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Engineering: Archimedes of Syracuse

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Archimedes and Hiero II's Syracuse

Archimedes was and remains the most famous person from Syracuse, Sicily, in history. He belonged to the prosperous and sophisticated culture which the dominantly Greek population had built in the east of the island. The civilisation of the whole of ancient Sicily and South Italy was called by the Romans 'Magna Graecia' or 'Great Greece'. The citis of Magna Graecia began to be annexed by the Roman Republic from 327 BCE, and most of Sicily was conquered by 272. But Syracuse, a large and magnificent kingdom, the size of Athens and a major player in the politics of the Mediterranean world throughout antiquity, succeeded in staying independent until 212. This was because its kings were allies of Rome in the face of the constant threat from Carthage. Archimedes was born into this free and vibrant port city in about 287 BCE, and as far as we know lived there all his life. When he was about twelve, the formidable Hiero II came to the throne, and there followed more than half a century of peace in the city, despite momentous power struggles going on as the Romans clashed with the Carthaginians and Greeks beyond Syracuse's borders. Hiero encouraged arts and sciences, massively expanding the famous theatre.

Archimedes' background enabled him to fulfil his huge inborn intellectual talents to the full. His father was an astronomer named Pheidias. He was probably sent to study as a young man to Alexandria, home of the famous library, where he seems to have became close friend and correspondent of the great geographer and astonomer Eratosthenes, later to become Chief Librarian. Archimedes recorded his proofs and calculations as letters written in the native Doric Greek of Syracuse, and sent them to other scholars including Eratosthenes. Archimedes was related to the Syracusan royal family, as well, and Hiero, as a military star, in charge of a large army and huge fleet, encouraged him to design machines for use in warfare.

'Do Not Disturb My Circles'

To understand Archimedes' commitment to science, let us begin at the end, with his brutal death in 212 BCE, at the hands of the Romans. Hiero's long and peaceful reign came to an end when he died in 215 BCE. He was succeeded by his 15-year-old grandson Hieronymus who, under pressure from older advisors, transferred his allegiance from Rome to Carthage, which was scoring huge successes under its rising star, Hannibal. The Romans had no choice but to besiege Syracuse. It resisted the siege for more than two years, helped by Archimedes' war machines. But it was betrayed and captured by the Romans under Marcus Claudius Marcellus in 212 BCE during the Second Punic War.

Plutarch tells us that Archimedes was intently pondering a mathematical diagram drawn on the ground when the city fell. A Roman soldier commanded him to come and meet General Marcellus. But he refused, saying that he needed to complete his soluion to the problem. The furious soldier killed him with his sword. Archimedes' last words were reported to have been 'Do not disturb my circles'—he seems to have been more interested in protecting his diagram than in preserving his own life. His intellectual commitment and pride in his life's work are also suggested by his instruction that his tomb should be topped with a sculpture representing his favoruite mathematical breakthrough. This was his proof that in a sphere and a cylinder of the same height and the same diameter, the volume and surface area of the sphere are two thirds that of the cylinder including its bases.

Most Romans were not interested in Mathematics. Under their rule, his tomb was neglected and fell into disrepair. But in 75 BCE—so 137 years later—Cicero held the office of quaestor in Sicily. He made enquiries and at length discovered the tomb near the Agrgentine Gate, crumbling and overgrown. Cicero had it cleaned up. He said that among the Greeks 'geometry was held in highest honor; nothing was more glorious than mathematics. But we Romans have limited the usefulness of this art to measuring and calculating'. The tomb disappeared again and has never been found. It was probably in the large Hellenistic necropolis to the west of the city. But painters have re-imagined it for us.

The Archimedes Palimpsest

Archimedes was a world-changing mathematician as well as a physicist, engineer and inventor. He also foreshadowed modern calculus, arrived at a close approximation of π, and proved the theorem allowing the calculation of the area under a parabola. Our understanding of the processes by which he arrived at his mathematical conclusions has been much illuminated by the painstaking decipherment of what is known as the *Archimedes Palimpsest*. This is a parchment codex from 10th-century Byzantium, which had been overwritten with a Christian treatise in the 13th century. The palimpsest has had its own extraordinary adventures. Some of underlying Archimedes text was published in 1915, but the palimpsest went missing from Istanbul during the Greco-Turkish exchange of populations in 1922. It got into the hands of a rather shady French businessman, named Marie Louis Sirieix, who kept it in a cellar where it was damaged by moisture and mould. While in his possession, the codex was further wrecked by a forger, who added gold plate portraits to increase its value.

