CELESTIAL GEARBOX

The oldest known computer is a mechanism designed to calculate the location of the sun, moon, and planets.

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Photos: Department of Mechanical Engineering, Aristotle University of Thessaloniki

Like many great discoveries, the Antikythera Mechanism was found by accident. In 1900, sponge divers came across a shipwreck off the coast of the Greek island of Antikythera, and over the next year or so, they retrieved a number of artifacts—statues, coins, jewelry, and so on. One item they brought to the surface was not immediately recognized: a lump of corroded bronze and wood, broken into several calcified fragments.

The artifacts were all sent to the National Museum of Archaeology in Athens for cataloguing and restoration, but the bronze lump sat almost unnoticed. When researchers finally turned their attention to it, they couldn't agree on what it was. The bronze lump seemed to contain gears and dials, suggesting it was a navigational device or perhaps even a clock. Some archaeologists suggested that it was a mechanism too advanced for the date of the shipwreck—the first century B.C.—and thought it might have been lost at sea more recently.

In time, however, analysis using X-ray and other advanced imaging revealed its true nature, and the Antikythera Mechanism is now considered as important for technology and sciences as the Acropolis for the architecture and arts. The object is the remains of the earliest known analog computer.

Now we know that it was an extremely advanced mechanism that could be used to calculate and predict astronomical events. Detailed studies of the mechanism by various researchers have shown that it could predict with astonishing accuracy the position of the sun, moon, and the planets on the sky. It could also determine the phases of the moon, adjust the calendar, determine the dates of the ancient Olympic Games, and predict solar and lunar eclipses.

But before researchers like myself could make that assertion with full confidence, we would have to go beyond simply observing the artifact with sophisticated imaging tools. We would have to use that data to create a working model, and test our theories against the recreated mechanism itself.

IDENTIFYING THE COMPONENTS

Almost since the Antikythera Mechanism was first subjected to X-ray imaging, people have tried to reconstruct it. The unsolved purpose of the artifact often attracted amateurs and scientists operating outside their field of expertise. Ioannis Theofanidis, a Greek naval officer turned historical researcher, worked on the problem in the 1920s and 1930s; the English physicist Derek John de Solla Price published analyses of the device beginning in 1959; Allan Bromley, an Australian historian of computing, made in 1985 a rudimentary working model; and science museum curator Michael Wright built in 2005 a more complete operating model that showed the mechanism could predict eclipses. But the detail gathered through X-rays and examination of the external surfaces was relatively low, so these models were not accurate and complete.

To get a more-detailed understanding of the interior of the device, in 2005 researchers brought in a computed tomography imager—a machine for taking X-ray images through objects at incrementally changing angles—to make high-resolution three-dimensional scans of the mechanism. Using these data it was possible to dive inside the fragments and to identify all the mechanism's components. The first complete catalogue of all the components of the Antikythera Mechanism was created.

That data enabled dozens of researchers—myself included—a fuller understanding of the device as it had been built. The bronze pieces were originally housed in a wooden box, measuring about 32 cm × 18 cm × 10 cm, not much larger than a modern laptop. All told, the analysis found that the device incorporated seven pointers for taking readings, 19 shafts and axles, and at least 39 gears. The calcified fragments contain 29 identifiable gears and the existence of ten more has been inferred on account their necessity for calculating all the astronomical phenomena indicated in the inscriptions on the bronze plates. (Why display them if you cannot calculate them?)

The whole mechanism is linked, so that when the crank was turned or a pointer was adjusted by hand, all the gears and pointers moved in concert.

The axles and shafts were supported by three bronze plates, two of which were external (front and back), bearing the scientific scales and some inscriptions, as well as by a central support plate.

On the front side, there were two concentric circular scales. The outer scale had 365 subdivisions and the names of the 12 Egyptian months written in Greek. The inner scale had 360 subdivisions and the names of the 12 zodiac constellations. Behind the outer scale, which was removable, there were 365 holes.

Every four years the operator could detach the scale and shift it by one hole, thus taking into account leap years. Against these two scales, indicators for the sun, moon, and most probably the five planets known to the ancient Greeks moved, driven by the internal gears.

A rotating spherule, adapted with a crown gear to the pointer of the Moon, displayed the phases of the Moon. The movement of the Moon is not circular but elliptical. The display of this movement, which compensates for the anomaly caused by its eccentric orbit around the Earth, was achieved by the use of two eccentric gears, the axes of which are offset by 1.1 mm. The lower gear has a pin that engages with a slot on the upper gear, forcing it thus to rotate by a pin-and-slot arrangement. The epicyclical movement of the upper gear tracked the motion of the Moon in the sky with great accuracy.

