the solar longitude gear *b'*, about which more presently.

The most successful part of Price's scheme is the train of gears leading from *b2* through to *b4* (a gear that does not actually exist, but functionally corresponds to *e2*). With tooth counts consistent with Karakalos's estimates except that Price gave *d2* 127 teeth instead of Karakalos's 128, this train applies a ratio of 254:19 to the rotational rate of *b1-b2*, which there was already reason to suspect represented the solar year. Price knew that the number 19 appeared in the Back Cover Inscription in a context certainly relating to calendrical cycles, and the Metonic calendrical equation of 19 solar years with 235 lunar months implies also that 19 solar years equal 254 revolutions of the moon through the zodiac. Thus this part of the gearwork yielded a rate of rotation perfectly appropriate for a pointer on the front dial indicating the moon's position in the zodiac. But Karakalos and Price were

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[55] Price, *Gears from the Greeks*, 1974, 1975.

[56] Price, "Clockwork before the Clock," 1975, 376.

unable to resolve the gearwork involving the *b* and *e* axes correctly, with the result that the output motion driving the lunar pointer would have had the opposite sense of rotation to *b1*. Hence to have both the solar and lunar pointers revolving in the correct eastward sense around the zodiac scale, Price had to hypothesize that *b1* had a lost twin (*b'* in Figure 7), also driven by the crown gear *a1* but in the reverse sense.

The train leading from the large double-gear *e3-e4* to the lower back dials (lower right in Figure 7) is structurally correct in Price's scheme, and five of the seven gears have correct tooth counts. The exceptions, *f1* and *g1*, are characteristic of Price's approach. Karakalos had estimated *f1*'s count as 54 and *g1*'s as 54 or 55; the correct counts are now known to be respectively 53 and 54, confirming the quality of Karakalos's work. Price adopted counts diverging from Karakalos's by a full 10 percent simply in order to get outputs that made sense to him, but the adjustments were misguided since his rate of rotation for *e3-e4* was itself wrong.

The structure and function of *e3-e4* and the system of epicyclic gears *e5-k1-k2-e6* (which has now been identified as the pin-and-slot apparatus by which means the Mechanism introduced an anomalistic component in the moon's longitudinal motion) would have been a tremendous challenge to make sense of from direct inspection and two-dimensional radiographs. The slot in *k2* was indeed visible—it had already been noticed by Rediadis—but was misinterpreted as the trace of an ancient repair. Moreover, Karakalos detected the presence of *k1* behind *k2*, but *e5* was not observed as distinct from *e6*. (Price thought *k2* and *e5* were just unusually thick gears.) And crucially, the gear *m3* that engaged with *e3*, thus linking the trains of the upper and lower back dials, was lost without a physical trace; Price was unable to decide on a function for *e3*, but thought it might have driven another output.

Price famously and ingeniously interpreted *e3-e4* as a "differential turntable" that harnessed the epicyclic gears as the agents of its revolution, thereby subtracting half the sun's longitudinal motion from half the moon's to yield a rotation with half the synodic month as its period. The connection of this turntable to the lower back dials suggested that those dials were synodic month counters, motivating Price's willful adjustments of Karakalos's tooth counts for *f1* and *g1*. Since, so far as he knew, differential gearing was otherwise not known before the 16th century, Price highlighted this feature of his reconstruction as his chief exhibit attesting to the unexpected sophistication of the Hellenistic mechanical technology embedded in the Mechanism.[57]

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[57] Price, *Gears from the Greeks*, 1974, 60–61.

An attentive reading of Price's analysis of the Mechanism's gear trains cannot miss the many points on which he had doubts about the interpretation of the evidence or made choices where there was not a preponderating basis for preferring one option; when he presented the outcomes of this process as a gearing-scheme diagram, however, the effect was to make the reconstruction appear more definitive than it actually was. The mistakes of detail that more recent research has made apparent should not deduct from the broad new insight that *Gears from the Greeks* added to those arising from Price's 1958 work, namely that a detailed mapping of the mechanical elements, and especially the tooth counts and interconnections of the gears, had become feasible through radiography. As it turned out, this information would be a necessary but not a sufficient basis for recovering the full range of the Mechanism's functions.

From Price to the Present, and What Price Missed

The popular attention that Price obtained for the Mechanism after his first round of research in 1958 peaked with his 1959 *Scientific American* article—the cover article of its issue. Except for a somewhat disreputable supporting role in Erich von Däniken's *Chariots of the Gods*, as an artifact the ancient Greeks could never have made without guidance from extraterrestrial visitors, it dropped virtually out of sight. Even when *Gears from the Greeks* came out, its reception was primarily a matter of (unanimously favorable) reviews in scholarly journals. Most of these were in the fields of history of science and technology or popular science, few in classical studies; even a quarter of a century later, the Mechanism was much more widely familiar to scientists and historians of science than to specialists in Greco-Roman antiquity.