Sirieix died in 1956. His daughter Anne wanted to make a fortune out of the palimpsest. She asked Christie's to auction it in 1998. This led to a dramatic ownership case in the New York Federal Court. The Greek Orthodox Patriarchate of Jerusalem claimed ownership, but the judge decided in favour of Christie's and the palimpsest was bought by a mysterious private American, probably Jeff Bezos, for two million dollars. Fortunately, he seems to have handed it over voluntarily to the Walters Art Museum in Baltimore, where, in an astonishing feat of conservation and imaging, using ultraviolet and infrared light and X-ray, the full Archimedian text was deciphered between 1998 and 2008.

This has given us our sole known Greek copy of three treatises: *Stomachion, Method of Mechanical Theorems*,and *On Floating Bodies*. The first explores the mathematical properties of the fourteen pieces that are produced when a square is dissected into fourteen polygonal pieces. He asked, how many ways the fourteen pieces can be recombined to make a perfect square? The answer is 17,152 combinations.This was the design of a popular ancient board game, in which players rearranged the pieces to create non-square objects, such as an elephant. Archimedes' *Method of Mechanical Theorems*, however, contains the first known explicit use of infinitesimals. The method relies on the law of the lever, to which we shall return.

'Eureka, Eureka!'

The third newly found Greek treatise, *On Floating Bodies*, the first known work on hydrostatics, examined the positions that various solids will assume when floating in a fluid, according to their form and the variation in their specific gravities. But it also brings us on to the discovery for which Archimedes is surely most famous—the one that he made in his bath. It contains the first statement of the fundamental law of Physics, central to Fluid Mechanics, which is known as the 'Archimedes Principle':

> The upward buoyant force that is exerted on a body immersed in a fluid, whether fully or partially submerged, is equal to the weight of the fluid that the body displaces.

This principle has had thousands of practical applications, most obviously in the worlds of submarine engineering, ship building and aviation.

The fullest account we have of this momentous discovery comes from the Roman architect Vitruvius' *On Architecture*. Hiero had vowed to bestow a gold crown in a temple in thanks to the gods for his successes. He negotiated a fixed price with the contractor, and weighed out a precise amount of gold. An exquisite crown was made. But an accusation was made that some of the gold had been taken away and the weight made up with silver. Hiero asked Archimedes for advice. Archimedes, like many of us, did some of his best thinking in the bath. He ran one, and got into it, and noticed that the more his body was submerged, the more water ran out over the edge of the tub. He leapt out of the tub and ran home naked, shouting *'Eureka, Eureka'* (I've found [it], I've found [it]).

He then made two masses of the same weight as the crown, one of gold and the other of silver. He filled a large vessel with water to the very brim, and dropped the mass of silver into it. He measured the displaced water. He repeated the exercise with the gold mass, and discovered that less water was displaced—an amount corresponding to the lesser bulk of a mass of gold relative to a silver mass of the same weight. Then he dropped in the actual crown, and since more water was lost than in the case of the gold mass, he could deduce that the gold of the crown had indeed been diluted with silver. I've enjoyed the picture research for thi part of the lecture. The manufacturers or a mechanical bath seat that can lower you into and raise you out of the water has chosen ARCHIMEDES as brandname.

'Give Me a Place to Stand On and I Will Move the Earth'

Besides 'don't disturb my circles' and 'Eureka!', a third often-repeated saying is attributed to Archimedes: 'Give me a place to stand on, and I will move the Earth'. This resonant statement of confidence has inspired many repurposings, especially amongst revolutionary politicians. British radical democrat Tom Paine was himself an engineer, who designed Wearmouth Iron Bridge, and therefore much admired Archimedes. But he suggested that the leverage statement could be applied politically. In his *Rights of Man* he quotes the rousing statement, saying that it can equally be applied to Reason and Liberty: if we had 'a place to stand upon, we might raise the world'. But what Archimedes seems actually to have said, with more scientific precision, is 'Give me a lever long enough and a fulcrum on which to place it, and I shall move the world'. And he was right. You can indeed lift enormous weights with a beam, if it is long and strong enough, and you have worked out where to put the fulcrum.

