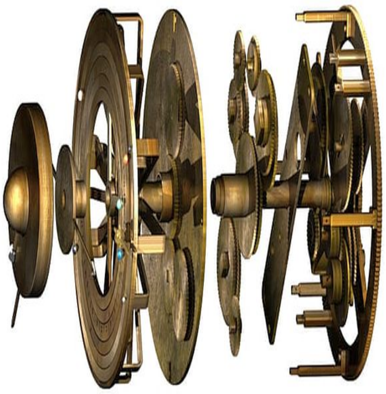


Het mechanisme van Antikythera 2/3

Beschrijving

Dit is het 2e deel van de blog over het **mechanisme van Antikythera**, een analoge computer gebouwd in Griekenland rond 80 v.Chr.

De Britse onderzoekers hebben nu, onder leiding van wetenschapper *Tony Freeth* (UCL â?? University College London), een computermodel van het mechanisme gemaakt om te achterhalen hoe de radertjes in elkaar zaten. Voor de reconstructie maakten ze gebruik van de inscripties en een wiskundig model van de beweging van de planeten dat voor het eerst werd bedacht door de oude Griekse filosoof *Parmenides*, zo schrijven ze in *Scientific Reports*. Volgens het UCL team gaf het mechanisme de beweging van de zon, de maan en de planeten weer op concentrische ringen (met hetzelfde middelpunt) die konden draaien. Op die ringen zouden gekleurde steentjes de positie van de planeten aanduiden.

The UCL Antikythera Research Team

We geven het woord aan Tony Freeth (in het Engels):

In March 2021 my group at University College London, known as the UCL Antikythera Research Team, published a new analysis of the machine. The team includes me (a mathematician and filmmaker); *Adam Wojcik* (a materials scientist); *Lindsay MacDonald* (an imaging scientist); *Myrto Georgakopoulou* (an archaeometallurgist); and two graduate students, *David Higgon* (a horologist) and *Aris Dacanalis* (a physicist). Our paper posits a new explanation for the gearing on the front of the mechanism, where the evidence had previously been unresolved. We now have an even better appreciation for the sophistication of the deviceâ??an understanding that challenges many of our preconceptions about the technological capabilities of the ancient *Greeks*.

The UCL Antikythera Research Team

Ancient Astronomy

We know the Greeks of that era were accomplished naked-eye astronomers. They viewed the night sky from a geocentric perspectiveâ??every night, as *Earth* turned on its axis, they saw the dome of stars rotating. The starsâ?? relative positions remained unchanged, so the Greeks called them the â??*fixed stars*.â?• These early astronomers also saw bodies moving against the background of stars: the moon goes through a rotation against the stars every 27.3 days; the sun takes a year.

The other moving bodies are the planets, named â??*wanderers*â?• by the Greeks because of their erratic motions. They were the deepest problem for astronomy at the time. Scientists wondered what they were and noticed that sometimes the wanderers move in the same direction as the sunâ??in â??*prograde*â?• motionâ??then come to a stop and reverse direction to move in â??*retrograde*.â?• After a while they reach another stationary point and resume prograde motion again. These rotations are called the synodic cycles of the planetsâ??their cycles relative to the sun. The seemingly strange reversals happen because, as we know now, the planets orbit the sunâ??not, as the ancient Greeks believed, Earth.

Primary function

In modern terms, all the moving astronomical bodies have orbits close to the plane of Earthâ??s motion around the sunâ??the so-called eclipticâ??meaning that they all follow much the same path through the stars. Predicting the positions of the planets along the ecliptic was very difficult for early astronomers. This task, it turns out, was one of the primary functions of the *Antikythera mechanism*. Another function was to track the positions of the sun and moon, which also have variable motions against the stars.

Babylon

Much of the mechanismâ??s design relies on wisdom from earlier Middle Eastern scientists. Astronomy in particular went through a transformation during the first millennium B.C.E. in *Babylon* and *Uruk* (both in modern-day *Iraq*). The *Babylonians* recorded the daily positions of the astronomical bodies on clay tablets, which revealed that the sun, moon and planets moved in repeating cyclesâ??a fact that was critical for making predictions. The moon, for instance, goes through 254 cycles against the backdrop of the stars every 19 yearsâ??an example of a so-called period relation. The *Antikythera mechanism*â??s design uses several of the *Babylonian* period relations.

