HERON OF ALEXANDRIA
(c. 10–85 AD)

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Abstract. Heron of Alexandria was a mathematician, physicist and engineer who lived around 10–85 AD. He taught at Alexandria's Musaeum and wrote many books on Mathematics, Geometry and Engineering, which were in use till the medieval times. His most important invention was the Aeolipile, the first steam turbine. Other inventions include automated machines for temples and theaters, surveying instruments, and military machines and weapons.

Introduction

The ancient Greek technology developed mostly in the period 300 BC to 150 AD and was in use for more than one thousand years. It had a profound impact both on Western and Muslim civilization. Notable inventions include cranes, screws, gears, organs, odometer, dial and pointer devices, wheelbarrows, diving bells, parchment, crossbows, torsion catapults, rutways, showers, roof tiles, breakwaters, and many more. Greek engineers were pioneers in three of the first four means of non-human propulsion known prior to the Industrial Age: watermills, windmills, and steam engines, although only water power was used extensively, (Lahanas, Web). Among the Ancient Greek Engineers, the most prominent include Archimedes, Ktesibios, Heron, and Pappos.

Heron (or Hero) of Alexandria (in Greek Ἥρων ο Αλεξανδρεύς), see Figure 1, was a mathematician, physicist and engineer who lived in the Hellenistic times in Alexandria, Egypt, at that time part of the Roman empire. He was made famous for documenting the first steam turbine, the *aelolipile*. He also invented many mechanisms for temples and theaters while he advanced or improved inventions by others, for example the *hydraulis*, originally in-

Fig. 1. Heron of Alexandria (O'Connor, 1999).

vented by Ktesibius. Heron was also called *Michanikos* (Μηχανικός), the Greek word for Engineer.

It is important to stress that in the Ancient World, technology was not considered as very important for the growth of philosophy and science. The dominant motive in philosophy was understanding or wisdom, while the connection between science and technology was not as extensive as it is today. In this context, Heron, as well as the other engineers, were on the exception side (Lloyd, 1991).

Biographical Notes

The chronology of Heron's works is disputed and not absolutely certain to date. Many contradictory references on Heron exist, partly because the name was quite common. However, historians cite that he came after Apollonius, whom he quotes, and before Pappos, who cites him. This suggests that he must have lived between 150 BC and 250 AD (Thomas, 2005). In 1938, Neugebauer, based on a reference in Heron's *Dioptra* book of a moon eclipse, he found that this must have happened on March 13, 62 AD, (Neugebauer, 1938). Since the reference was made to readers who could easily remember the eclipse, this suggests that Heron flourished in the late first century AD. According to Lewis (2001), and assuming that *Cheirobalistra*, a powerful catapult, is genuinely his, Heron should have been alive at least till 84 AD, the year in which the *Cheirobalistra*, was introduced.

Because most of his writings appear as lecture notes for courses in mathematics, mechanics, physics and pneumatics, it is almost certain that Heron taught at the Musaeum of Alexandria, an institution for literary and scientific scholars supported by the Ptolemies, which included the famous Library of Alexandria. Many scholars believe that not only he taught at the Musaeum, but that in addition he served as its Director and that he developed it as the first Polytechnic School, or Technical Institute. He is the last recorded member of the School, and the best known (Lewis, 2001).

According to Drachmann (1963), Heron was a man who knew his business thoroughly, who was a skillful mathematician, astronomer, engineer and inventor of his time. Based on the content of the book *Pneumatica*, a number of researchers expressed doubts about his capabilities. However, this book appears to be an unfinished collection of notes and may have been altered through the years.

An important characteristic of Heron's work was clarity in expressing his ideas, something not common in ancient writings. As Drachmann (1963) states, "a man who is always able to present his subject in such a way that is readily understood, is a man who understands it himself, and he is certainly not a fool or a bungler."

Mahoney notes the following about Heron, "In the light of recent scholarship, he now appears as a well-educated and often ingenious applied mathematician, as well as a vital link in a continuous tradition of practical mathematics from the Babylonians, through the Arabs, to Renaissance Europe" (Drachmann and Mahoney, 1970). Furthermore, Heath writes that, "The practical utility of Heron's manuals being so great, it was natural that they should have great vogue, and equally natural that the most popular of them at any rate should be re-edited, altered and added to by later writers; this was inevitable with books which, like the *Elements* of Euclid, were in regular use in Greek, Byzantine, Roman, and Arabian education for centuries" (Heath, 1931).

In many of his works, Heron would start by reviewing past works. However, he would not always give credit to previous inventors and would tend to dismiss easily the work of others, before presenting his own solutions.

Heron recognized the value of experimental work. The example passage, taken from Lloyd (1973), attacks first those (like Aristotle) who denied absolutely that a void can exist, accusing them of following their faith as opposed to evidence:

> *Those then who assert generally that there is no vacuum are satisfied with inventing many arguments for this and perhaps seeming plausible with their theory in the absence of sensible proof. If, however, by*

> *referring to the appearances and to what is accessible to sensation, it is shown that there is a continuous vacuum, but only one produced contrary to nature; that there is a natural vacuum, but one scattered in tiny quantities; and that bodies fill up these scattered vacua by compression; then those who put forward plausible arguments on these matters will no longer have any loop-hole.*

Following this statement, Heron described an apparatus designed to show the existence of vacuum. This is basically a metal hollow sphere with a small hole and a thin tube of bronze attached to the hole. Heron argued that if one blows air into the sphere, then air enters it and therefore it must be compressible. This compressibility was attributed to the existence of small pockets of vacuum. He also continued his argument by saying that one can also draw air out of the sphere by inhaling air. Once this is done, then the sphere must contain more vacuum than before.

Although arguments of this sort may be commonplace today, they were not necessarily the norm two thousand years before, and therefore, this attitude towards experiments is considered to be very important.