Archimedes did not invent the lever, which in a simple form was used millennia earlier in Mesopotamia and Egypt. Some of Aristotle's pupils had succeeded in describing some aspects of the lever. But Archimedes was the first to offer a scientific explanation of how it worked, which allowed more precise calculation of the length of levers and positions of fulcrums in order to lift objects of different weight. And he also designed block-and-tackle pulley systems, allowing sailors to use the principle of leverage to lift objects that would otherwise have been too heavy to move.

Archimedes' Screw

Along with the bulk of the displaced bath water and the lever, Archimedes' most famous discovery is certainly his screw pump. This machine consisted of a revolving screw-shaped blade inside a cylinder. It was turned by hand, and one of its most important applications was for transferring water from a low-lying body of water into irrigation canals higher up. The Sicilian historian Diodorus, writing in the 1st century BCE, notices that an entire island in the delta of the Nile is easily irrigated by a device invented by his compatriot Archimedes, called a *kochlias*—the word for a snail with a spiral shell. Archimedes' screw is still used in the Nile delta today. It is, once again, Vitruvius who provides with a detailed description of an ancient Archimedian screw. It began with a tree trunk shaped into a cylindrical core, with a length 16 times its diameter. Eight helical blades were attached to it by nailing flexible willow twigs up to a height equal to the radius of the core. An outer cylinder was attached, and pitch coating applied to make it watertight. The rigid screw was then mounted so that it could be rotateed and tilted in the direction of the hypotenuse of a 3-4-5 triangle.

The Archimedes' screw is still in use today for pumping liquids—water in treatment plants, and granulated solids such as coal and grain. It has recently been adopted as one of the most environmentally friendly ways of moving water around. The Archimedes screw turbine (AST) has been described as 'fish friendly' based on the magnitude of observed impacts, such as low rates of direct damage and mortality due to blade strike, and in terms of longterm impacts—it alters fish behaviour far less. But the mechanism also had an important role to play in the development of the modern ship. SS Archimedes was a steamship built in Britain in 1839. She was the world's first steamship to be driven by a screw propeller. This ship affected subsequent ship development, and encouraged the adoption of screw propulsion by the Royal Navy as well as by commercial shipping companies. It was loaned to the Great Western Steamship Company, which was in the process of constructing the world's largest steamship, SS *Great Britain*. Great Western's principal engineer, Isambard Kingdom Brunel, tested *Archimedes* with a variety of different propellers in an attempt to find the most efficient design, and screw propulsion was adopted as being lighter in weight and less bulky than a paddle-wheel, so saving on fuel and releasing more space for cargo. It was also cheaper and more stable. SS *Great Britain* became the first iron steamer to cross the Atlantic, which she did in 1845, in the time of 14 days.

This maritime excursus seems particularly appropriate because the ancient Greeks believed that Archimedes had come up with the idea of the screw pump in response to another demand from Hiero II. Athenaeus tells us of the enormous ship which Hiero built, called the *Syracusia*. But its sheer size caused problems. Even the shell was too big to launch with existing technology, so Archimedes invented the windlass. Then the top part of the ship was built to hold no fewer than twenty banks of rowers, with three gangways, and thirty officers' cabins with room for between four and thirty couches each. On the upper level were a gymnasium, promenades, plant and flower beds, with inbuilt watering mechanisms, a shrine of Aphrodite, a library, elegant bathhouse, aquarium, and art gallery. Archimedes designed and added to the ship a weapon which could throw stones or javelins of enormous size automatically. But his important invention prompted by the *Syracusia* was the screw-pump. The sheer weight of the ship meant that a great deal of water leaked into the hull. With the aid of Archimedes' amazing screw, Athenaeus tells us, 'the bilge-water, even when it became very deep, could easily be pumped out by just one man'.