One of the central researchers in the early years of *Antikythera* research was German philologist *Albert Rehm*, the first person to understand the mechanism as a calculating machine. Between 1905 and 1906 he made crucial discoveries that he recorded in his unpublished research notes. He found, for instance, the number 19 inscribed on one of the surviving Antikythera fragments. This figure was a reference to the 19-year period relation of the moon known as the *Metonic cycle*, named after Greek astronomer *Meton* but discovered much earlier by the *Babylonians*. On the same fragment, *Rehm* found the numbers 76, a Greek refinement of the 19-year cycle, and 223, for the number of lunar months in a *Babylonian* eclipse-prediction cycle called the *saros* cycle. These repeating astronomical cycles were the driving force behind *Babylonian* predictive astronomy.

Cicero, Archimedes and Derek J. de Solla Price

The second key figure in the history of *Antikythera* research was British physicist turned historian of science *Derek J. de Solla Price*. In 1974, after 20 years of research, he published an important paper, â??*Gears from the Greeks*.â?• It referred to remarkable quotations by Roman lawyer, orator and politician *Cicero* (106â??43 B.C.E.).
One of these described a machine made by mathematician and inventor *Archimedes* (circa 287â??212 B.C.E.) â??*on which were delineated the motions of the sun and moon and of those five stars which are called wanderers â?¦* (the five planets) *â?¦ Archimedes â?¦ had thought out a way to represent accurately by a single device for turning the globe those various and divergent movements with their different rates of speed.*â?• This machine sounds just like the *Antikythera* mechanism. The passage suggests that *Archimedes*, although he lived before we believe the device was built, might have founded the tradition that led to the *Antikythera* mechanism. It may well be that the *Antikythera mechanism* was based on a design by *Archimedes*.

Fiendishly Complex

For decades researchers were stuck trying to decipher the workings of the device by looking at the surface of its disintegrating fragments. In the early 1970s they finally got to peek inside. *Price* worked with Greek radiologist *Charalambos Karakalos* to obtain x-ray scans of the fragments. To their astonishment, the researchers found 30 distinct gears: 27 in the largest fragment and one each in three others. *Karakalos*, with his wife, *Emily*, was able to estimate the tooth counts of the gearwheels for the first time, a critical step in understanding what the mechanism calculated. The machine was looking more complicated than anyone had conceived.

The x-ray scans were two-dimensional, meaning that the structure of the gearing appeared flattened, and they revealed only partial pictures of most of the gears. Scientists could only infer the number of teeth on many of the gears. Despite these shortcomings, *Price* identified a gear trainâ??a set of linked gearsâ??that calculated the average position of the moon on any specific date by using its period relation of 254 sidereal rotations in 19 years. Driven by a prominent feature on the front of the mechanism called the main drive wheel, this gear train starts with a 38-tooth gear (two times 19, as a gear with just 19 teeth would be a bit too small). This 38-tooth gear drives (via some other gears) a 127-tooth gear (half of 254; the full number would require too large a gear).

Zodiac Dial

It seems that the device could be used to predict the positions of the sun, moon and planets on any specific day in the past or future. The maker of the machine would have had to calibrate it with the known positions of these bodies. A user could then simply turn a crank to the desired time frame to see astronomical predictions. The mechanism displayed positions, for instance, on a â??*zodiac dial*â?• on the front of the mechanism, where the ecliptic was divided into a dozen 30-degree sections representing the constellations of the zodiac. Based on the x-ray data, *Price* developed a complete model of all the gearing on the device.

Demolition of Priceâ??s model or not?

*Price*â??s model was my introduction to the *Antikythera mechanism*. My first paper, in fact, â??*Challenging the Classic Research*,â?• was a comprehensive demolition of most of *Price*â??s proposed gearing structure for the machine. Nevertheless, *Price* correctly determined the relative positions of the major fragments and defined the overall architecture of the machine, with date and zodiac dials at the front and two large dial systems at the back.
*Price*â??s achievements were a significant step in decoding the *Antikythera* mystery.