Price's involvement in research concerning the Mechanism also wound down after *Gears from the Greeks*. Even the discovery of a significant new fragment, E, in the storerooms of the National Archaeological Museum did not lead him to revisit his work, though, as we will see, it bore suggestive clues that, properly recognized, might have put him on the track to a better understanding of the Mechanism's back face.[58] On the publicity side, he appeared in an episode of the 1980 British television series *Arthur C. Clarke's Mysterious World*, in which a segment on the Mechanism uncomfortably rubbed shoulders with more dubious exemplars of "ancient wisdom," the alleged pre-Columbian "crystal skulls" and the so-called "Baghdad battery." Before

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[58] Correspondence between Price and Petros Kalligas, 1976, at the Adler Planetarium; the photographs that Kalligas sent Price are also in the Adler collection.

the camera, Price shows specimens of Karakalos's gamma ray and X-ray radiographs and operates working models built by Robert Deroski according to Price's gearing scheme. This was to be the first of many television documentaries that have broadcast the mystique of the Mechanism to nonspecialist audiences.

Others, however, soon began reconsidering the Mechanism as an incompletely solved problem. In a lecture at the Royal Institution of Great Britain in 1985, the mathematician Christopher Zeeman summarized the story of the Mechanism's discovery and Price's reconstruction. Almost as an afterthought Zeeman remarked that a weakness of the reconstruction was that it required an input motion through the presumed side knob and gear *a1* to be the starting point of all the trains, involving a very large "stepping up" of rates of revolution from *b1*, revolving with a nominal period of one solar year, by way of the heavily loaded and non-centrally mounted differential turntable, whose period is two lunar months, to *f1*, whose period is half a lunar month (i.e., less than a twenty-fourth of a solar year). This would be "like trying to alter a clock by pushing the hour hand, and expecting this to drive the minute hand 12 times as fast."[59] Zeeman's concern had been confirmed by Michael Wright of the London Science Museum, who had found that one of Deroski's models did not function properly for this reason. (Price's demonstration in the television program, on the other hand, apparently verifies that the gearing scheme *could* be made viable.)[60] Wright also brought this to the attention of Allan Bromley, a historian of computers, and Bromley began devising modified gearing schemes in part with a view to reducing the mechanical strain.[61] At this point Price's critics were wholly dependent on *Gears from the Greeks* for the physical evidence of the fragments.

Another area of doubt was the appropriateness of Price's designation of the Mechanism as a "calendar computer," in other words that its functions were limited to the apparent motions of the sun and moon and time relations arising from those motions. Price had not quite shut the door on the notion that there might have been some output relating to the planets, observing that his scheme allowed some space just behind the front dial plate where a block of planetary gearing could have been "if this is to be conjecturally restored."[62] But he does not appear to have considered this possibility to be worth pursuing even speculatively, and it did not fit well with his sense that the increasing

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[59] Zeeman, "Gears from the Greeks," 150–51.

[60] John Gleave also built successfully working models based on Price's gearing scheme; see Edmunds and Morgan, "Antikythera Mechanism," 6.13.

[61] Bromley, "Notes on the Antikythera Mechanism."

[62] Price, *Gears from the Greeks*, 1974, 21, 28.

refinement of Greek planetary theory between Archimedes and Hipparchus would have rendered obsolete a display of mere mean motions, and uniform rates of rotation were all that he thought the varieties of gearwork found in the Mechanism were capable of.[63] In the early 2000s, Mike Edmunds and Philip Morgan, Michael Wright, and Tony Freeth all published articles proposing that the Mechanism could have had a partial or full planetarium display with representation of the planets' synodic cycles of varying apparent speed and direction.[64] Of these reconstructions, Wright's had been tested through the building of a working model.

Wright was also by now in a much stronger position to dispute Price's work because, starting in the late 1980s, he and Bromley had made several visits to the National Archaeological Museum to study the fragments intensively, supplementing direct examination with X-ray radiography and linear tomography, an analog technique of radiography producing images that reveal depth through a linear blur that increases with distance from a chosen plane. Following Bromley's death in 2002, Wright produced a remarkable series of papers in which he refined and corrected Price's data and solved several of the remaining puzzles of the reconstruction.

The last major data-gathering was carried out in 2005 by a collaboration initiated by Edmunds and Freeth under the name Antikythera Mechanism Research Project.[65] It comprised microfocus X-ray computed tomography and reflectance transformation imaging of all 82 identified fragments.[66] The AMRP team rapidly produced a gearing scheme that built on and substantially completed Price's and Wright's work.[67] With a comparatively minor correction obtained in 2008, this is the consensus reconstruction illustrated above in Figure 4.[68] A comprehensive edition and study of the Mechanism's inscriptions followed in 2016, and the AMRP data have been employed in other publications by members of the team and other scholars.[69]

If we compare the present understanding of the Mechanism to Price's in *Gears from the Greeks*, the following are the most prominent differences:

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[63] Price, *Gears from the Greeks*, 1974, 59.