Archimedes' Claw

Maritime engineering, specifically for naval warfare, prompted Archimedes to invent further ingenious devices. He improved catapult technology considerably. He constructed all manner of defensive machines that could hurl wave after wave of enormous missiles semi-automatically. But his most famous feat was the invention, for use in naval warfare, of his 'Claw'. During the siege of Syracuse, when the Roman fleet of 60 terrifying quinqueremes was looming in the area of the port,

> huge poles thrust out from the walls over the ships sunk some by the great weights which they let down from on high upon them; others they lifted up into the air by an iron hand or beak like a crane's beak and, when they had drawn them up by the prow, and set them on end upon the poop, they plunged them to the bottom of the sea, . . . with great destruction of the soldiers that were aboard them. A ship was frequently lifted up to a great height in the air (a dreadful thing to behold), and was rolled to and fro, and kept swinging, until the mariners were all thrown out, when at length it was dashed against the rocks, or let fall.

General Marcellus was baffled and ordered his remaining ships to retreat to what he thought was a safe distance. He then resorted to a land assault at dead of night, but discovered that Archimedes' machines were protecting the city walls just as effetively:

> Instantly a shower of darts and other missile weapons was again cast upon them. And when stones came tumbling down perpendicularly upon their heads, and, as it were, the whole wall shot out arrows at them, they retired. And now, again, as they were going off, arrows and darts of a longer range inflicted a great slaughter among them, and their ships were driven one against another; while they themselves were not able to retaliate in any way. For Archimedes had provided and fixed most of his engines immediately under the wall; whence the Romans, seeing that indefinite mischief overwhelmed them from no visible means, began to think they were fighting with the gods.
>
> Such terror had seized upon the Romans, that, if they did but see a little rope or a piece of wood from the wall, instantly crying out, that there it was again, Archimedes was about to let fly some engine at them, they turned their backs and fled.

Marcellus was completely frustrated by Archimedes' machines, and decided to play the long game, waiting to starve the Syracusans out. In the end the city was betrayed from the inside.

The Claw of Archimedes was also known as the 'ship-shaker'. Its practicality has been much doubted. But the ancient sources are clear that Archimedes designed several units of this machine to defend the seaward portion of Syracuse's city wall against amphibious assault. And a television documentary entitled *Superweapons of the Ancient World* reconstructed a physical version of the claw and concluded that it was a feasible contraption.

Archimedes' Mirrors

Far more controversial is the feasibility of a weapon some sources say Archimedes devised, the 'Heat Ray' or 'Burning Mirrors'. This is first mentioned by the satirical essayist Lucian in the second century CE, who says that Archimedes 'burned the enemy ships by means of his science'. The Greek doctor Galen says that it was by means of 'flammable materials'. But Apuleius tells us more precisely about Archimedes' work on mirrors, on which he had apparently written an enormous book (*volume ingens*, *Apologia* 18), asking questions such as these:

> Why is it that in flat mirrors all images and objects reflected are shown in almost precisely their original dimensions, whereas in convex and spherical mirrors everything is seen smaller, in concave mirrors on the other hand larger than nature? Why again and under what circumstances are left and right reversed? When does one and the same mirror seem now to withdraw the image into its depths, now to extrude it forth to view? *Why do concave mirrors when held at right angles to the rays of the sun kindle tinder set opposite them*? What is the cause of the prismatic colours of the rainbow, or of the appearance in heaven of two rival images of the sun?

The earliest detailed descriptions of the mirror technique for setting fire to ships, however, come from much later, in Zonaras and Tzetzes, two Byzantine authors of the 12th century CE. They did both have access to much earlier texts, however, so we need not be completely sceptical about their reliability of sources. They both claim to be citing a much earlier work, which has unfortunately not survived for us to consult, called *The Siege of Syracuse*, which apparently said as follows:

> When Marcellus had placed the ships a bow shot off, the old man [Archimedes] constructed a sort of hexagonal mirror. He placed at proper distances from the mirror other smaller mirrors of the same kind, which were moved by means of their hinges and certain plates of metal. He placed it amid the rays of the sun at noon, both in summer and winter. The rays being reflected by this, a frightful fiery kindling was excited on the ships, and it reduced them to ashes, from the distance of a bow shot. Thus the old man baffled Marcellus, by means of his inventions.