List of Main Works

The main works of Heron are published in five volumes in the Teubner Series, (Heiberg, 1912; Schmidt, 1899). Among them, the most well-known books related to engineering include

- *Pneumatica* (Pneumatics), a treatise on the use of air, water, or steam, in Greek.
- *Automatopoietica* (Gr. Περί αυτοματοποιητικής, i.e. about making automatic devices), a description of automated machines using mechanical or pneumatical means, most for temples, in Greek.
- *Belopoeica* (from the Greek βέλος, meaning arrow, and ποιώ, meaning to make), on the constructions of machines of war, in Greek.
- *Mechanics*, which covers mechanisms and simple machines and has survived in Arabic, with a few fragments in Greek preserved by Pappos.
- *Barulkos* (Gr. Βαρούλκος from βαρύς, meaning heavy and έλκω, meaning to pull), that discusses methods of lifting heavy weights. Perhaps this is the same as *Mechanics*.

- *Dioptra*, which describes a theodolite-like instrument used in surveying and methods to measure length, in Greek and Arabic.
- *Catoptrica* (Catoptrics), on light propagation and reflection, and on the use of mirrors.
- *Cheirobalistra* (On Catapults), about catapults, in Greek.

Heron has also contributed to Mathematics and Geometry. Although some of them are of disputed authorship, his works in this area include

- *Metrica*, describes how to calculate surfaces and volumes of diverse objects, in Arabic.
- *Geometrica* (Geometria), a collection of equations based on the first chapter of Metrica, in Greek.
- *Stereometrica* (i. and ii.), examples of three-dimensional calculations based on the second chapter of Metrica, in Greek.
- *Geodaesia*, surveying analysis, in Greek.
- *Mensurae*, tools which can be used to conduct measurements based on *Stereometrica* and *Metrica* (disputed authorship), in Greek.
- *Definitiones* (Definitions), containing definitions of terms for geometry, in Greek, (disputed authorship).

Unlike other ancient works in Greek, the language in Heron's book is quite easy to be read by non-scholars, even today. Except the *Definitiones*, these books mostly consist of methods for obtaining the areas and volumes, of plane or solid figures. In these, Heron gave methods for computing very close approximations to the square roots of numbers, which are not complete squares and even cubic roots of numbers, which are not complete cubes. Heron also provided expressions for computing the areas of regular polygons of five to twelve sides in terms of the squares of the sides that lead to important trigonometrical ratio approximations. In general, it is believed that these books were based on Heron's works, but also that they were altered by people after him. Heron's most important work on geometry, *Metrica*, was missing until it was discovered in Constantinople in 1896 by R. Schöne. This work is the closest to its original form.

Review of Main Works on Mechanism Design

Mechanics

Heron wrote important books on mechanics that describe simple mechanical machines and methods for lifting weights. His *Mechanics* are divided in three books. The first is an introduction and describes the theory of motion, statics, balance, and how to construct three-dimensional shapes in proportion to a given shape (pantographs). The second contains an exposition of the theory of the five “powers”: the windlass, the lever, the pulley, the wedge, and the screw (incl. the worm gear) and examines methods of lifting heavy objects with their help. It also deals with finding of the center of mass of planar bodies. The third book presents applications of the five powers, i.e. methods of moving objects by means of sledges, cranes, etc. He also discusses wine presses. *Mechanics* is written for architects and contractors, and except for some chapters that appear to be out of place, the work is well arranged (Drachmann, 1963). The contents of this book have a lot of overlap with *Barulkos*, so many believe that these are not separate books.

Dioptra

Dioptra is a book on surveying and instruments for it. It begins with an introduction to “the science of dioptrics” and gives a description of the *dioptra* (Gr. διόπτρα), a combined theodolite and water-level. Heron here presents all previous works on the subjects and quickly dismisses them. Later, he gives instructions on how to construct a dioptra instrument, and how to use it. The book also contains a description of a *hodometer* (Gr. οδόμετρον), a device for measuring displacements. The book starts to degenerate after chapter 35, while the next chapter is missing. Chapter 37 describes the *barulkos*, a device designed for lifting weights, while the next one and proposes a hodometer for ships. The book ends with an appendix on other surveying methods (Drachmann, 1963; Lewis, 2001). The contents of *Dioptra* up to chapter 34 are listed in the Appendix and can give a good idea of the issues discussed in the book.

Automatopoietica

Automatopoietica is the oldest text that describes automatic machines and devices. Heron’s automatic devices were based on water, fire, and compressed air. Among these, the most well-known include an automatic system to open the doors of a Temple when a fire was started at the altar, a coin-operated machine that was providing water, and toy-like motions of puppets, such as bird automata. Another device, called the Hercules and the Dragon, has Hercules hitting the head of the dragon, while the dragon shoots water on his face. Heron is also credited with the construction of the first analog computer, a computing device based on gears and pins. Many of the "automata" of Heron's were constructed around 1589 by Giovanni Battista Aleoti.

Belopoeica and Cheirobalistra

The *Belopoeica* deals with the construction of war machines. It has some similarities with works written by Philon and Vitruvius, and perhaps was based on the work of Ktesibios.

The *Cheirobalistra* deals with catapults and serves as a lexicon (dictionary) of their parts. However, it is not certain that it was written by Heron.

Pneumatica

The *Pneumatica* is a controversial work in two books, with 43 chapters in the first and 37 in the second. The book starts with an analysis on fluid pressure, which at some parts is correct and elsewhere is not. It also describes mechanical toys, singing birds, sounding trumpets, etc. In total, more than one hundred machines and devices are described in its chapters. Although most of them work with steam or water, they all include mechanisms, either for transmitting power, or motion and signals.

The most famous device is the *aeolipile*, a steam turbine device, which is described in more detail later. The aeolipile was not used to produce mechanical work, perhaps because at that time, the need to use machines for producing mechanical work was not so crucial and, hence, it was not driving the process of building such devices.

This observation is more general. Researchers agree that most of these toys and devices were not designed to perform particular tasks, but rather to teach physics to students, i.e. Heron was demonstrating what can be done with physics, but not how to solve particular engineering problems.

Pneumatics stirred great interest among Renaissance scholars. The works were translated and published for the first time by Giovanni Battista Aleotti in 1589 under the title *Gli Artificiosi et Curiosi Moti Spiritali dit Herrone*,

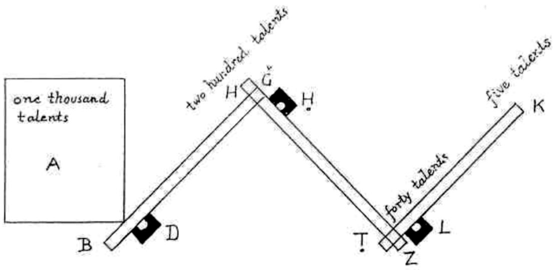


Fig. 2. Multi-link lever (Drachmann, 1963).

where the translator added some of his own ideas. Other translations were provided by Alessandro Giorgi da Urbino in 1592 and 1595 (Lahanas, Web).