A third key figure in the history of *Antikythera* research is *Michael Wright*, a former curator of mechanical engineering at *Londonâ??s Science Museum*. In collaboration with Australian professor of computer science *Alan G. Bromley*, *Wright* carried out a second x-ray study of the mechanism in 1990 using an early 3-D x-ray technique called linear tomography. *Bromley* died before this work bore fruit, but *Wright* was persistent, making important advances, for example, in identifying the crucial tooth counts of the gears and in understanding the upper dial on the back of the device.

The *Antikythera mechanism*, with its precision gears bearing teeth about a millimeter long, is completely unlike anything else from the ancient world.

Surprise by X-Ray study

In 2000 I proposed the third x-ray study, which was carried out in 2005 by a team of academics from *England* and *Greece* in collaboration with the *National Archaeological Museum* in *Athens*. *X-Tek Systems* (now owned by *Nikon*) developed a prototype x-ray machine to take high-resolution 3-D x-ray images using microfocus x-ray computed tomography (x-ray CT). *Hewlett-Packard* used a brilliant digital imaging technique called polynomial texture mapping for enhancing surface details.

The new data surprised us.

The first major breakthrough was my discovery that the mechanism predicted eclipses in addition to the motions of the astronomical bodies. This finding was connected to the inscription *Rehm* had found that mentioned the 223-month saros eclipse cycle. The new x-rays revealed a large, 223-tooth gear at the rear of the mechanism that turns a pointer around a dial that spirals out, making four turns in total that are divided into 223 sections, for 223 months. Named after the customary name of the *Babylonian* eclipse cycle, the *saros* dial predicts which months will feature eclipses, along with characteristics of each eclipse as described by inscriptions in the mechanism. The finding revealed an impressive new feature of the device, but it left a massive problem: a group of four gears lying within the circumference of the large gear that appeared to have no function.

It took months to understand these gears. When I did, the results were astonishing. These gears turned out to calculate the variable motion of the moon in a very beautiful way. In modern terms, the moon has variable motion because it has an elliptical orbit: when it is farther from Earth, it moves more slowly against the stars; when it is closer, it moves more quickly. The moonâ??s orbit, however, is not fixed in space: the whole orbit rotates in a period of just under nine years. The ancient Greeks did not know about elliptical orbits, but they explained the moonâ??s subtle motion by combining two circular motions in what is called an epicyclic theory.

I figured out how the mechanism calculated the epicyclic theory by building on a remarkable observation by *Wright*.
He had studied two of the four mysterious gears at the back of the mechanism. He saw that one of them has a pin on its face that engages with a slot on the other gear. It might seem to be a useless arrangement because the gears will surely just turn together at the same rate. But Wright noticed that the gears turn on different axes separated by just over a millimeter, meaning that the system generates variable motion. All these details appear in the x-ray CT scan. The axes of the gears are not fixedâ??they are mounted epicyclically on the large 223-tooth gear.

Wright was right

Wright discarded the idea that these gears calculated the moonâ??s variable motion because in his model, the 223-tooth gear turned much too fast for it to make sense. But in my model, the 223-tooth gear rotates very slowly to turn the pointer for the *saros* dial. Calculating the epicyclic theory of the moon with epicyclic pin-and-slot gears in this subtle and indirect way was an extraordinary conception by the ancient Greeks.
This ingenuity reinforces the idea that the machine was designed by *Archimedes*. This research on the back dials and gearing completed our understanding of the back of the mechanism, reconciling all the evidence to date.
My colleagues and I published our findings in 2006 in *Nature*. The other side of the device, however, was still very much a mystery.

The Front of the Mechanism

The most prominent feature of the front of the largest fragment is the main drive wheel, which was designed to rotate once a year. It is not a flat disc like most of the other gears; this one has four spokes and is covered in puzzling features. The spokes show evidence that they held bearings: there are circular holes in them for turning axles. The outer edge of the gear contains a ring of pillarsâ??little fingers that stick up perpendicularly, with shoulders and pierced ends that were clearly intended to carry plates. Four short pillars held a rectangular plate, and four long pillars held a circular plate.

