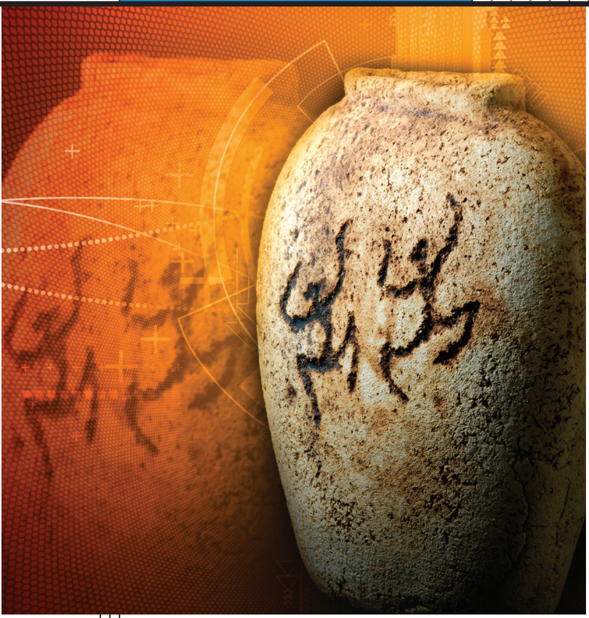

Using Computation to Decode the First Known Computer

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Researchers have used many different kinds of software to analyze the structure and astronomical functions of the Antikythera mechanism's surviving fragments. This ancient Greek calculator contains 30 gear wheels and has an extraordinarily sophisticated mechanical design.

It seems appropriate that scientists are using modern computing methods to investigate the earliest known mechanical "computer," the Antikythera mechanism, made in ancient Greece. Technically, the mechanism is more of a specialized astronomical calculator or display device, but the sophistication of its design is quite extraordinary. So far, researchers have used an array of computational tools—simple spreadsheets, image analysis, simulations, and advanced animations—to decipher the mechanism.[1,2] After more than 100 years of study, the calculator's functions—if not its ultimate purpose—are at last reasonably well understood.

The story of its discovery is widely known.[3,4] In 1900, sponge divers discovered the wreck of an ancient trading ship off the island of Antikythera in the Mediterranean Sea. From 1900 to 1901, the National Archaeological Museum in Athens and the Greek Navy carried out what was effectively the first major underwater archaeological recovery mission. Historians have dated the wreck to somewhere between 80 and 60 BCE; its rich contents are currently on display at the National Archaeological Museum in Athens.

One artifact from the wreck—a lump of corroded bronze—split open after a few months in the museum, revealing toothed bronze gear wheels. Prior to this discovery, no evidence of metal gear technology in the classical world existed. Subsequent examination, fragmentation, and cleaning revealed an interior structure and inscriptions in ancient Greek that clearly indicated the device had an astronomical connection and dated back to the second century BCE. German philologist Albert Rhem was the first to recognize, in 1905, that the mechanism was essentially an astronomical calculator. Its true complexity—30 gear wheels in situ—became apparent in the 1970s, through the use of photographic radiography by Charalambos Karakalos and Derek de Solla Price.[3] Subsequent work, most notably by Michael Wright,[5-7] added more mechanical understanding.

In 2005, an international team of scientists initiated the Antikythera Mechanism Research Project (AMRP; www.antikythera-mechanism.gr) with the aim of obtaining fresh data by applying the latest imaging and analysis techniques to the mechanism's surviving fragments. So far, our international team's efforts have yielded both detailed surface imaging and microfocus X-ray computed tomography—the latter providing a complete 3D "body scan"—of the fragments. These efforts have led to the discovery of new features, prompting a reinterpretation of the device's overall structure, and a mass of new inscriptions to decipher.

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Figure 1. Applying surface imaging to fragment 19, the Antikythera mechanism's back cover: (left) photograph and (right) reflectance transformation image that enhances the text in what amounts to the mechanism's instruction manual. The text highlighted in red identifies the ancient Babylonian cycles that underlie the gearing: "76 years" refers to the Callippic cycle, "19 years" to the Metonic cycle, and "223" to the Saros cycle. *Copyright 2006-2008 Antikythera Mechanism Research Project*.