In principle, this seems plausible enough. As children, many of us tried to set fire to a small piece of kindling by concentrating the rays of the sun on it through a magnifying glass. Some of us even succeeded. A small concave parabolic mirror can reflect the sun's rays onto a small point in the same way. These Byzantine writers suggest that Archimedes managed to do this on such a massive scale and with such huge or mirrors that he could focus the heat onto ships 'a bow shot' distant. How far is a bow shot? Certainly no more than a few hundred feet.

To my knowledge, no experimental reconstruction of Archimedes' Heat Ray Mirrors has ever been successful, although I would love to be corrected. But the principle is not in doubt. Between 1996 and 1999, the U.S. Department of Energy, with a consortium of utilities and industry, successfully operated a large-scale demonstration solar power tower in the desert near Barstow, California, known as Solar Two, which had a 10 MW power capacity.

Solar Two used hot melted salt to capture and store the sun's heat. Nearly two thousand mirrors reflected the sun to a tower in the middle of them. It had a large target at the top full of the salt, which absorbed the heat. The mirrors were tilted and moved under computer control to maximise the sunlight captured. The heat from the salt was transferred to a water boiler on the ground. This produced steam to drive a turbine/generator that created electricity like any power-plant. The station entailed a large number of mirrors that reflected the sun to a tower in their centre.

So, could Archimedes have focussed mirrors like this onto a wooden ship, rather than onto a target consisting of a tank of salt atop a tower, and succeeded in setting it on fire? Historians of science are divided. The target salt tank could reach temperatures higher than 1,000 Fahrenheit, which is above the auto-ignition point of most wood. However, each of the installation's nearly two thousand mirrors were huge (130 square metres, that is more than 6 metres long and 6 metres wide). Scientists doubt that, however rich Syracuse was at the time, such a number of enormous mirrors could have been manufactured in the first place. The device is technically feasible, but did Archimedes really have the resources to create the tools it required?

Archimedes Measuring Space and Time

Several other inventions are attributed to Archimedes. One was an *odometer*, a contraption which could measure the distance travelled by a vehicle. Perhaps it was used by ancient road transport providers to help them calculate how much to charge their passengers, as taxi drivers use their taximeters today. He may also have invented an adaptation of his odometer which could be attached to a ship to measure distance sailed. Our account of these comes, once again, in the Roman architect Vitruvius (*de Architectura* X.9). The wheels of the chariot are made of a specific diameter and circumference. A box was attached to an axle and a system of interlocking toothed wheels which in turn led to a ball falling into a bronze container every time a mile was passed. 'Thus', says Vitruvius, by the dropping of the balls, and of the noise they make, we know every mile passed over; and each day one may ascertain, by the number of balls collected in the bottom, the number of miles in the day's journey'. He then explains how an axis and toothed wheels attached to paddles can be fixed on a seagoing vessel

But if your concern was with measuring time rather than distance, Archimedes could help you out here too. Some of Archimedes' works were translated into Arabic in the 9th century by Al-Ṣābiʾ Thābit ibn Qurrah al-Ḥarrānī, a mathematician, astronomer and translator who lived in Baghdad. It was probably this Mesopotamian who compiled the Arabic *Book of Archimedes on the Construction of Water-Clocks* (Kitāb Arshimīdas fī al-binkāmāt), in which there is described a spectacular ticking clock, which Archimedes is said to have contrived. It was a complex hydraulic clock with many automatically moving objects. Its main body consisted of the central storage container which supplied the water. The water went through a smaller container which ensured the stability of the water level (with a conical valve on a float), leading to the outflow nozzle. The supply of the flow was regulated, turning the nozzle on a calibrated semi-circular disc. On the two columns of its facade, two rings (and two statuettes) indicated the hours that had been covered and the hours which remained respectively. On each hour, the pupils of the human eyes on a mask spookily changed colour and a small sphere fell into another container from the automatic opening of a crow's beak, with a loud bang. Simultaneously, the water fell into a volumetric container which, on the hour, was automatically reversed and two small metallic snakes slid towards metal birds sitting on the branches of a tree, who tweeted in terror. As well they might.