The contents of *Pneumatica* are listed in the Appendix. They provide a good picture of the devices and methods discussed therein.

Modern Interpretation of Main Contributions to Mechanism Design

It is quite interesting to examine some of the machines and devices described by Heron from a modern standpoint. In particular, we will attempt to do this, focusing in a number of characteristic devices, which are of interest regarding the included mechanisms and/or their design. To this end, we will present and discuss (a) mechanisms such as *levers*, *gears*, *weight-lifting devices*, *presses*, *pantographs*, and *hodometers*, (b) automatic devices such as *automatic libations* and *automatic opening of temple doors*, (c) engines of war such as the *cheirobalistra* and the *palintonon*, and (d) important devices, such as the *dioptra*, the *aeolipile*, and the *hydraulis*.

(a) Mechanisms

Levers

In Heron's *Mechanics*, one can find many types of levers, some simple, some more complex. Figure 2 shows a multi-link lever system with many fulcra. The figure also shows the multiplication of force at various points. A force equal to five talents (one talent is about 26 kg), is multiplied by two hundred to become one thousand talents after fulcrum D. The original text, translated into English reads (Drachmann, 1963)

> *<25> As for the lever, the same weight is moved by the same power by this arrangement: Let the weight be at point A, and let the lever be BG, and let the stone that is under the lever be at point D, and let the moving of the weight by the lever take place while it is parallel to the ground, and let GD be five times DB; then the power that is at G, which balances the thousand talents, is two hundred talents. Let there now be another lever, which is HZ, and let point H be the point be the one at the head of the lever, engaging point G, so that G is moved by the moving of H, and let the stone that is under the lever be at point H, and let it be moved towards D, and let ZH be five times* $H'H$*; then the power that is at Z will be forty talents. Let there be another lever, which is* $T'K$*, and let us place the point* T' *on the point Z, and let it be moved in the opposite direction of H. And let the stone that is under the lever be at the point L, and let it be moved the way in which the point H is not moved, and let KL be eight times* LT'*; then the power that is at K will be five talents, and it will balance the weight. And if we want the power to overcome the weight, we shall have to make KL more than eight times* LT'*; but if KL is eight times* LT' *and ZD five times* $H'H$ *and GD more than five times DB, the power will overcome the weight.*

Reading the above passage, one finds that it is quite descriptive and quantitative and predicts the force (power) multiplication correctly. In the next paragraph, the text also recognizes that this force multiplication is done at the expense of a large delay (large displacement), which is of the same proportion as the force magnification.

One may note that the figure itself is drawn in a singular configuration in which actually the mechanism will not work as described. However, this particular configuration is not inferred from the text. Perhaps this was done either to save paper, or this figure was drafted by someone who was not aware of the exact workings of levers.

Gears

Heron used gears extensively. In general, unlike today's gears, these tend to be triangular in shape. The spur gears are more common, but Heron also used other types, like the worm gear in conjunction with a worm, see Figure 3.

Again, the text is quite descriptive and explains how to calculate the velocity (gear) ratio as follows (Drachmann, 1963):

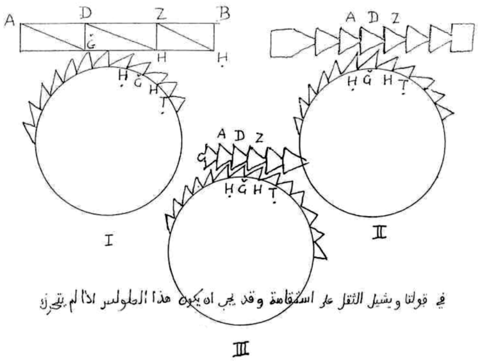


Fig. 3. Endless screw (worm gear) and driven gear (worm). Inscriptions in Arabic (Drachmann, 1963). The figure is used to calculate the velocity ratio of the gears.

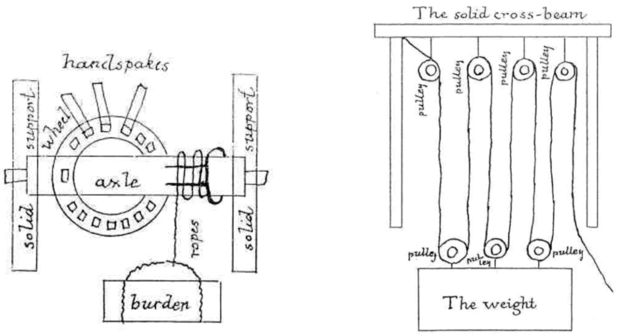
> *<18> When it is the case that a wheel with teeth engages the screw furrow, then for every one turn the screw is turned, it will move one tooth of the wheel. And we can prove this in the following way . . .*

It is worth noting that Heron used the worm gear and worm transmission in many of his mechanisms, possibly because this combination is not backdriveable, a characteristic very handy in the case of lifting ways. In such cases, the worm is connected to a handle and the operator of the mechanism can stop applying torque on it without having the weight fall.

Weight-lifting devices

Weight-lifting devices were very important in the ancient times. Traditionally, this was done with the use of enormous man-power, for example with many people pulling or lifting weights against their own. The mechanisms discussed by Heron allowed the lifting of big weights used in construction, by a single person.

Figure 4a shows an axle supported on its two ends and connected to a wheel with handles (handspakes). A rope is wound around the axle and lifts a weight. Again, this is a force multiplying device, and works best when the wheel has a large diameter R and the axle has a small one, r, since the multiplication of the force is proportional to R/r. As one can see in Figure 4a, someone who read the book with the figure was aware of this, and therefore designed the part of the axle around which the rope winds with a smaller



(a) (b)

Fig. 4. Lifting mechanisms. (a) Small force maltiplication. (b) Compound pulley mechanism (Drachmann, 1963).