SURFACE IMAGING

On archaeological digs, it is standard practice to take aerial photographs of the site shortly after sunrise or just before sunset when the sun is low in the sky. The shadows cast by the glancing sunlight enhance faint surface irregularities or texture differences on the land, making underlying physical structures visible.

Tom Malzbender and his team at Hewlett-Packard Labs in Palo Alto, California, developed a portable relighting tool for artifact surfaces that enabled us to obtain similar images of the Antikythera mechanism fragments. We placed a 1-meter-diameter geodesic hemisphere over each fragment, with 50 electronic flashbulbs distributed across the hemisphere's inner surface, fired off in sequence by a laptop computer that also controls a digital camera at the dome's zenith, which takes a picture for each flash. We use software to combine the sequence of 50 differently lit images at will, with or without further image processing. When displayed interactively, the effect is of being able to hold the object in your hand and turn it in all directions relative to the light, greatly aiding the comprehension of faint detail.

Malzbender's approach uses *polynomial texture maps* (PTMs; www.hpl.hp.com/research/ptm/ri.html) to represent image pixels as functions of the lighting source's direction to specify red, green, and blue on surface components. A PTM fitter fits a low-order polynomial to lighted samples of the object represented in the image sequence. We use a PTM viewer to evaluate this polynomial for each pixel to produce a *reflectance transformation image* (RTI) that enhances the object's surface detail under variable lighting conditions. Even low-end computers can handle this reconstruction at real-time rates because of the polynomial's simplicity.

Figure 1 compares a photo and RTI of fragment 19, the mechanism's back cover. Interactive RTIs of all 82 surviving fragments are available at www.hpl.hp.com/research/ptm/antikythera_mechanism/index.html. Examples of a wide range of PTM applications to other archaeological artifacts such as stone tools, ceramics, coins, and rock art can be viewed at http://c-h-i.org/examples/ptm/ptm.html.

MICROFOCUS X-RAY COMPUTED TOMOGRAPHY

In archaeology, computed tomography (CT) involves mounting an object of interest on a turntable and taking a series of 2D X-ray projection images called radiographs via computer as the turntable rotates 360 degrees in angular steps. Researchers analyze the resulting data with special software that reconstructs the 2D projections into a 3D volume.

X-Tek Systems (now part of Nikon Metrology) built and operated for us a special prototype 450-keV BladeRunner CT system, the high energy of which could penetrate the Antikythera mechanism's largest surviving fragment. The system's *microfocus* X-ray source has a small but intense beam diameter that allows much greater spatial resolution than typical CT medical scanners. The detector was a 16-inch Perkin Elmer flat panel with 2,048 × 2,048 square 400-micron pixels.

With this microfocus source, we could geometrically magnify fragment samples on the detector by many magnitudes, allowing resolutions in the range of 40 to 100 microns, depending on sample size. We imaged most of the fragments at X-ray potentials of 225 keV and 366 keV, scaling the 16-bit monochromatic radiographs from the detector to fit the dynamic range by converting them to 8-bit images with 256 gray levels, before compressing and saving them as JPEGs. Example images of mechanism fragments can be found at www.shawinspectionsystems.com/library/antikythera/dr/dr.htm.