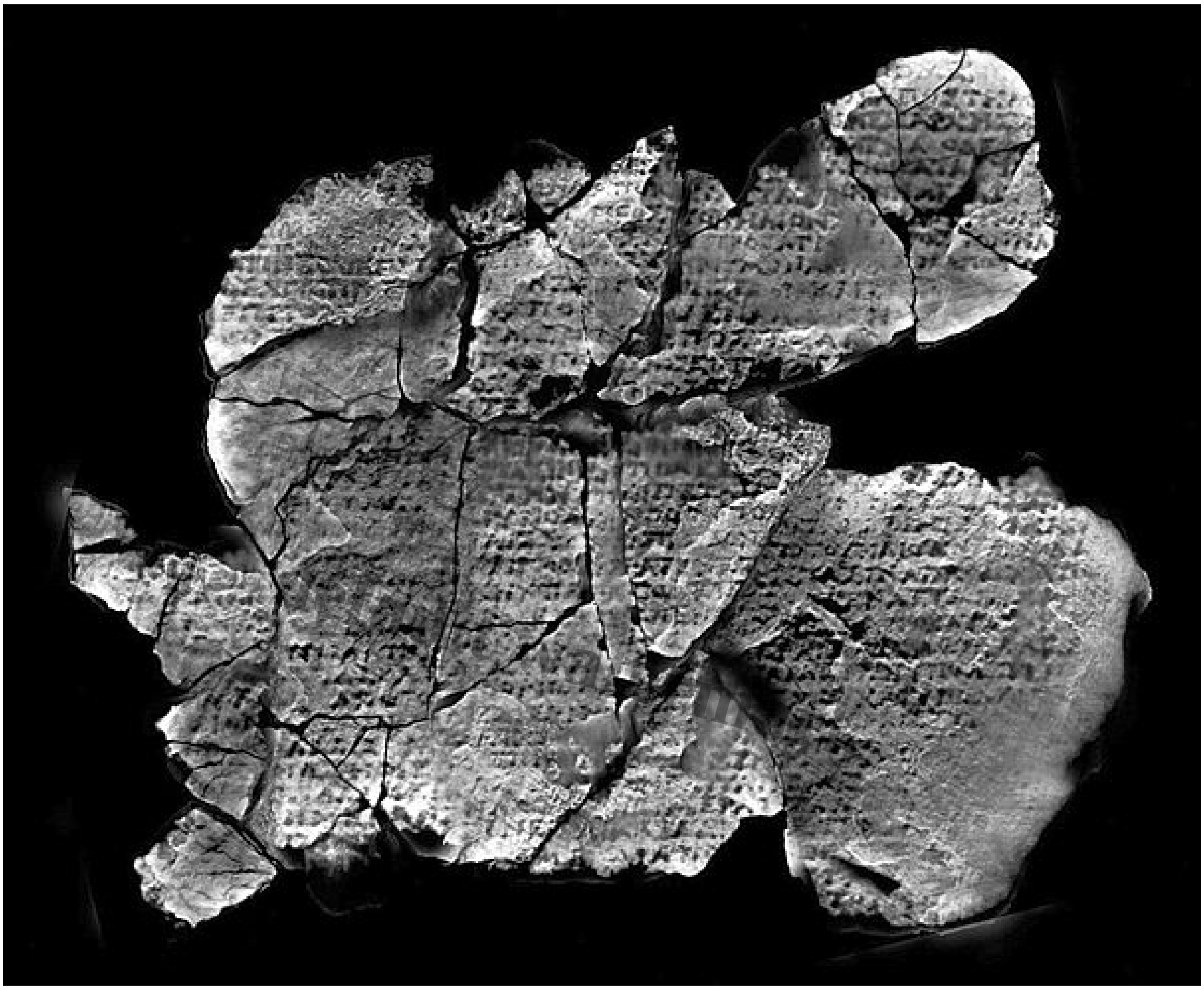
Following *Price*, *Wright* proposed that an extensive epicyclic systemâ??the two-circles idea the Greeks used to explain the odd reversing motions of the planetsâ??had been mounted on the main drive wheel. *Wright* even constructed an actual model gearing system in brass to show how it worked. In 2002 he published a groundbreaking planetarium model for the *Antikythera mechanism* that displayed all five planets known in the ancient world. (The discovery of Uranus and Neptune in the 18th and 19th centuries, respectively, required the advent of telescopes.) *Wright* showed that the epicyclic theories could be translated into epicyclic gear trains with pin-and-slot mechanisms to display the planetsâ?? variable motions.