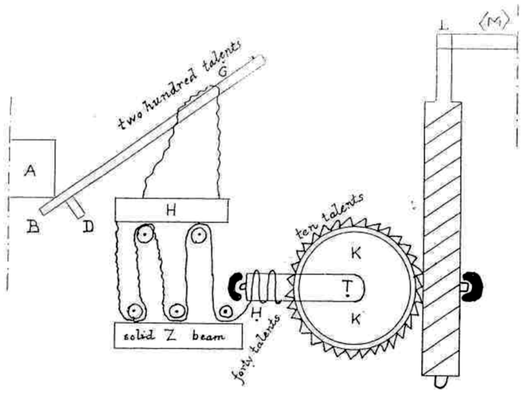


Fig. 5. Complex lifting mechanism showing force amplification (Drachmann, 1963).

diameter than that of the rest of the axle. Here, too, a "delay" is present, as many wheel rotations are needed to lift the weight.

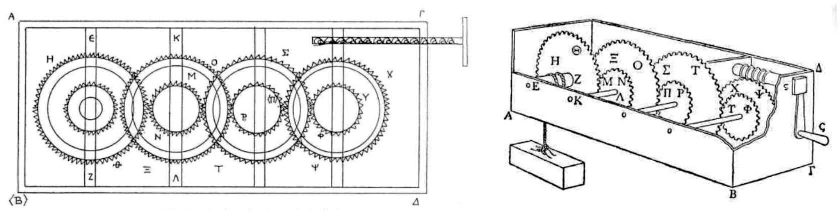
Figure 4b shows a compound pulley system that is used to lift a weight. One end of the rope is attached to the solid cross-beam, while the other end is pulled by a person. Heron recognized that levers, lifting axles and pulleys, all work similarly in that they multiply forces by a factor and require at the same time displacements also multiplied by the same factor.

Figure 5 shows a complex lifting mechanism that contains a lever, a compound pulley system, an axle, and a worm gear with a worm. From its appearance, it seems that this mechanism is provided as a teaching example and not as the description of a particular lifting device. The figure also shows the force multiplication from the hand lever to the weight. It also shows the bearings of the axle, and the lever (wedge) fulcrum. The base of the entire mechanism is not shown in the figure. However, Heron mentioned that

> *<29> … And this support like a chest should be in a firm place, in a place strong in its foundation, solidly built. When the handspake is turned, the weight is lifted.*

From the above passage, one can notice that not only a strong supportive base is required, but also Heron recognizes the importance of estimating correctly the need for taking into account strength calculations.

Heron also provides the description of a weight lifting device, based entirely on gears, see Figure 6.



(a) (b)

Fig. 6. Weight lifting compound gearbox. (a) Original drawing (Drachmann, 1963). (b) 3D drawing (Thomas, 2005).

The device is called the *barulkos*, and includes a non-backdriveable worm gear and a compound gear train with four parallel axes. It allows one to lift a large weight with a small effort, by turning the crank. The description of this device is found in Heron's *Dioptra*, chapter 37. In this, the author describes in detail the gearbox and recognizes that all axles must be able to rotate freely. This means of course that first the axles should be rotating, but also that they must not be subject to large frictional torques. This is important, as gear trains with many stages, like the *barulkos* were not very efficient.

Presses

In ancient times, presses were used to produce oil from olives or wine from grapes. In Heron's *Mechanics*, the author describes a two-screw press that is

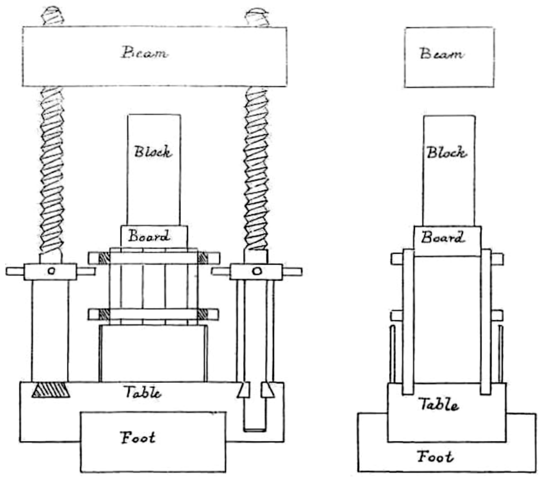


Fig. 7. Double-screw press (Drachmann, 1963).

used for pressing olives, see Figure 7. Unlike the single screw press, which may be backdriveable, the double screw press is not backdriveable, and therefore can hold its pressure without the need to apply force on the hand wheels. According to Drachmann (1963), Heron introduces the press as follows:

> *<19> These instruments, whose construction we shall now describe, serve for pressing of oil, and they are easy to work, they can be moved and put up in any place we want, and there is no need in them for a long, straight beam of a hard nature, nor for a very heavy stone, nor for strong ropes, and there is in them no hindrance from the stiffness of the ropes, but they are free from all that, and press with a strong pressure and the juices come out altogether. And their construction is what we now are going to describe.*

Passages like the above illustrate the clarity and compactness of Heron's writings. In this, he recognizes that the press works due to internal forces, and therefore, no long levers, pulleys, or mere weights are necessary to produce a large force (pressure). Despite the fact that large forces are produced, the press itself can be relatively lightweight and mobile; it does not even need a permanent base.

Figure 7 was drawn by Drachmann (1963), based on size information given in the original text. Since people at Heron's times had lathes, it seems that the screws were made with the help of one. However, it is Heron in

Dioptra, who presents the first extant description of a machine for cutting screws (Lloyd, 1973).

Pantograph

In his *Mechanics*, Heron described pantographs, i.e. mechanisms used for copying figures at a different size from the original. As explained in chapter 15, see (Drachmann, 1963):

> *<15> And let us now prove how to make a figure similar to the known plane figure in the given ratio by means of an instrument. We make two wheels on the same centre, fixed to it, and provided with teeth, moving on a single axle in the plane where is the figure we want to copy; and the ratio of one wheel to the other should be the given ratio* . . .