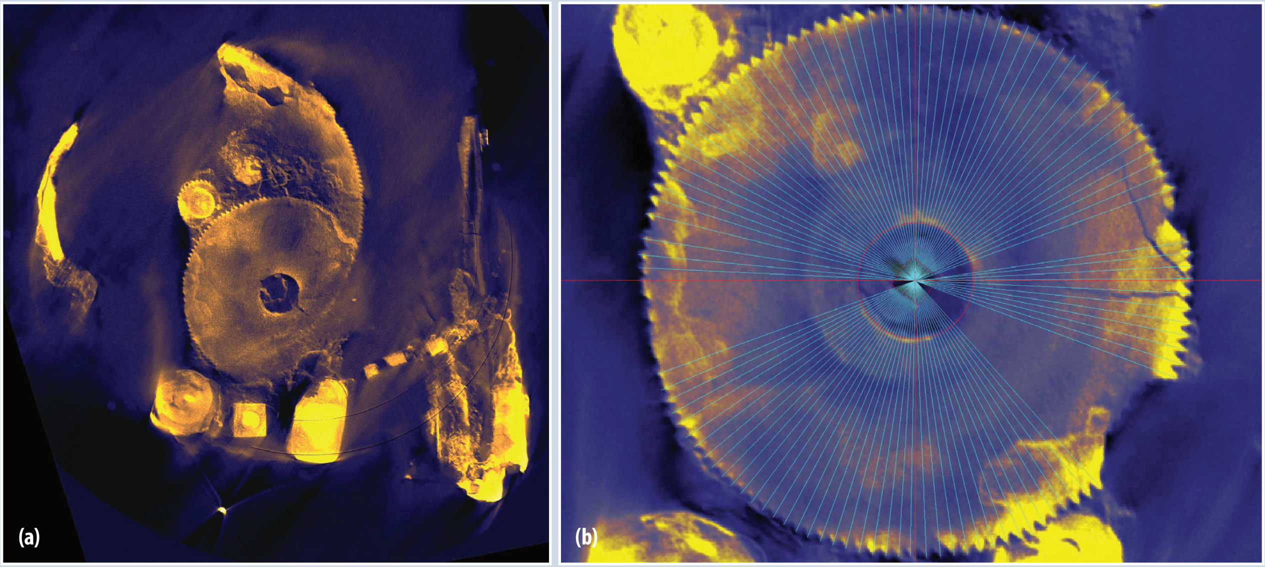

Figure 2. Typical X-ray CT slices, in a false color scale. (a) A gear with 127 teeth in the center that calculates the mean motion of the moon against the stars, according to the Metonic cycle. The large partial gear originally had 223 teeth and drives the Saros dial. (b) The 127-tooth gear, marked in Vectorworks for counting the teeth. ***Copyright 2006-2008 Antikythera Mechanism Research Project*****.**

The key analysis tool for the X-ray CT was Volume Graphics' VGStudio Max, a powerful software program for analyzing 3D X-ray volumes that runs on a standard PC or Mac. For our volumes, we needed a minimum of 8 Gbytes of RAM on a machine running four processor cores, and we could have used considerably more computing power. VGStudio Max produces 3D images, but, as Figure 2 shows, we found that the most powerful technique was to view slices of each fragment through the reconstructed X-ray volumes.

These slices can be angled at any orientation, which is fortunate because nothing in the surviving fragments is truly flat. The software also includes sophisticated measurement and shape-fitting tools to extract metric data for constructing a model.

We anticipated that the X-ray data would help us try to understand the 3D disposition of the mechanism's gears, but one of the surprising revelations was that we could also use it to read many new inscriptions hidden deep inside the fragments. Our Greek colleagues in the AMRP, Yanis Bitsakis and Agamemnon Tselikas, took the lead on deciphering these inscriptions. They found more than 2,000 additional text characters, some via RTIs but the majority through X-ray CT. Most of the new text could not be read in a single CT slice—for one of the calendar dials, we needed more than 60 slices, spaced at 100 microns apart, to read all the month names. The names, as interpreted by our colleague Alexander Jones, imply that the machine was designed for use in Corinthian Greece.

THE GEARS

After we obtained the X-ray data, we next needed to establish reliable tooth counts for all the gears. The mechanism's astronomical function is essentially encoded in the gear ratios, although the inscriptions on the mechanism do give some valuable hints. We believe the gears were laid out and cut by hand, with the teeth appearing to be simple equilateral triangles, slightly rounded at the tips. Only five of the surviving 30 gear wheels have a complete set of teeth, although with some irregularity in tooth spacing; the others also show varying amounts of damage, incompleteness, and physical tooth spacing. For each gear, we imported several parallel CT slices into a CAD program, Nemetschek's Vectorworks, which let us superimpose a geometry on the slices. We could then estimate the assumed gear center and mark the angular positions of the surviving gear teeth tips. Next, we exported data to an Excel spreadsheet for a tooth-count analysis.