Archimedes' Astronomical Instruments

But this extraordinary scientist and engineer was also fascinated by the movements of the stars, and here we return to the dramatic moment of his death, after Syracuse had been betrayed by friends of the Romans inside the city. Cicero (106–43 BC) mentions Archimedes briefly in his dialogue *de Re publica* I.21.22, which portrays a fictional conversation taking place in 129 BCE. After the capture of Syracuse in 212 BCE, General Marcellus was said to have taken back to Rome two mechanisms, planetaria, constructed by Archimedes and used as aids in astronomy. They showed the motion of the Sun, Moon and five planets. He was not the first to design such a mechanism– Cicero says that Thales of Miletus had already constructed one centuries earlier. But it seems to have been very special and perhaps a major advance on previous models of its type. Cicero says that it was a 'newer kind of globe' and that 'the invention of Archimedes deserved special admiration because he 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. And when Gallus moved the globe, it was actually true that the moon was always as many revolutions behind the sun on the bronze contrivance as would agree with the number of days it was behind in the sky. Thus the same eclipse of the sun happened on the globe as would actually happen.'

The dialogue says that Marcellus kept one of the devices as his only personal loot from Syracuse, and donated the other to the Temple of Virtue in Rome. It seems to have been moved to the temple of Vesta, which is where the poet Ovid saw it a few decades later (*Fasti*, VI.277-9). 'There stands a globe hung by Syracusan art in closed air, a small image of the vast vault of heaven, and the Earth is equally distant from the top and bottom. That is brought about by its round shape'. This implies an outer celestial sphere of glass with a small sphere for the Earth at its centre.

Sadly, we cannot be sure exactly what Archimedes' sphere looked like, because his work *On the Construction of Spheres* (*Sphairopoiïa*) mentioned by the scholar Pappus of Alexandria in the fourth century CE (*Mathematical Collection*, 8.2) has not survived. But we can be sure that the beauty and intellectual achievement of Archimedes' celestial sphere provoked some figures in antiquity, both pagan and Christian, to compare it one way or another with the work of a divinity. In another text, Cicero comments that some people 'they think more highly of the achievement of Archimedes in making a model of the revolutions of the firmament than of that of nature in creating them, although the perfection of the original shows a craftsmanship many times as great as does the counterfeit (*de Natura deorum*, II. 34-5). But the early Christian writer Lactantius used a comparison between Archimedes' skill and God's to argue that Stoics were wrong to question the argument for an all-powerful creator god that rests on the universe's supposedly perfect design (*Divine Institutes*, II.5):

> Could Archimedes the Sicilian have devised from hollow brass a likeness and figure of the world, in which he so arranged the sun and moon that they should effect unequal motions and those like to the celestial changes for each day as it were, and display or exhibit, not only the risings and settings of the sun and the waxing and waning of the moon, but even the unequal courses of revolutions of the heavens, and that sphere, while it revolved, exhibited not only the approaches and the wandering of the stars as that sphere turned, and yet God Himself be unable to fashion and accomplish what the skill of a man could simulate by imitation? Which answers, therefore, would a Stoic give if he had seen the forms of stars painted and reproduced in that sphere? Would he say that they were moved by their own purpose, or would he not rather say by the skill of the designer?

The poet Claudian wrote a whole poem on Archimedes' sphere (*Carmina Minora* no. 51) in which he imagined Jupiter himself protesting at Archimedes' skill:

> When Jove looked down and saw the heavens figured in a sphere of glass he laughed and said to the other gods: "Has the power of mortal effort gone so far? Is my handiwork now mimicked in a fragile globe? An old man of Syracuse has imitated on earth the laws of the heavens, the order of nature, and the ordinances of the gods. Some hidden influence within the sphere directs the various courses of the stars and actuates the lifelike mass with definite motions. A false zodiac runs through a year of its own, and a toy moon waxes and wanes month by month. Now bold invention rejoices to make its own heaven revolve and sets the stars in motion by human wit...
> Here the feeble hand of man has proved to be Nature's rival

Scientists were always sceptical about such reports, and questioned whether there really was even in antiquity sufficient understanding of mechanics for Archimedes' sphere to have worked (especially sophisticated understanding of differential gearing). But the discovery of an ancient machine with apparently the same ability to predict eclipses has changed all that.