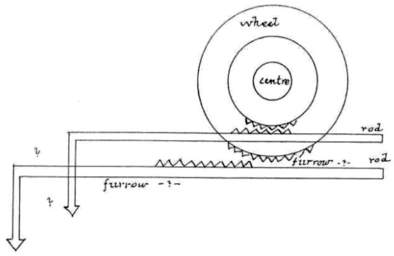
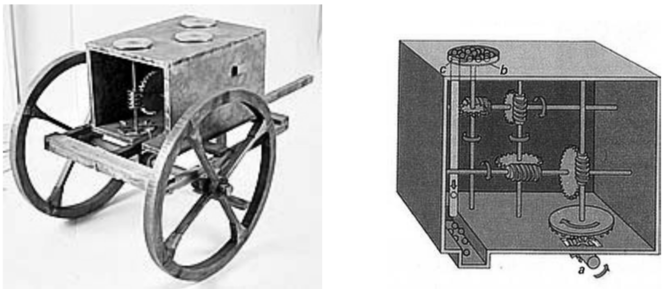


Fig. 8. Pantograph (Drachmann, 1963).

Figure 8 shows a pantograph taken from a copy of the book at the British Museum. It shows the two teethed wheels and the teethed copying rods, and mostly illustrates the principle and not the exact construction of the pantograph. The two wheels rotate at the same angular speed. When one of the rods is displaced in a given direction, the corresponding wheel rotates and since this is connected to the other one, this rotates and carries with it the other rod. Obviously, the two rods then have velocities and displacements proportional to their distance from the center of rotation, and therefore, their path is similar, too. If one of the rods is rotated, as opposed to be translated, then the other rod must remain parallel to the rotated one.

Hodometer

A *hodometer* (or odometer, Gr. οδόμετρον) is a device that indicates the dis-



(a) (b)

Fig. 9. (a) A reconstruction of Heron's hodometer, (b) mechanism geartrains (Lahanas, Web).

tance traveled by a vehicle. Hodometers have been described by others before Heron, including Vitruvius (c. 25 AD), and even Archimedes (c. 287 BC–c. 212 BC). However, it seems that none of these had ever worked or even that they were built. The same is probably true for his hodometer. Leonardo da Vinci tried to build it according to the given description, but did not succeed.

Heron describes the construction of his hodometer in chapter 34 of the *Dioptra* as a mechanism made of wheels and axles and housed in a small wooden box, see Figure 9. Heron observes that chariots with wheels of four feet diameter turn exactly four hundred times when the chariot covers one Roman mile, or about 1500 m.

Therefore he proposed a mechanism in which a pin on the chariots axle engages a fourhundred tooth cogwheel, that makes a complete rotation per mile. Then, a transmission of five axles and four worm gear and worm geartrains, drive an index showing the miles traveled. Alternatively, they engage a disk with holes along the circumference, where pebbles are located, that drop one by one into a box. In this case, the number of miles traveled is given simply by counting the number of pebbles (Lahanas, Web).

In chapter 38 of *Dioptra*, a naval hodometer is mentioned. Here, an external to a vessel paddlewheel is connected to a mechanism like that of the hodometer, which is located inside the vessel. The last wheel in the series made a full revolution every Roman mile. The naval log was replicated by K. N. Rados in wood and brass and exhibited at the International Exhibition in Bordeaux in 1907. The odometer was reconstructed recently by Dutch engi-

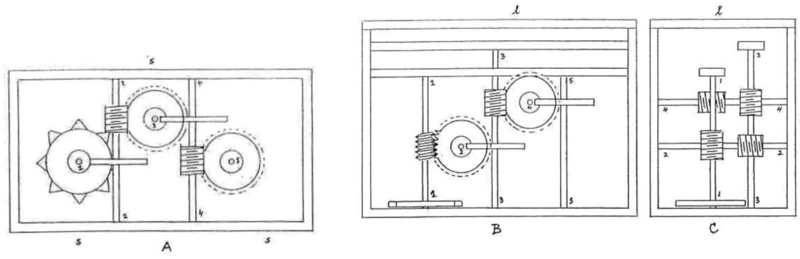


Fig. 10. Five axle hodometer described by Heron in *Dioptra*, chapter 34. (A) Aspect from above, (B) from the side, (C) from one end (Drachmann, 1963).

neer Andre Sleeswyk, who presented it at a special congress on technology held in Athens in 1987 (Thessaloniki Technology Museum, Web).

(b) Automatic Devices

Automatic libations
In *Pneumatics*, Heron describes several devices that operate on hot air or steam and are designed to produce astonishment and wonder (Lloyd, 1973). One such device is described in *Pneumatics I*, chapter 12, and is shown in Figure 11. The figures standing next to a hollow altar pour libations when a fire is lit on the altar.

The way this works is the following. When a fire is lit, the air in the hollow altar expands and drives out the liquid contained in the altarŠs pedestal. Then, the liquid passes through tubes in the figure bodies and appears to be poured by the figures.

Automatic opening of temple doors Another device designed by Heron, allows the doors of a temple to open when a fire is lit at the altar, see Figure 12. The doors are connected though a set of axles, pulleys, and ropes to a large bucket. Initially, the system is statically neutral and the weight of the bucket is balanced with counterweights. When a fire is lit, the air in the altar is heated and, as it expands, it enters a hollow sphere full of water. Due to the rising pressure in the sphere, some of the water is displaced into the bucket. As the bucket becomes more heavy, it is lowered, opening the doors of the temple (Figure 12). When the fire at the altar was put out, the pressure inside the altar would drop, and water would go back to the hollow sphere, pushed by

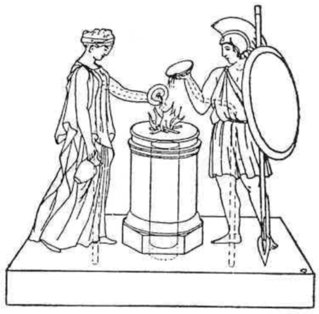


Fig. 11. Altar libations produced by fire (Lloyd, 1973).