Based on our examination of the gear image, we selected potential contiguous runs of teeth and read them from the spreadsheet into a Mathematica program written to fit a model with n perfectly spaced teeth. This gave us an arbitrary start position and allowed us to move the assumed gear center around. The "goodness of fit" parameter was simply the reciprocal of the least-squares deviation between model and data, but it worked remarkably well. In most cases, a well-defined maximum in the fit parameter appeared when plotted against n and the angular center displacement using Mathematica's Plot3D function. We could establish firm tooth counts, with just a few gears uncertain by one or two teeth. Some of the definite counts—38, 53, 127—show a deliberate choice by the maker to include the gears necessary for astronomical ratios. For example, 38 is 2×19 for the 19-year cycle of the moon.

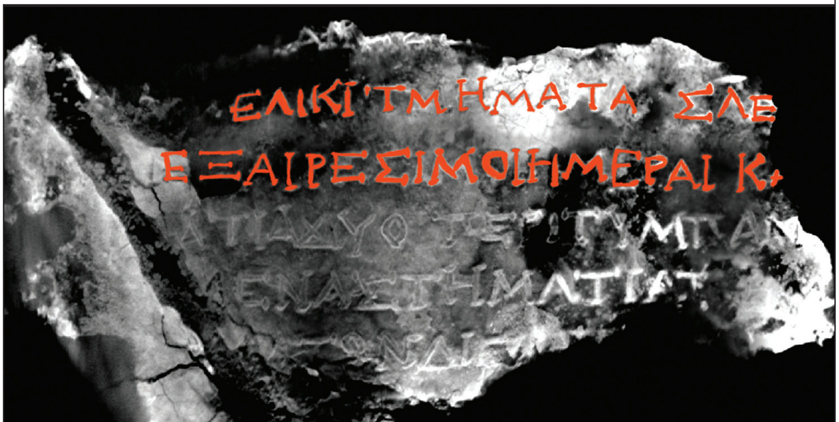

Figure 3. Composite of several X-ray CT slices through Fragment E, which form part of the back cover. The text is roughly 1.6 mm high, and the only word visible on the surface is ΕΛΙΚΙ, meaning "spiral." The highlighted text reads "Spiral subdivisions 235" and "Excluded days twenty [two]." These both refer to the mathematical organization of the 19-year Metonic calendar dial. *Copyright 2006-2008 Antikythera Mechanism Research Project*.

The upper dial on the back

Researchers—particularly Derek de Solla Price and Michael Wright—had established their own advanced frameworks for understanding the gear trains before we began our work. It was evident that the mechanism was originally in a case approximately $34 \times 20 \times 10$ cm in size and had one large dial at the front and two smaller dials mounted one above the other on the back. Some portions of all three dials survive and are the earliest known divided—that is, carefully marked out—scientific scales. The mechanism also featured several subsidiary dials. Price recorded inscriptions containing the numbers 19 and 76; although he was less certain about the number 223, our work with the PTM confirmed it as well.

These numbers have immediate relevance for what was known about astronomy in Greek times: 19 years almost exactly equals 235 lunar months, as measured from new moon to new moon (the Synodic month). This match was known to the Babylonians and introduced to the Greek world between 430 and 440 BCE by the Athenian astronomer Meton, hence its name. The Metonic cycle's virtue is that it lets users predict dates for lunar phases, which were of great interest in preparing calendars. This cycle is still used to fix the date of Easter.

Quite early on in our investigation, we were lucky to read a new inscription—"the spiral divided into 235 sections"—on a fragment, some of which was part of the mechanism's back cover. This was a vital clue. It confirmed Derek de Solla Price's idea that the upper back dial might be a 235-month calendar—an idea that Michael Wright had revived. Wright had already concluded that the two dials on the back weren't circular but actually formed five- and four-turn spirals. As Figure 3 shows, the inscriptions exactly reinforced the application of our Mathematica gear-tooth-fitting program. Both the inscription and Mathematica's extrapolation from the surviving scale divisions implied that the dial had 235 divisions, corresponding to the 235 lunar months of the 19-year Metonic cycle.