A transparent model of the Antikythera Mechanism—three times larger than the original—allows researchers to better see the interior and observe the movements of the shafts, axles, and gears.
Photo: Department of Mechanical Engineering Aristotle University of Thessaloniki

The pointers of the two spiral dials on the back side of the mechanism had at one end a small vertical rectangular guiding pin that followed the gap of the spiral scales. The pin followed the spiral exactly like the tip of a record player needle. The pointers on the back side tracked eclipse cycles and the date of the Olympic Games.

Two more plates, attached on the internal sides of the protective wooden covers of the wooden box were fully covered with inscriptions that were likely a user's manual.

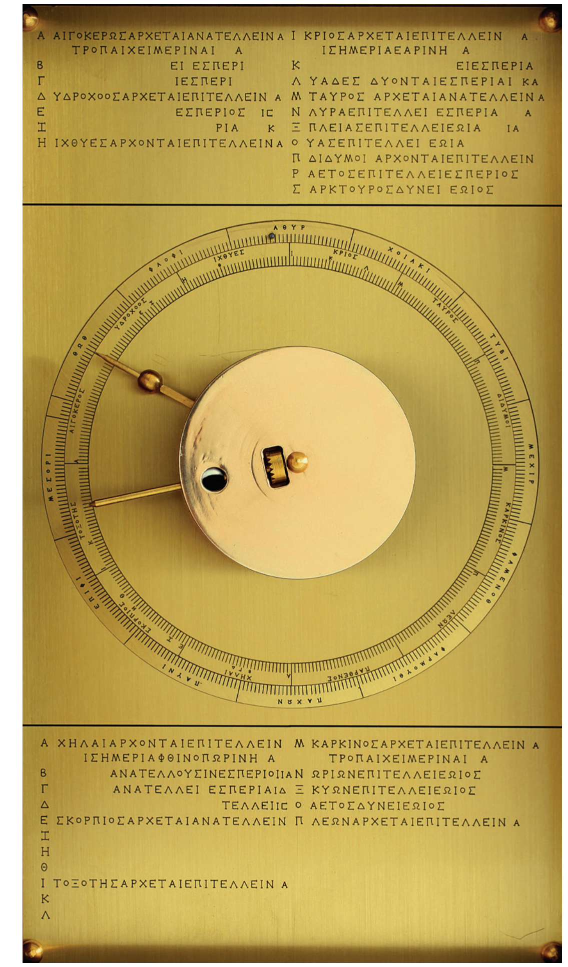
While the computed tomographic imaging could help researchers determine the dimensions and geometry of the gears of the artefact, there was a great uncertainty in how those measurements related to the original mechanism. The fragments had spent 2,100 years at the bottom of the sea and had suffered considerable damage. As a result, projecting those measurements onto the original geometrical parameters of the gears comes with large error bars.

One critical measurement for verifying the accuracy of the Antikythera Mechanism—the root and tip diameters of all gears and the teeth's root angle—could only be estimated based on the X-ray analysis. To better understand the device, we would have to construct a working model.

GEOMETRICAL PARAMETERS

The gears found in the Mechanism are the first in the history of mankind resembling the shape and philosophy of modern gears. Their triangular teeth are capable of transmitting angular motion but less so for power.

Our team at Aristotle University of Thessaloniki has been analyzing these basic geometrical parameters and the dimensions of the triangular teeth, and we have developed a mathematical model to estimate their original condition. Using the gears measured data and the equations of the mathematical model as input to an advanced software program, we found a common root angle and a common module for all gears of the Antikythera Mechanism.



The front of the Mechanism had pointers showing the location of the sun and moon against the zodiac, and a rotating spherule that indicated the moon's phase. Inscriptions suggest that the machine could also compute the location of the known planets.
Photo: Department of Mechanical Engineering Aristotle University of Thessaloniki