The bronze machine was discovered in 1900 by Greek divers investigating a large shipwreck off the coast of the tiny Aegean island of Cythera. The ship had lain on the seabed since about 65 BCE. In the 1970s, radiography showed that it was a complex device with at least thirty gear wheels. And in 2016, most of the texts on its surfaces were decoded, although we await full publication. The object is in Athens Archaeological Museum. The front of the Antikythera mechanism pointed to the location of the Sun and Moon alongside a display of the phase of the moon. It seems to have been designed as a kind of calculator which could analyse and predict the relative positions of the heavenly bodies when past or future dates were entered into the device. On the back, dials showed a 19-year cycle of lunar months, lunar and solar eclipses, and what is believed to be a four-year cycle of competitions, including the Olympic Games. About the size of a large shoe box, it also had dials on both the front and back. These dials were turned using a handle on the side. Although 30 gears have been found, it is probably contained many more.

Death and Legacy of Archimedes

Even in his own lifetime, Archimedes' intellectual powers were often described, it seems, in quasi-supernatural terms. When Marcellus was forced to give up his naval blockade of Syracuse, he said to his men, 'Let us stop fighting against this geometrical Briareus, who uses our ships like cups to ladle water from the sea… and with the many missiles which he shoots against us all at once, outdoes the hundred-handed monsters of mythology.' Plutarch tells us that Archimedes was always concentrating so hard on mathematical and mechanical problems that he neglected to look after himself:

> …under the lasting charm of some familiar and domestic Siren, he forgot even his food and neglected the care of his person; and how, when he was dragged by main force, as he often was, to the place for bathing and anointing his body, he would trace geometrical figures in the ashes, and draw lines with his finger in the oil with which his body was anointed, being possessed by a great delight, and in very truth a captive of the Muses.

But his most elegant surviving work, *The Sand Reckoner*, suggests a cheerful, lucid and friendly communicator who has gone out of his way to make extremely complicated mathematical problems comprehensible to the non-specialist reader. He writes to Hiero's son, setting out to determine an upper bound for the number of grains of sand that fit into the Universe. For the size of the universe, he takes the estimate of Aristarchus, a slightly older scientist who had proposed a Heliocentric model.

People who encountered him or his findings and inventions tended to become obsessed with him, and not only his colleagues in Alexandria or his royal relatives in Sicily. Plutarch tells us that Marcellus was deeply traumatised by Archimedes' death, even though he and his Roman forces had suffered so much from his machines. Plutarch records an alternative version of Archimedes' demise:

> As Archimedes was carrying to Marcellus some of his mathematical instruments, such as sun-dials and spheres and quadrants, by means of which he made the magnitude of the sun appreciable to the eye, some soldiers fell in with him, and thinking that he was carrying gold in the box, slew him. However, it is generally agreed that Marcellus was afflicted at his death, and turned away from his slayer as from a polluted person, and sought out the kindred of Archimedes and paid them honour.

But Archimedes' discoveries were to change the world again in the European Renaissance, when he attracted even more significant admirers, and inspired extraordinary new intellectual leaps, when his works were painstakingly translated, reconstructed and analysed.

In his *de Motu*, one of his earliest works, Galileo Galilei referred to the 'superhuman Archimedes, whose name I never mention without a feeling of awe'. Elsewhere he calls him 'inimitable', 'peerless' and the 'most divine Archimedes'. Galileo considered Archimedes divine for his ingenuity in using mathematical methods in such physical sciences as theoretical mechanics and hydrostatics and for the elegance and rigour of his mathematical demonstrations. One historian of science, Alexandre Koyre, has shown that Galileo sought to emulate Archimedes from very early in his career, so that Archimedes was thus the 'true forerunner of modern physics'. And Paul Lawrence Rose, in his seminal book *The Italian Renaissance of Mathematics*, stresses that without what he calls the 'Archimedean revival', Renaissance science and mathematics would be 'difficult to imagine'.

And in this lecture, we have seen at least two Archimedian inventions being used to experiment with systems for moving water and creating heat without causing any environmental damage. Archimedes is still inspiring us, and that's not solely because the full text of the Archimedes Palimpsest is yet to be published Perhaps the crisis facing our planet will soon lead to another, equally seminal, Archimedian revival as was seen in Galileo's time.

Further Reading

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