As Figure 4 shows, some of the gears required to drive the Metonic pointer have not survived, but Wright proposed a plausible gear train. The use of a five-turn spiral dial is rather elegant, for it would obviously be more difficult to inscribe with text and read a small, single-turn circular dial with 235 divisions. The dial's pointer—parts of which are visible via CT—had a pin that fits into a continuous spiral groove between the scales, causing the pointer to show which turn of the spiral was being indicated.

Eclipse predictions and lunar motion

The number 223 in the inscriptions is the number of lunar months in the Saros cycle, which was identified by the Babylonians at least by the 7th century BCE as being an eclipse prediction cycle. Could this be the function of the lower back dial?

Four rather strange glyph symbols visible on a surviving part of the dial face strengthen this idea because of their possible interpretation as indicating lunar or solar events. The Saros cycle relies on the observation that if a lunar or solar eclipse occurs (which can only happen at a full and new moon, respectively), a similar eclipse is likely to occur 223 lunar months later, shifted in time by eight hours. From a list of the month and year in which eclipses have occurred, it is fairly straightforward to predict future lunar months in which an eclipse is possible.

The key observation was the discovery via CT images of 14 additional glyphs hidden on the lower back dial scales. Crucially, analysis of the dial also showed 223 divisions around the four-turn spiral. We realized that the glyphs must be the eclipse predictions themselves, so we tried to match the glyph positions in the month divisions on the dial with eclipses over the last four centuries BCE. Fred Espenak's NASA website (http://eclipse.gsfc.nasa.gov/eclipse.html) offers theoretical retrodictions of eclipses. Because the problem was identical to matching a short DNA sequence to a much longer sequence, we coded the data as