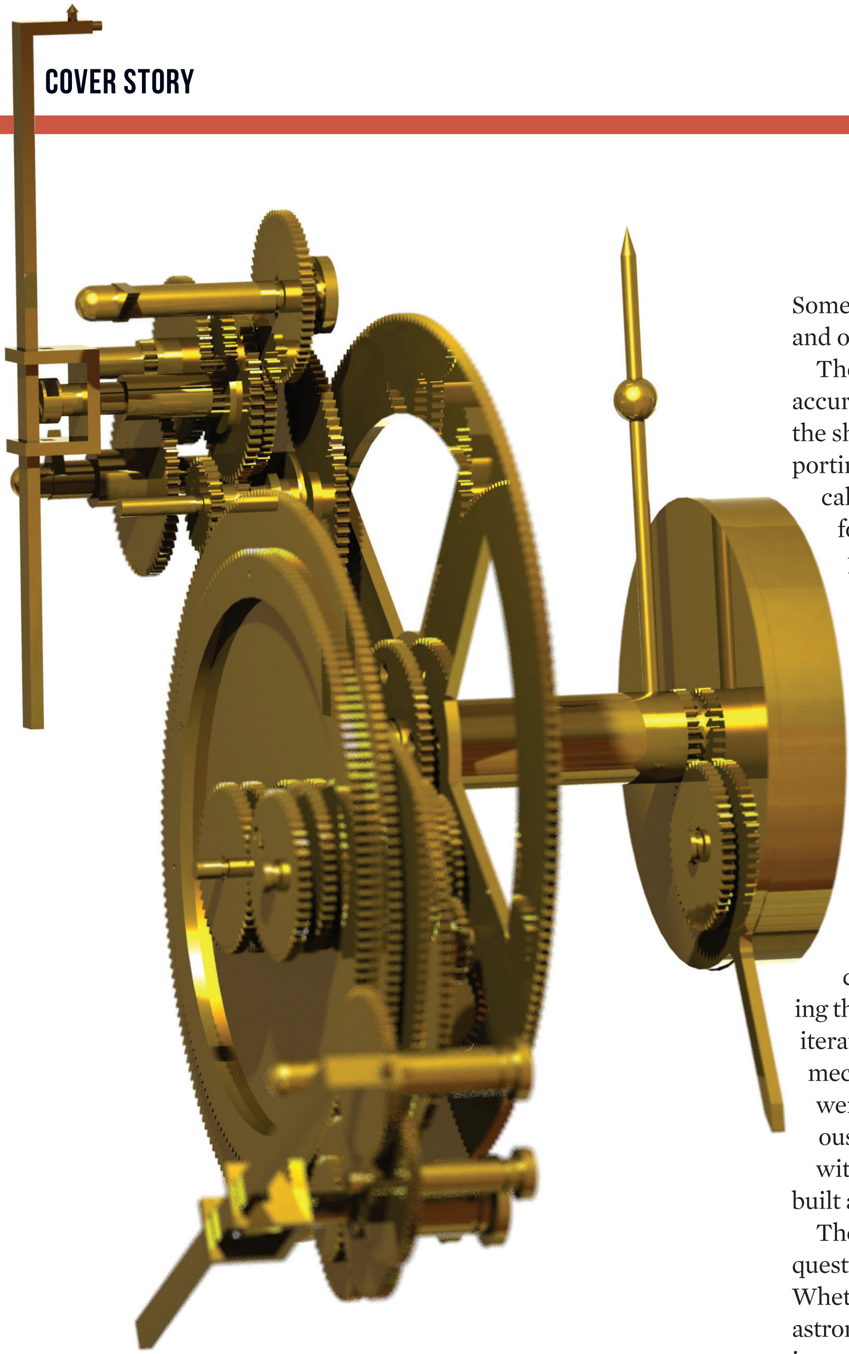
In the design of gears with triangular-shape teeth, the module is the ratio between the tip diameter and the number of teeth of a gear, with the formula:

$m = d/z$

We could compute the geometrical parameters of all gears and construct an accurate and functional model of the Mechanism, taking into account that the values we found are within the measured tolerances of the fragments.

There are other constraints on cooperating gears with triangular-shaped teeth. The minimal axial distance of two gears with triangular teeth must be a bit longer than that found in modern gears with involute-shape teeth in order to avoid blocking. There is also a maximum axial distance where the teeth of the two gears are still in contact.

A full investigation of the axial distances of the gears requires, beyond the theoretical approach mentioned earlier, a detailed investigation of the fragments of the Mechanism. Using the software



The Mechanism was a complex astronomical computer, featuring at least 42 gears, 21 axles and shafts, and eight pointers (shown here in a 3-D rendering). Advanced software is enabling us to learn more about how—and how accurately—the machine worked. *Illustration: 3D Solidforms*

package "VG Studio Max" to study the tomographies of the fragments, the center of each axle or shaft and the corresponding distances between them were measured. Occasionally these measurements are affected by errors due to the damage of the fragments, leading to a non-perfect alignment of the corresponding tomography section.

With the aid of advanced software and using the measurements of the axial distances of the cooperating gears, the minimum and maximum permissible values of the axial distances between the cooperating gears were calculated. Then an intermediate value within the limits of the tolerances of the axial distances measured at the fragments was determined as the final value to be used for the reconstruction of the Antikythera Mechanism.

Apart from their dimensions, the gears differ in their shape only by the form of their central hole. Some have round holes, others have squares ones, and one has a pentagonal hole.