[64] Edmunds and Morgan, "Antikythera Mechanism"; Wright, "Planetarium Display"; Freeth, "Antikythera Mechanism 1"; and Freeth, "Antikythera Mechanism 2."

[65] Edmunds et al., "Antikythera Mechanism."

[66] The tomography was carried out by X-Tek Systems Ltd. (now part of Nikon Metrology), the RTI by a team from Hewlett-Packard Corp.

[67] Freeth et al., "Decoding the Ancient Greek."

[68] Freeth et al., "Calendars with Olympiad Display."

[69] Special issue of *Almagest*, 7.1.

- The physical locations and connections of the surviving gears are now known exactly, and the tooth counts have been estimated to greater precision and verified from the agreement of the behavior of the resulting gear trains with the formats and inscriptions of the output dials.[70]
- The principal upper and lower dials of the back face are now known to be spirals, not concentric circular rings; hence a complete traversal of one of these dials is not achieved in a single revolution of the pointer but when the pointer has traced along all the turns of the spiral.[71]
- The lost gears completing the gear trains leading to the upper dials of the back face have been determined securely on the basis of surviving physical evidence, the dial scales and their inscriptions, and passages of the Back Cover Inscription.[72] The identities of these dials as described above (Metonic, Games, and Callippic), have thus been established with certitude.
- The trains leading to the lower dials of the back face have been completed as branching off the train to the upper dials, with the restoration of one lost gear (*m3*).[73] The large double gear *b3-b4* that provides the main link between the upper and lower dial systems turns out to revolve with the longitudinal period of the apogee of the moon's orbit. The identities of the lower dials (Saros and Exeligmos) are determined independently of the gear train by the dial scales and their inscriptions, with confirmation from passages of the Back Cover Inscription.
- The train leading to the lunar longitude output on the front dial, which had been successfully described by Price as far as *d2*, is now completely known. The sense of the lunar longitude output was reversed by an idler gear that Price missed.[74] The motion is then transferred to the epicyclic gearwork mounted on *b3-b4*, where the pin-and-slot device introduces a periodic variation in the rate of revolution corresponding to the moon's first anomaly.[75] This now anomalistic motion is returned to the front of the Mechanism through a pipe. It then drives not only a pointer indicating the moon's zodiacal longitude, but also an epicyclically mounted

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[70] Wright, "New Gearing Scheme," esp. 5; and Freeth et al., "Decoding the Ancient Greek."

[71] Wright, "Scholar, the Mechanic."

[72] Wright, "Counting Months and Years"; and Freeth et al., "Calendars with Olympiad Display."

[73] Freeth et al., "Decoding the Ancient Greek."

[74] Wright, "New Gearing Scheme," 2.

[75] Freeth et al., "Decoding the Ancient Greek."

crown gear revolving the parti-colored ball of the lunar phase display.[76]

- As we have already seen, the improved texts of the Back and Front Cover Inscriptions have strongly reinforced the argument that the front dial displayed the motions of the five planets through the zodiac, by means of a lost system of gearwork that can only be conjecturally reconstructed.

Since these discoveries resulted from research projects that were both inspired by and methodologically extrapolated from Price's, it is tempting to ask whether Price might in other circumstances have arrived at any of them.

One major impediment was his lack of radiography that could yield satisfactory depth information or images projected along axes parallel to the major fragments' principal planes. His confusion about the gears along and near the *b* axis is an obvious example of the inadequacy for his purposes of radiographs that projected all elements into a plane parallel to the gear wheels. A simpler but revealing case is the interpretation of a feature prominent on C-2 resembling a circular jar-lid (see Figure 2). Like previous investigators, Price was puzzled by this element, suggesting as alternatives that "it might be some part of the dial work for the center of the front dial, possibly a plate indicating the position of the Moon," or that it might have been the crank handle driving *a1* from outside the Mechanism's case.[77] After Wright and Bromley's linear tomography revealed the presence of gear teeth embedded in the fragment, they subjected Fragment C to conventional radiography along an axis nearly parallel to the surface and perpendicular to the teeth, an aspect selection that Karakos seems not to have attempted (nor indeed had reason to attempt).[78] This showed that the teeth belonged to a broken crown gear (*s1* in Figure 4), the crucial clue leading Wright to the realization that the jar-lid was the remains of a visual lunar phase display. While Price's first hypothesis seems to be on the way to this explanation, he could not have known about the mechanical element that completed it and rendered it utterly convincing.