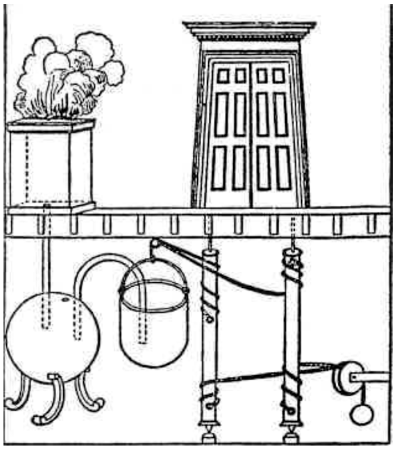


Fig. 12. The doors of the temple open automatically when a fire is started at the altar (Lloyd, 1973).

atmospheric pressure. Then, the counterweights would force the doors of the temple to close.

(c) Engines of War

Cheirobalistra

The *Cheirobalistra* (Gr. χειροβαλίστρα from χείρ which means hand and βάλλω which means to throw) is a device that hurls arrows over a large distance. In this device, the springs made of twisted hair or tendons, are stretched in two separate metal casings. A metal stud is attached at the top of

Fig. 13. The cheirobalistra as reconstructed by E. W. Marsden (Lahanas, Web).

each of the field frames, to hold them together. Another stud was attached to the bottom of the field frames and the base of the engine, to hold the spring casings in place (Marsden, 1971). A small handle wheel at the back of the base was used to load the springs. The cheirobalistra must have had a quick release mechanism for throwing the arrow. Heron's cheirobalistra was the most advanced two-armed torsion engine used by the Roman army (Lahanas, Web). The cheirobalistra was probably introduced around 84 AD and was definitely in service in 101–102 AD, as attested on Trajan's Column (Lewis, 2001).

Palintonon

A device similar to the cheirobalistra, but much bigger and powerful was the *Palintonon* (Gr. παλίτονον, from πάλιν meaning backwards, and τόνος/τείνω, meaning force, stress. It translates to a V-spring (see Figure 14).

This device is described in chapter 3 of *Belopoeica* and was made for throwing stones. It appears that it could fire an 8-pound stone over 300 yards. A similar but smaller device to throw arrows was called *Euthytonon* (Gr. ευθύτονον from ευθύς, meaning straight, and τόνος/τεινω, meaning force, stress. It translates to a straight-spring).

(d) Important Devices

Dioptra

A simple dioptra consists of a long rectangular rod with two sights. One of them has a pin-point aperture and is fixed on the rod, while the other one is

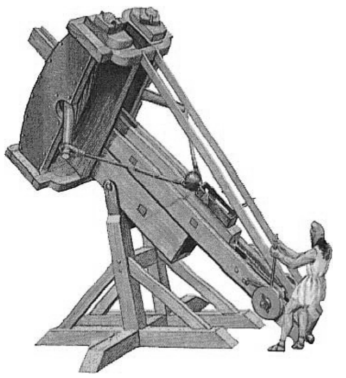


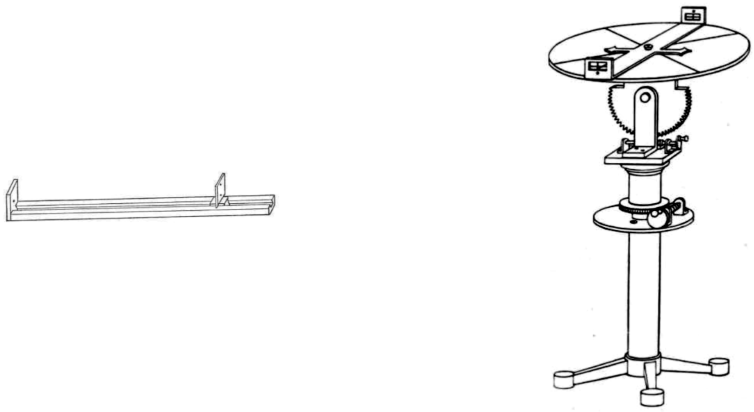
Fig. 14. Heron's palintonon (stone-thrower) (Lahanas, Web).

movable along the rod and is aligned with a target (see Figure 15a). Heron dismissed all previous dioptra designs as inadequate stating that they were all good for limited uses only. Some of them could be only mounted vertically, while others only horizontally.

Heron claimed to have constructed one that was able to perform all the tasks of his predecessors, and more (Lewis, 2001). Indeed, his dioptra could be used. It could be used as a level, a distance-measuring device, or an angle-measuring instrument. The dioptra, see Figure 15b, was probably based on a tripod and was designed such that the dioptra could attain any attitude. This was done with a 3R mechanism, with all three axes passing through the same point. This design is employed today in robot wrists, and one could describe easily its attitude with a Z-Y-Z type of Euler angles. The first two degrees of freedom were based on his favorite worm gear and worm transmission, driven by a small crank, while the last one was carrying the dioptra and was simply rotated by hand. The instrument could be leveled, but it was quite expensive to built and to many difficult to operate.

Aeolipile

Although there are indications that Archimedes and Philo made some simple use of steam, scholars agree that the discovery of the steam engine belongs to Heron. Heron's *aeolipile* is described in his *Pneumatics* 2.11. The name aeolipile is derived from Aeolos (Gr. Αίολος, the Greek god of the winds) and the Greek word pilos (Gr. πίλος, meaning sphere), and translates to "the sphere of Aeolos".



(a) (b)

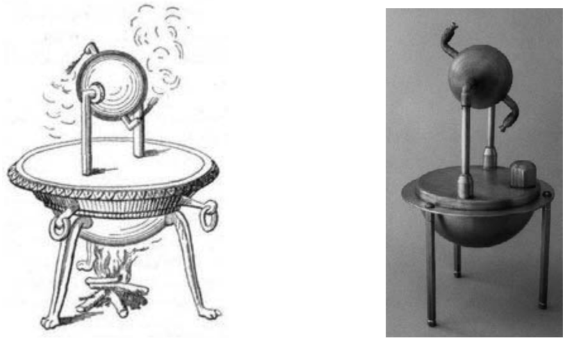
Fig. 15. (a) Simple dioptra, (b) Heron's dioptra (Drachmann, 1963).

The aeolipile (see Figure 16), is a device consisting of an air-tight sphere that receives steam through tubing along one of its major diameters. This piping also serves as an axis of rotation for the sphere. The steam is produced in a cauldron that also serves as the base of the device. The sphere is equipped with two L-shaped bent tubes, which allow the steam accumulated in the sphere to exit in such a way as to create a reaction torque around the axis of rotation of the device. This torque makes the sphere rotate at high speeds (1500 rpm).