The fragment's tomographic data cannot give accurate information about the dimensions and the shapes of the shafts, the axles, and the supporting components due to the damage of the calcified fragments, which are corroded, deformed, and sometimes shattered after 2,100 years on the bottom of the sea. But the shape of the central holes enables us to determine which gears turned on the same axis.

Two pairs of shafts, for instance, are concentric, which means that one of the two shafts passes through the other; the two shafts rotated independently. Also there is an axis which has two eccentric cylindrical bearing points for two gears.

We started to create a new model of the device via parametric design. For each part, the geometric and dimensional values were examined in a way that those parts could be changed easily without the need of redesigning the other functional elements. Through an iterative process, we developed a design of the mechanism and simulated its operation, then were able to study how all the parts and the various elements operated. When we were satisfied with the results of the design process, we finally built a physical model for testing.

The hope was that we could address a still-open question about the purpose of the Mechanism: Whether it was originally a teaching tool for the astronomical schools of antiquity or a calculator intended to compute exact predictions of celestial phenomena.

PRACTICAL CONFIRMATION

One clue to the purpose of the mechanism comes from the way the device was operated. The gears were linked so that an operator could manually rotate one pointer to the position he wanted to input—say, moving the sun pointer to a particular day in the year—and the other indicators would turn in response. Theoretically, the operator could turn any of the pointers, but most investigators assumed that the most efficient means for setting the device involved manually adjusting either the sun pointer or the moon pointer, both located on the front plate, or a crank that worked a crown gear on the side of the mechanism that cooperated with a gear that rotated the sun pointer through the year.

An analysis made by our research team at Aristotle University of Thessaloniki—which included ourselves, John Seiradakis, Magdalini Anastasiou, Alexandros Basiakoulis, and Alexandros Tourtas—concluded that the three methods were not equal.

Because both the sun and the moon pointers made a full circuit for each cycle they represented—a year or a month, respectively—moon pointer would make 13.368 rotations for every rotation of the sun. Or for a single turn of the moon pointer, the sun pointer would travel in an arc of just 26.9 degrees. Not only does operating the mechanism through the moon pointer allow for greater precision, but it can also be accomplished with very little torque, almost 1/14th the amount needed to move the sun pointer.

Practical confirmation through our physical model confirms the theoretical conclusion: it is much easier and more precise to operate the mechanism through the moon pointer or by rotating the axis the pointer is attached.

Our research also uncovered a heretofore unnoticed calculation the mechanism could perform.

"Its sophistication suggests that it was not the first of its kind, but one of a sequence."

Among the fragments pulled from the seafloor was one labeled "D." In modern studies, fragment D is considered as a lone fragment, whose function had yet to be discovered. After an extensive study of fragment D, our team produced evidence that it was part of an arrangement used to calculate the equation of time—that is, the difference between the apparent position of the Sun and its mean annual position. A realistic simulated mechanical model that uses parts found in the fragment components, a gear and a cam, has been designed. The output of the proposed arrangement is a pointer on a scale of the front plate of the Antikythera Mechanism, which reproduces the equation of time for the epoch of its construction, around 150 B.C.

Taking into account these results, the mechanism now can be said to have had at least 42 gears, 21 axles and shafts, and eight pointers.

One difference between our model and others is the absence of pointers indicating the position of the planets. As we noted, the names of the planets known to the ancient Greeks are found on various fragments of the Mechanism, so it made sense to model-builders to assume gearing that could simulate the position of the planets using the pin-slot gearing found elsewhere in the Antikythera Mechanism. Up to now, however, no gears or axles or any other related mechanical elements that could calculate planetary position have been discovered among the fragments of the Mechanism. We cannot rule out the possibility that such gear-systems were part of the original Mechanism, but without actual evidence for their existence, our team decided not to include them in our model.

A SOPHISTICATED INSTRUMENT

In addition to a 1:1 scale model, we have also constructed a transparent model of the Antikythera Mechanism three times larger than the original ancient artifact (scale 3:1), so that during operation, one can better see the interior and observe the movements of the shafts, axles, and gears.

With the help of this model we are currently studying the accuracy of the mechanism's predictions. The first test results show that it accurately predicts astronomical phenomena, which leads us to the conclusion that the Antikythera Mechanism was a scientific instrument, an analog computer, which predicted accurately astronomical phenomena, and which had only a secondary use as an educational tool.

The Mechanism has been called the first computer, but that is likely not accurate. Its sophistication suggests that it was not the first of its kind, but one of a sequence that had been built for astronomical calculation. In antiquity, such calculating machines may not have been common, but it's unlikely the relic found on the sea floor off Antikythera was unique.

We might also ask ourselves, was astronomical calculation the only purpose that the ancient Greeks and others found for this sort of geared mechanism? No such machine has survived to the present, but that is not proof that none were ever constructed. ME

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