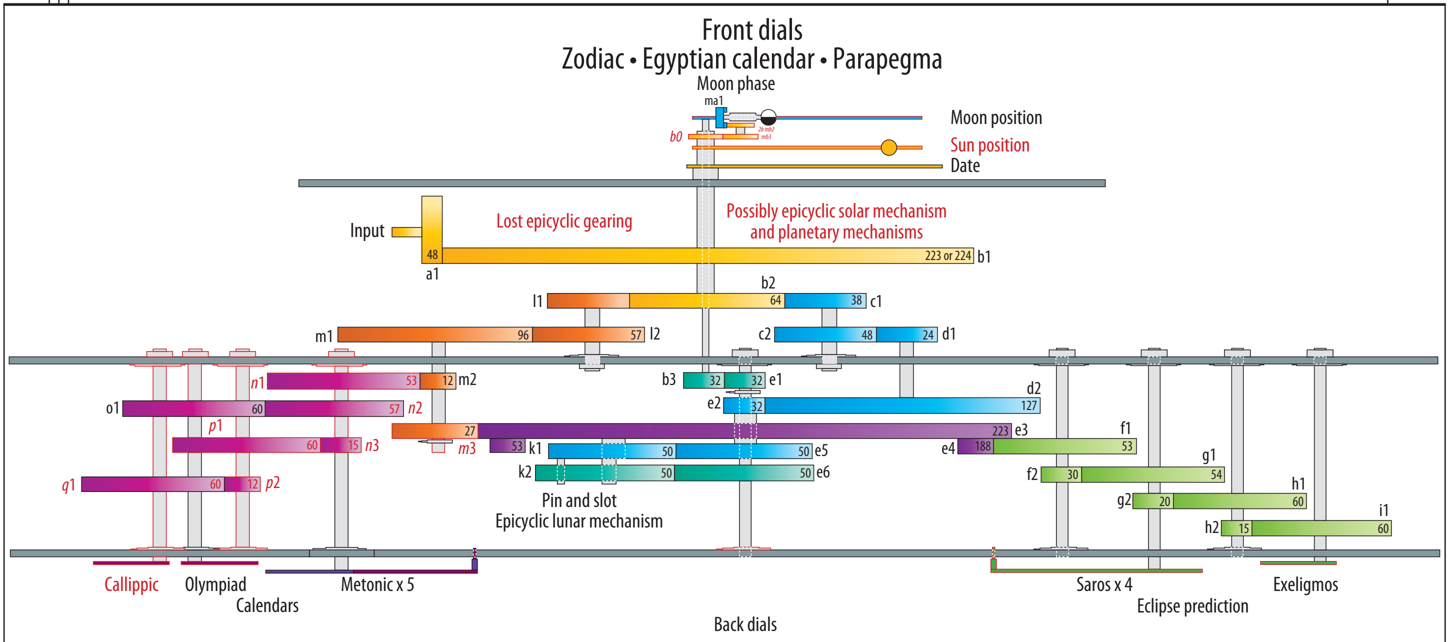

Figure 4. Schematic gear diagram. Elements in black are those for which there is evidence; those in red are conjectural. Note that two gears have 38 teeth (= 2 × 19); one gear has 127; and one gear (or possibly two) has 223. Three gears have 53 teeth, the first of which contributes to the correct rotation for the lunar anomaly; the other two cancel out the effect of the first, where this prime factor isn't wanted. ***Copyright 2011 Images First Ltd.***

DNA and sent it to a website offering a DNA matching service. Although the date seemed implausible, an immediate match was received.

Of course, the dial works over many decades because the cycles repeat, and we subsequently found many different possible matches between the glyph sequence and the historical eclipse record using the rather mundane technique of a brute-force Excel macro. We also found evidence for a small extra dial whose purpose was to indicate an extension to three Saros cycles, known as an Exeligmos cycle.

Once we determined that the lower back definitely displayed a Saros cycle, it was relatively easy to discover how to turn the dial pointer. We needed a gear with 223 teeth, and there was only one candidate—a large gear visible on the back of the main fragment for more than 100 years whose purpose had previously been misinterpreted. The back of this gear has a system of four small gears, two of which the large gear carries epicyclically—that is, their axes are mounted on the large gear, so they move around with it. What were they doing there?

Although these four gears looked fairly equal in size, their tooth counts were uncertain, so we entered all the thousands of combinations of credible tooth counts into a huge Excel spreadsheet. After months of frustration, nothing plausible emerged until we remembered that Michael Wright had noticed a rectangular slot in one of the four gears, into which fit a pin from the gear directly behind it. He also proposed that this pair of gears was mounted with the individual gear centers slightly displaced from each other. As the lower gear turned regularly, it would superimpose a quasi-sinusoidal motion when driving the other gear: the pin driving the upper gear would sometimes be nearer its center, sometimes farther away.

Although Wright made this brilliant observation, he understandably dismissed it because it appeared to have no sensible function in his own model. In our new model, these smaller gears were mounted on a very slow-moving larger gear that might make them calculate the variation of the moon's motion during its orbit. This incredibly clever device caused a drive variation that mimicked the "first anomaly" of the moon's motion—the variation in its angular motion across the sky from night to night. Although the Greeks did not recognize the cause, this real astronomical variation is due to the lunar orbit being elliptical rather than circular.

For this to work, all tooth counts on the four small gears needed to be equal—our initial mistake had been to follow Wright's model in making them unequal. The pin and slot made them relevant, not their subtle tooth counts. The input to the system was the moon's mean rotation relative to the stars; by mounting this pin-and-slot gear device on the turntable gear, the designer had ingeniously arranged for the system's output to be the variation in lunar motion. It not only had the right amplitude but also the right period—one slightly different from the full-moon to full-moon month due to the precession of the moon's orbit by the sun's gravitational influence.