A second impediment was the fragmentary and only partially legible state of the inscriptions. His collaboration with Stamires had resulted in transcriptions of the major texts that were close to the limit of extent and accuracy achievable by direct inspection—at this date, the assistance offered by photography was negligible—but with the exception of the Parapegma Inscription, only patches of text were

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[76] Wright, "Antikythera Mechanism and Early History."

[77] Price, *Gears from the Greeks*, 1974, 20.

[78] Wright, "Antikythera Mechanism and Early History," 327.

intelligible and yielded useful information about the Mechanism. The tiny month names in the cells of the Metonic Dial scale, which might have pointed to the calendrical function of the dial, were almost entirely unreadable, and only three examples of the more legible but coded eclipse predictions in cells of the Saros Dial scale were visible, too little by themselves for Price to divine more than that they related to the sun and moon and to times in hours.[79] It required the computed tomography and reflectance transformation imaging of the AMRP project to enhance the legibility of the exposed inscriptions as well as making accessible substantial parts of the inscriptions that are embedded inside the fragments. Aside from the back dials, an aspect of the Mechanism that Price might have reconsidered if he had had better knowledge of the inscriptions is the question of whether it had a planetary display. The Price-Stamires text of the Back Cover Inscription in *Gears from the Greeks* contains a mention of Venus, though Price makes no comment on this and its possible significance, but it was missing the names of at least three of the four other planets that are now known to be there, while the disjointed scraps of the Front Cover Inscription in their transcription miss all the recognizable references to the planets and their synodic cycles.

In addition there are undoubtedly mistakes of observation and interpretation in *Gears from the Greeks* that were not inevitable consequences of the limited visualization techniques available to him. In one instance a "near miss" kept him from a chain of deductions by which he might have anticipated several elements of the present consensus reconstruction. As we have seen, Price (like his predecessors in the study of the Mechanism) assumed that the main upper and lower back dials consisted of sets of concentric, presumably mobile, rings, whereas the present reconstruction has them as spirals, composed of semicircles of progressively increasing diameter. As a matter of fact, the remains of the slots in Fragments A and B belong almost entirely to the right halves of their respective dials. However, in Karakalos's radiographs of B, Price could clearly see, inside the five slotted arcs, a small segment of a sixth arc that comes to a squared end just along the vertical line of symmetry of the back plate.[80] He dismissed this as probably an accidental crack rather than a partial ring, whereas in fact it is the inner end of the Metonic Dial spiral. Again, the axis of the lower dial's

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[79] Price, "Ancient Greek Computer," 64–65. These texts are not discussed in Price, *Gears from the Greeks*, 1974.

[80] Price, *Gears from the Greeks*, 1974, 15 and cf. 33, fig. 26.

pointer (driven by *g1-g2*) is noticeably higher along the vertical line of symmetry than the geometrical center of the lower dial's slotted arcs, a fact that, so far as I can see, Price did not remark on—perhaps he explained it away as an effect of distortion of the lower dial's rings—but that is actually a symptom of the composite nature of the spiral. Wright did notice both phenomena, and on this initially rather slender evidence he proposed the spiral structures.[81]

Suppose that Price had anticipated Wright in identifying the spirals. A natural corollary would have been that the effective period of each dial was represented by the full length of its scale, which was visibly divided into cells subtending approximately equal angles. Price had estimated that a full circle of the upper dial comprised either 47 or 48 cells, so the complete spiral would have comprised either 235 or 240 cells.[82] It was left to Wright to make this calculation and recognize that 235 was the number of lunar months in a "Metonic" 19-year calendrical cycle, a realization that did not depend at all on being able to read the month names in the cells.[83] Though the part of the Saros Dial that is exposed to direct view is smaller and Price's measurement of the cell arcs (as approximately 1/58 of a circle) is slightly too small, it is conceivable that with additional care he might also have got the 223 cells corresponding to the lunar months of the Saros eclipse cycle, all the more so since he knew that the number 223 was in the Back Cover Inscription.[84] In both cases, knowledge of the output periods of the dials would have provided helpful constraints in reconstructing the gear trains.

As an intriguing postscript to this speculation of what might have been, the photographs of Fragment E that Price received in 1976 showed easily legible new mirror-image bits of the Back Cover Inscription, including ΕΛΙΚΙ, "spiral," and the numeral ΣΛΕ, "235"; but he seems not to have observed these clues either. The researchers who have followed in Price's footsteps may be grateful that he missed such things, leaving to them a large part of the satisfaction of untangling one of the most complex problems ever presented by a single archaeological artifact.

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[81] Wright, "Scholar, the Mechanic," 10.

[82] Price, *Gears from the Greeks*, 1974, 15.

[83] Wright, "Counting Months and Years."

[84] The recognition of the Saros in the lower dial was first obtained by Freeth et al., "Decoding the Ancient Greek," by which time more of the spiral had come to light in Fragments E and F.

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