Wrightâ??s model improved

When I first saw Wrightâ??s model, I was shocked by its mechanical complexity. It even featured eight coaxial outputsâ??tubes all centered on a single axisâ??that brought information to the front display of the device. Was it really plausible that the ancient Greeks could build such an advanced system? I now believe that Wrightâ??s conception of coaxial outputs must be correct, but his gearing system does not match the economy and ingenuity of the known gear trains. The challenge our UCL team faced was to reconcile Wrightâ??s coaxial outputs with what we knew about the rest of the device.

User manual

One crucial clue came from the 2005 x-ray CT study. In addition to showing the gears in three dimensions, these scans made an unexpected revelationâ??thousands of new text characters hidden inside the fragments and unread for more than 2,000 years. In his research notes from 1905 to 1906, *Rehm* proposed that the positions of the sun and planets were displayed in a concentric system of rings. The mechanism originally had two coversâ??front and backâ??that protected the displays and included extensive inscriptions. The back-cover inscription, revealed in the 2005 scans, was a user manual for the device. In 2016 *Alexander Jones*, a professor of the history of astronomy at *New York University*, discovered definitive evidence for *Rehm*â??s idea within this inscription: a detailed description of how the sun and planets were displayed in rings, with marker beads to show their positions.



Hidden message: X-ray CT scans made in 2005 revealed previously unseen inscriptions on the Antikythera mechanism, including a list of planetary cycles on the front cover (*shown here*) and a â??userâ??s manualâ?• on the back cover. Credit: Â© 2005 Nikon X-Tek Systems

Any model for the workings of the mechanism should match this descriptionâ??an explanation literally inscribed onto the back cover of the device describing how the sun and planets were displayed. Yet previous models had failed to incorporate this ring system because of a technical problem that we could not solve. *Wright* had discovered that the device used a semisilvered ball to show the phase of the moon, which it calculated mechanically by subtracting an input for the sun from an input for the moon. But such a process appeared to be incompatible with a ring system for displaying the planets because the outputs for Mercury and Venus prevented the moon-phase device from accessing the input from the sun gear system. In 2018 *Higgon*, one of the graduate students on our UCL team, came up with a surprisingly simple idea that neatly fixed this technical problem and explained a mysterious pierced block on one of the spokes of the main drive wheel. This block could transmit the â??*mean sun*â?• rotation (as opposed to the variable â??*true sun*â?• rotation) directly to the moon-phase device. This setup enabled a ring system for the front of the *Antikythera mechanism* that fully reflected the description in the back-cover inscription.

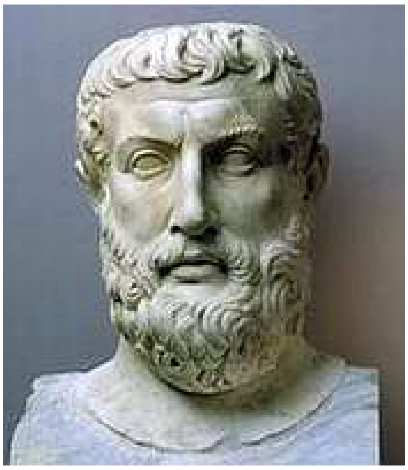
In trying to decipher the front of the device, it was imperative to identify the planetary cycles built into the mechanism because they define how the gear trains calculated planetary positions. Earlier research assumed that they would be based on the planetary period relations derived by the *Babylonians*. But in 2016 *Jones* made a discovery that forced us to discard that assumption.

Babylonians refined

The x-ray CT of the front-cover inscription shows it is divided into sections for each of the five planets. In the *Venus* section, *Jones* found the number 462; in the *Saturn* section, he found the number 442. These numbers were astonishing. No previous research had suggested that ancient astronomers knew them. In fact, they represent more accurate period relations than the ones found by the *Babylonians*. It seems that the makers of the *Antikythera* device discovered their own improved period relations for two of the planets: 289 synodic cycles in 462 years for *Venus* and 427 synodic cycles in 442 years for *Saturn*.