Figure 5. Computer reconstructions using Lightwave 3D. (left) The mechanism's front, showing pointers for the date, sun, moon, and three conjectural planets: Mercury, Venus, and Mars. The inscriptions are a calendar describing the rising and setting of stars in the annual cycle. (right) Exploded model, showing the complexity of the lunar anomaly mechanism's gearing as well as sliding pointers that follow the spiral dials of the Metonic calendar and the Saros eclipse prediction scale. ***Copyright 2011 Images First Ltd.***

The Greeks, like the Babylonians before them, were well aware of these subtle period differences, although, again, they knew nothing of their physical causes. The mechanism's designer modeled the lunar anomaly in the gearing by mounting the pin-and-slot gears on the large 223-tooth gear that turned the Saros pointer. The result was a very slightly lengthened period to accommodate the variation produced by the pin-and-slot gears.

In modern astronomical terms, the rate needed for the large gear's rotation was the rotation of the long axis of the moon's orbit, which precesses slowly in a period just under nine years. The designer arranged for this large gear to turn at the correct rate, which requires the number 53 as one of the prime factors. The presence of 53-tooth gears in the chain was some of the most powerful evidence that we could possibly have that our theory was correct. Everything else fell into place—now we could explain all the tooth counts in the 30 surviving gears (except for one, which is still a mystery) in terms of two great lunar-solar cycles from Babylonian astronomy.

With this evidence that the ancient Greeks possessed extraordinary technical design ability, it is tempting to speculate on what else they might have designed and built. Did they, for example, have other mechanical calculators for surveying or commercial calculations? No surviving artifact or literary evidence suggests that they did, but the existence of astronomical mechanisms and display devices is mentioned several times in well-authenticated texts.

VISUALIZATION AND ANIMATION

Scientists and researchers, including Michael Wright, often use physical models in bronze or brass to gain scientific insight. However, we chose to make a computer model because it would remain far more flexible as our theories developed. Perhaps the best choice would have been to use a CAD program for this, but one member of our team was a former filmmaker, so we used Newtek's Lightwave 3D film and TV animation software. As Figure 5 shows, with this software we could build complex objects from primitive forms by using processes such as cloning, beveling, and Boolean operations. The software introduces mathematical expressions to turn and rotate the gears and pointers at their correct relative rates. This powerful software has the great advantage of allowing the use of ray tracing to produce animated photorealistic models; the animations have proven invaluable for presentations, exhibitions, and a film that is currently in production. A video made by Nature shows examples of these models (www.nature.com/nature/videoarchive/antikythera).

We recently enhanced our model with all the axles, pointers, dials, plates, rivets, and pins revealed in the CT images. The Antikythera mechanism is engineered at a tiny scale—the offset between the axis of the gear with the pin and that of the one with the slot is just over 1 millimeter. It offers evidence of a lost tradition of engineering that seemingly never achieved its full potential. Why this engineering capability did not develop in the classical world outside the field of astronomical calculating machines remains a mystery. Evidence for the tradition seems to have largely disappeared for a millennium (with the exception of a simple geared device in the 6th century), until the production of Islamic and Chinese mechanisms in the 10th and 11th centuries and the great astronomical clocks of the 14th century.

The use of surface imaging and CT has the extraordinary advantage, in archaeological terms, of being noninvasive and leaving the primary material unchanged.

HOW WELL DID THE CALCULATOR WORK?

Future experiments with metal reconstructions of the mechanism could give insight into its likely performance in use, but as a first step, we used computer simulations[8] and reexamined the CT images used in counting the gear teeth. To estimate manufacturing errors, we used Mathematica to fit models to the angular positions of the teeth. For example, the random error in tooth-center placement varies between gears from about 0.1 to 1 degree. A few showed a more systematic variation characterized by a sinusoidal variation around the whole gear.