The device can be described as a reaction turbine, since it makes use of the reaction force that appears due to the momentum change in the jet of steam which is applied to the bent pipe.

At the time the aeolipile was invented, the device was thought of as a toy. It was only much later that the device gained recognition and accumulated interest.

According to Landels (2000), who made a working reconstruction of the device, due to the device's high rotational speed, a high gear ratio would be needed to make it useful (i.e. develop a high torque at low speeds). The worst engineering problem of the device was the sleeve joint, where the pipe from the cauldron enters the sphere. If this joint is too loose, steam escapes and the device becomes inefficient; if it is too tight, there is a lot of friction increasing the power losses. Therefore, due to the technology level of the time, this jet engine, "to do the work of one man, it would have required the



(a) (b)

Fig. 16. (a) Heron's aeolipile, and (b) a modern replica photographed by Katie Crisalli (Wikipedia).

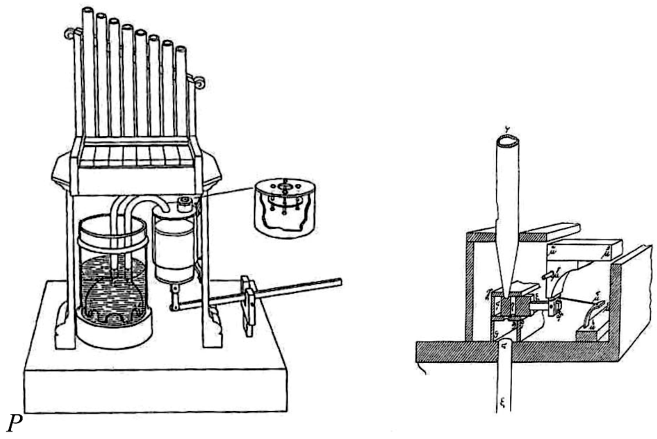
input of several men. In other words, it would have been a labor-using device rather than a labor-saving one" (Landels, 2000).

Hydraulis

Hydraulis (Gr. ύδραυλις from ύδωρ, meaning water, and αυλός, meaning pipe), was invented by Ktesibios of Alexandria (285–222 BC) and was a water organ with keyboard, see Figure 17a. It is generally considered to be the precursor of the modern pipe organ. Hydraulis works by forcing air coming from an air pump to reach a large copper chamber with water, which also contains a hemispherical or funnel-like copper "wind chest". The air is in the wind chest and its pressure is kept constant by water rising in it. The compressed air is driven continuously at constant pressure upwards, to blow the organ pipes.

To improve keyboard air valve of the organ, Heron designed a spool-type mechanism that would slide to open the air stream when a keyboard key was depressed, and would be restored to it original position by a spring force, see Figure 17b.

Heron describes the organ in *Pneumatics*, without referring to Ktesibios. However, it is believed that this was due to the fact that the inventor was well known. Since the organ requires an operator to drive the air pump, Heron designed a wind turbine (see Figure 18), and a mechanism for converting rotary motion to a periodic motion lifting the piston of the air pump. There is no other mention of wind power in Ancient works.



(a) (b)

Fig. 17. (a) Hydraulis was initially designed by Ktesibios and improved by Heron. The detail shows the air pump valve. (b) The organ air valve mechanism (Schmidt, 1899).

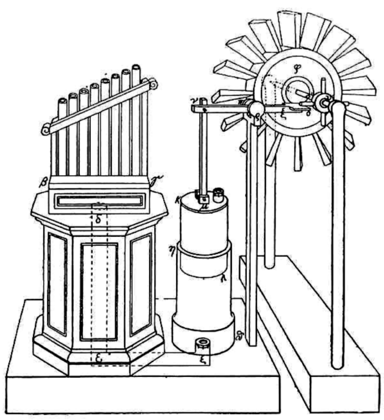


Fig. 18. Hydraulis connected to a wind turbine through a cam-like mechanism (Lazos, 1999).

As seen in this figure, the wind turbine axle included had radial rods, acting as primitive cams, that were forcing a lever connected to the air piston to move downwards, pushing the piston up. When the cam-like rod had rotated away from the lever, the lever was returning to its original position due to the weight of the piston. One could say that this is similar to the cam-driven automobile valve mechanism, where of course the weight restoring force is replaced by a spring force.

Professor Pantermalis of the Aristotelian University of Thessaloniki, recreated the organ recently which played during the Athens Olympics in 2004.

Conclusions

In this chapter, we presented a short introduction to Heron of Alexandria and his works. As many of the ancient scientists, Heron was a mathematician, a physicist and an engineer who wrote many books on Mathematics, Geometry and Engineering, in use till the medieval times. His devices were powered by single humans, water, steam or the wind, and contained many simple mechanisms. His major inventions include the Aeolipile, the first steam turbine, automated machines for temples and theaters, surveying instruments, and military machines and weapons.

Appendix

In detail, the first thirty-four *Dioptra chapters* include (Lahanas, Web):

1. & 2. Introduction to “the science of dioptrics”.
3. & 4. Instructions on how to construct a dioptra instrument.
5. Instructions on how to produce a stave for measurement.
6. To observe the difference in height between two points or if their height is the same.
7. To draw a straight line by dioptra from a given point to another invisible point, whatever the distance between them.
8. To find the horizontal (pros diabeten) interval between two given points, one near us, the other distant, without approaching the distant one.
9. To find the minimum width of a river while staying on the same bank.
10. To find the horizontal interval between two visible but distant points, and their direction.
11. To find a line at right angles at the end of a given line, without approaching either the line or its end.
12. To find the perpendicular height of a visible point above the horizontal plane drawn through our position, without approaching the point.