Parmenides of Elea

Jones never figured out how the ancient Greeks derived both these periods. We set out to try ourselves. *Dacanalis*, our other UCL graduate student, assembled a comprehensive list of the planetary period relations and their estimated errors from *Babylonian* astronomy. Could combinations of these earlier relations be the key to the more accurate *Antikythera* period relations? Eventually we found a process, developed by philosopher *Parmenides of Elea* (sixth to fifth century B.C.E.) and reported by *Plato* (fifth to fourth century B.C.E.), for combining known period relations to get better ones.



Parmenides of Elea

We proposed that any method the *Antikythera* creators used would have required three criteria: accuracy, factorizability and economy. The method must be accurate to match the known period relations for *Venus* and *Saturn*, and it must be factorizable so the planets could be calculated with gears small enough to fit into the mechanism. To make the system economical, different planets could share gears if their period relations shared prime factors, reducing the number of gears needed. Such economy is a key feature of the surviving gear trains. Based on these criteria, our team derived the periods 462 and 442 using the idea from *Parmenides* and employed the same methods to discover the missing periods for the other planets where the inscriptions were lost or damaged.

Mercury and Venus

Armed with the period relations for the planets, we could now understand how to fit the gear trains for the planets into the tight spaces available. For *Mercury* and *Venus*, we theorized economical five-gear mechanisms with pin-and-slot devices, similar to *Wrightâ??*s mechanisms for these planets. We found strong supporting evidence for our reconstruction in one four-centimeter-diameter fragment. Inside this piece, the x-ray CT shows a disk attached to a 63-tooth gear, which turns in a d-shaped plate. The number 63 shares the prime factors 3 and 7 with 462 (the *Venus* period). A gear train using the 63-tooth gear could be designed to match a bearing on one of the spokes of the main drive wheel. A similar design for *Mercury* matches the features on the opposite spoke. These observations gave us great confidence that we were on the right track for *Mercury* and *Venus*.

Mars, Jupiter and Saturn

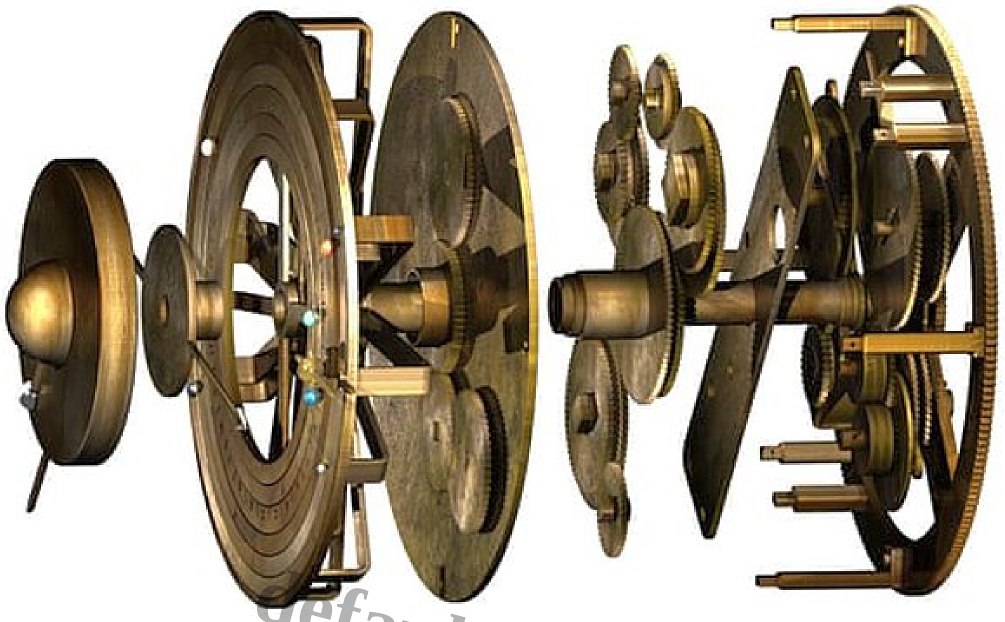
For the other known planetsâ??Mars, Jupiter and Saturnâ??our team conceived of very compact systems to fit the available space. These designs were a radical departure from *Wright*â??s systems for these planets. Working independently, *ChristiÃ¡n C. Carman* of the *National University* of *Quilmes* in *Argentina* and I had shown that the subtle indirect gearing system for the variable motion of the moon could be adapted for these planets. Our UCL team proved that these gearing systems could be extended to incorporate the new period relations for the planets. This system allowed the *Antikythera* makers to mount several gears on the same plate and design them to precisely match the period relations.