To investigate how this would have affected the calculator's performance, we simulated the gear trains in Mathematica, generating sets of gears with appropriate errors and using a simple linear interpolation to pass the drive from tooth to tooth to the pointer on the relevant dial. The mechanism's operation is based on one rotation of the big wheel (b1 in Figure 4) representing one year. A crown gear turned this wheel (a1 in Figure 4), with the crown almost certainly turned by hand using some kind of knob or crank handle. We repeated numerical gear-train experiments many times to build up a picture of how accurate a typical device's predictions would have been. Our preliminary conclusion is that the indications on the calendrical dials—for example, the Metonic month or the Saros eclipse prediction—were indeed sufficiently accurate for their purpose. The moon position indicator, however, involves "gearing up," amplifying angular errors so that the indicated position could differ by 20 degrees from the designer's intention. Such a large error is easily noticed when comparing predictions with the moon's actual position in the sky; it exceeds the amplitude of the "first anomaly" variation that the mechanism was so cleverly designed to incorporate. A possible interpretation is that truly accurate prediction was not the device's primary purpose—approximate prediction of astronomical phenomena by mechanical means was achievement enough.

The limited accuracy might suggest that this technology would have been inadequate for the demands of financial computation, explaining the lack of remains or reference to other kinds of mechanical calculators from classical times. However, the development of a more "digital" form, with the discrete gear stepping required for accurate numerical calculation, was possible. Indeed, aspects of it appear in the design (possibly only theoretical) of Heron's hodometer, a distance-measuring mechanism dating back to circa 10 to 70 AD.[9]

WHAT WAS THE ANTIKYTHERA MECHANISM FOR?

Although divers found the mechanism in a shipwreck, it was not a nautical device—it was simply being transported by sea when disaster struck. Recent computational research by some of our Greek colleagues on the astronomical information in the inscriptions suggests the optimum geographic latitude at which the device might have been intended to work.[10]

We now know a great deal more about what the mechanism could calculate and display, but its real purpose remains something of an enigma. The discovery that the mechanism had a four-year dial displaying the sequence of the pan-Hellenic games, including the Olympic games, implies a social as well as astronomical function.[2] When we began our investigation, we looked carefully for evidence that it had been built for astrological purposes, with mechanics or inscriptions related to things like the "lot of Fortune," but we found nothing of the sort.

Perhaps it was a material testament to what the Greeks knew about astronomy at the time, a working demonstration of their knowledge. The ancient Greeks considered the heavenly bodies to be embodiments of the divine, so it might have been a celebration of the cosmos, just as the later medieval astronomical clocks were constructed in cathedrals to celebrate God's great creation.

Although it is the only device of its kind that is so far known to have survived, the Antikythera mechanism is so sophisticated and complex that it must have developed from the inherited tradition of a long line of precursors. This line might go back directly to the greatest scientist of the ancient world, since texts by Cicero from the first century BCE mention two such devices made by Archimedes.

The use of surface imaging and CT has the extraordinary advantage, in archaeological terms, of being noninvasive and leaving the primary material unchanged. The gathering of such detailed information also provides a database that is both a resource for future research and insurance against any future deterioration of the artifact.

We have used a wide range of computing techniques, some of which were specialized and sophisticated, and others that were simplicity personified. The flexibility of a high-level language such as Mathematica allowed relatively rapid development of statistical analysis programs, letting us do "experimental archaeology" in an initial assessment of the device's accuracy in use. Constructing video simulations of the gear trains and the display dials not only provided superb material for explaining our discoveries to nonspecialists, but also developed our own understanding of the mechanism's structure. Our extensive use of so many different kinds of software might not be typical of general archaeology: our backgrounds are in astrophysics and mathematics, not classical studies or archaeology. Software use was always likely to be effective because of the artifact's mathematical nature.

Our work has stimulated a surprisingly large interest in the history of ancient technology, as demonstrated in a Web video of a magnificent Lego reconstruction of the mechanism's functions (www.youtube.com/watch?v=RLPVCJjTNgk). Our research team has expanded internationally, and researchers are exploring new avenues in many parts of the world. Our data continues to enable the reading of more inscriptions, and these are proving to be very fruitful areas of study. There are still many key questions: some we may be able to answer, some may never be resolved. Can we complete the model of how the mechanism worked? When exactly was it made? Who made it? Where was it made? Why did this extraordinary and powerful technology apparently disappear for hundreds of years? C

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