13. (a) To find the perpendicular height of one visible point above another, without approaching either point. (b) To find the direction of a line connecting two points, without approaching them.
14. To find the depth of a ditch, that is the perpendicular height from its floor to the horizontal plane either through our position or through any other point.
15. To tunnel through a hill in a straight line, where the mouths of the tunnel are given.
16. To sink shafts for a tunnel under a hill, perpendicular to the tunnel.
17. To lay out a harbour wall on a given segment of a circle between given ends.
18. To mound up the ground in a given segment of a spherical surface.
19. To grade the ground at a given angle, so that on a level site with the shape of an equal-sided parallelogram its gradient slopes to a single point.
20. To find a point on the surface above a tunnel so that a auxiliary shaft can be sunk.
21. To lay out with the dioptra a given distance in a given direction from us.
22. To lay out with the dioptra a given distance from another point, parallel to a given line, without approaching the point having the line on which to lay it out.
23. –30. The first five chapters refer to the dioptra setting out irregular shaped plots of land, while the remaining three explain how to determine the areas from those figures.
31. To measure the discharge or outflow of a spring.
32. & 33. Describes how to utilize the dioptra in a vertical mode for the purposes of astronomical observations.
34. This chapter informs the reader about the usage of another measuring instrument called the odometer, which has a device fitted to the wheels of a carriage such that the horizontal distance is evaluated in a very similar fashion in which a modern-day perambulator gives distance.

A good idea of the particular contents of the *Pneumatica* can be taken by listing the chapters of the books, as translated by Woodcroft (1851):

A Treatise on Pneumatics

1. The bent siphon.
2. Concentric or enclosed siphon.
3. Uniform discharge siphon.

4. Siphon which is capable of discharging a greater or less quantity of liquid with uniformity.
5. A vessel for withdrawing air from a siphon.
6. A vessel for retaining or discharging a liquid at pleasure.
7. A vessel for discharging liquids of different temperatures at pleasure.
8. A vessel for discharging liquids in varying proportions.
9. A water jet produced by mechanically compressed air.
10. A valve for a pump.
11. Libations on an altar produced by fire.
12. A vessel from which the contents flow when filled to a certain height.
13. Two vessels from which the contents flow, by a liquid being poured into one only.
14. A bird made to whistle by flowing water.
15. Birds made to sing and be silent alternately by flowing water.
16. Trumpets sounded by flowing water.
17. Sounds produced on the opening of a temple door.
18. Drinking horn from which either wine or water will flow.
19. A vessel containing a liquid of uniform height, although a stream flows from it.
20. A vessel which remains full, although vater be drawn from it.
21. Sacrificial vessel which flows only when money is introduced.
22. A vessel from which a variety of liquids may be made to flow through one pipe.
23. A flow of wine from one vessel, produced by water being poured into another.
24. A pipe from which flows wine and water in varying proportions.
25. A vessel from which wine flows in proportion as water is withdrawn.
26. A vessel from which wine flows in proportion as water is poured into another.
27. The fire-engine.
28. An automaton which drinks at certain times only, on a liquid being presented to it.
29. An automaton which may be made to drink at any time, on a liquid being presented to it.
30. An automaton which will drink any quantity that may he presented to it.
31. A wheel in a temple, which, on being turned liberates purifying water.

32. A vessel containing different wines, any one of which may be liberated by placing a certain weight in a cup.
33. A self-trimming lamp.
34. A vessel from which liquid may be made to flow, on any portion of water being poured into it.
35. A vessel which will hold a certain quantity of liquid when the supply is continuous, will only receive a portion of such liquid if the supply is intermittent.
36. A satyr pouring water from a wine-skin into a full washing-basin, without making the contents overflow.
37. Temple doors opened by fire on an altar.
38. Other intermediate means of opening temple doors by bire on an altar.
39. Wine flowing from a vessel may be arrested on the introduction of water, but, when the supply of water ceases, the wine flows again.
40. On an apple being lifted, Hercules shoots a dragon which then hisses.
41. A vessel from which uniform quantities only of liquid can be poured.
42. A water-jet actuated by compressed air from the lungs.
43. Notes from a bird produced at intervals by an intermittent stream of water.
44. Notes produced from several birds in succession, by a stream of water.
45. A jet of steam supporting a sphere.
46. The world represented in the centre of the universe.
47. A fountain which trickles by the action of the Sun's rays.
48. A thyrsus made to whistle by being submerged in water.
49. A trumpet, in the hands of an automaton, sounded by compressed air.
50. The steam-engine.
51. A vessel from which flowing water may be stopped at pleasure.
52. A drinking-horn in which a peculiarly formed siphon is fixed.
53. A vessel in which water and air ascend and descend alternately.
54. Water driven from the mouth of a wine-skin in the hands of a satyr, by means of compressed air.
55. A vessel, out of which water flows as it is poured in but if the supply is withheld, water will not flow again, until the vessel is half filled and on the supply. Being stopped again, it will then not flow until the vessel is filled.
56. A cupping-glass, to which is attached, an air exhausted compartment.
57. Description of a syringe.

58. A vessel from which a flow of wine can be stopped, by pouring into it a small measure of water.
59. A vessel from which wine or water may be made to flow, separately or mixed.
60. Libations poured on an altar, and a serpent made to hiss, by the action of fire.
61. Water flowing from a siphon ceases on surrounding the end of its longer side with water.
62. A vessel which emits a sound when a liquor is poured from it.
63. A water-clock, made to govern the quantities of liquid flowing from a vessel.
64. A drinking-horn from which a mixture of wine and water, or pure water may be made to flow alternately or together, at pleasure.
65. A vessel from which wine or water may be made to flow separately or mixed.
66. Wine discharged into a cup in any required quantity.
67. A goblet into which as much wine flows as is taken out.
68. A shrine over which a bird may be made to revolve and sing by worshippers turning a wheel.
69. A siphon fixed in a vessel from which the discharge shall cease at will.
70. Figures made to dance by fire on an altar.
71. A lamp in which the oil can be raised by water contained within its stand.
72. A lamp in which the oil is raised by blowing air into it.
73. A lamp in which the oil is raised by water as required.
74. A steam-boiler from which a hot-air blast, or hot-air mixed with steam is blown into the fire, and from which hot water flows on the introduction of cold.
75. A steam-boiler from which either a hot blast may be driven into the fire, a blackbird made to sing, or a triton to blow a horn.
76. An altar organ blown by manual labour.
77. An altar organ blown by the agency of a wind-mill.
78. An automaton, the head of which continues attached to the body, after a knife has entered the neck at one side, passed completely through it, and out at the other; which animal will drink immediately after the operation. Appendix.

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