These economical seven-gear trains could intricately interleave between the plates on the pillars of the main drive wheel so that their outputs conformed to the customary cosmological order of the celestial bodiesâ??*moon, Mercury, Venus, sun, Mars, Jupiter* and *Saturn*â??that determines the layout of the ring system. The dimensions of the available spaces between the plates were exactly right to accommodate these systems, with some spare capacity and some evidence still unexplained.

We added a mechanism for the variable motion of the sun and an epicyclic mechanism for calculating the â??*nodes*â?• of the moonâ??the points at which the moonâ??s orbit cuts through the plane of the ecliptic, making an eclipse possible. Eclipses happen only when the sun is close to one of these nodes during a full or new moon.
Medieval and renaissance astronomers called a double-ended pointer for the nodes of the moon a â??*dragon hand*.â?•
The epicyclic gearing for this dragon hand also exactly explained a prominent bearing on one of the spokes that had previously appeared to have no function. We had finally explained all the features on the main drive wheel; we published our findings in March 2021 in *Scientific Reports*.

A Beautiful Conception

We now understood how the front display matched the description in the back-cover userâ??s manual, with the sun and planets shown by marker beads on concentric rings. The front cover also displayed the moonâ??s phase, position and age (the number of days from a new moon), and the dragon hand that showed eclipse years and seasons.



Een reconstructie van het mechanisme van Antikythera met een geocentrisch beeld van het heelal Â© UCL

With the concentric rings for the planets, we realized that we could now make sense of the front-cover inscription as well. This writing is a formulaic list of the synodic events of each planet (such as its conjunctions with the sun and its stationary points) and the intervals in days between them. On the back plate, the eclipse inscriptions are indexed to markings on the *saros* dial. On the front plate, inscriptions about the risings and settings of stars are indexed to the *zodiac* dial. Our insight was that the inscriptions on the front could refer to index letters on the planetary rings: if the sun pointer is at one of these letters, then the corresponding inscription entry describes the number of days to the next synodic event. Because the left-hand side of the inscription, where we would expect these index letters to be, is missing, we cannot prove the hypothesisâ??but it is a compelling explanation.

The device is unique among discoveries from its time. It single-handedly rewrites our knowledge of the technology of the ancient Greeks. We knew they were highly capableâ??they built the *Parthenon* and the *Lighthouse of Alexandria* even earlier than the *Antikythera mechanism*. They had plumbing and used steam to operate equipment.
But before the discovery of the *Antikythera mechanism*, ancient Greek gears were thought to be restricted to crude wheels in windmills and water mills. Aside from this discovery, the first precision-geared mechanism known is a relatively simpleâ??yet impressive for the timeâ??geared sundial and calendar of *Byzantine* origin dating to about C.E. 600. It was not until the 14th century that scientists created the first sophisticated astronomical clocks.
The *Antikythera mechanism*, with its precision gears bearing teeth about a millimeter long, is completely unlike anything else from the ancient world.

Why did it take centuries for scientists to reinvent anything as sophisticated as the *Antikythera device*, and why havenâ??t archaeologists uncovered more such mechanisms? We have strong reasons to believe this object canâ??t have been the only model of its kindâ??there must have been precursors to its development. But bronze was a very valuable metal, and when an object like this stopped working, it probably would have been melted down for its materials.

Shipwrecks may be the best prospects for finding more of them. As for why the technology was seemingly lost for so long before being redeveloped, who knows? There are many gaps in the historical record, and future discoveries may well surprise us.

With the *Antikythera mechanism*, we are clearly not at the end of our story. We believe our work is a significant advance, but there are still mysteries to be solved. The *UCL Antikythera Research Team* is not certain that our reconstruction is entirely correct because of the huge loss of evidence. It is very hard to match all of the surviving information. Regardless, we can now see more clearly than ever what a towering achievement this object represents.

Datum aangemaakt
2021/12/15