Chapter 3
Mechanical Engineering in Antiquity

Like since the first man appeared on the face of the Earth, in Antiquity help was sought to overcome human physical limitations and to make the hard and most difficult tasks easier. In Antiquity, slaves were forced to carry out the most arduous tasks, but solutions were also contemplated in the form of machines or simple devices that would have replaced slaves or would have assisted them in several kinds of work. This machine design practice and activity established the first technical culture of independent competition and professional fields.

The fact is that the majority of automatic mechanisms of Antiquity have not been preserved, but their legacy can be found in some documents, artistic representations, and even in the literature. In general, machine engineering was relevant in Antiquity, mainly in Greece and during the Roman Empire.

The Greco-Roman world absorbed a large part of the technology that was developed by previous cultures, particularly in the Middle East. The Greeks' feelings for philosophy and science were nurtured by the ideas from Asia Minor, the East, and Egypt, and they were expressed in the form of the Hellenistic culture. Roman common, practical sense merged all these cultural backgrounds towards technological use.

Greece reached a high level in the field of technology. An emblematic example was the School of Alexandria in Egypt. From the third century BC in Alexandria there had been intense teaching and research activities on automatic devices. Since the beginning, there were outstanding personalities like Archimedes, Euclid, and Ctesibius, and later in the first century, Hero and Philon worked and taught there.

Hero was a brilliant example of personality in the School of Alexandria, who looked in depth at the different applications of automatons in his treatise entitled "Pneumatics". This treatise became a fundamental reference for automatic machine design in Antiquity and, even later when it was rediscovered, it has been used as an important source for machine design since the Renaissance time.

In fact, several historians consider Hero as the first engineer, since he was the first to produce detailed diagrams in accurate machine drawings. Up to that time, drawings had been more general and in inexact forms, which facilitated their disappearance and oblivion. On the contrary, the high definition of Hero's diagrams can be considered as proof that they are illustrations of machines that really existed.

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Greek culture evolved and progressed in combination with later Roman technology. The Romans developed a deep technical culture that spread throughout many fields such as civil engineering (roads, bridges, buildings, etc) and military applications (war machines, defence structures, etc.) when necessary, Roman engineers improved mechanical design and automation operation of existing machinery. A brilliant example of those engineers is Vitruvius, who lived in the first century BC and wrote the encyclopaedic treatise “De Architectura”, which was rediscovered and its chapter on machines was used as a kind of handbook from the Renaissance on. A later engineer personality is Frontinus who published “De aquaeductu urbis Romae” in the first century after Christ.

On Technological Evidence

Even without any need to refer to written texts, archaeology often provides evidence of machines illustrating the technological know-how of the peoples who built them. Paintings and bas-reliefs indirectly describe the machines that were used in Antiquity, even if the accompanying texts make no reference to technical contents.

As proof of the technological progress of the Egyptian civilisation, the use of lubricants was significant for lowering the resistance to sliding of large blocks of stone and statues. Figure 3.1 shows how a statue was moved during the twelfth Egyptian dynasty. Just in front of the statue there is a slave or operator whose job is to provide lubricant on the surface of the sliding path.

The Egyptians also made widespread use of war machines. One example is the war chariot in Fig. 3.2, whose efficiency depended on an appropriate mechanical design, with particular emphasis on rolling joints.

During the first dynasties of the Egyptian Empire, there is evidence that they had tools for drilling operations that were also aided by an abrasive that impregnated the rocks. This can be noted in Fig. 3.3 showing part of a bas-relief in the Egyptian Museum in Cairo.

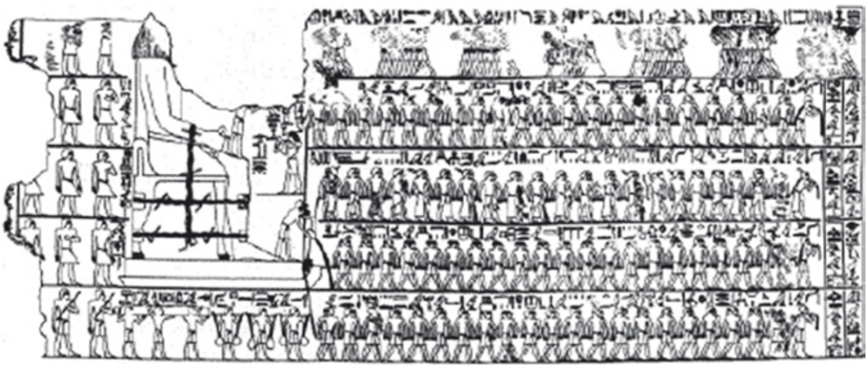

Fig. 3.1 Using a lubricant for moving a statue during the twelfth Egyptian dynasty

Fig. 3.2 Egyptian war chariot, from a relief of Ramesses II fighting at the battle of Kadesh, at Abu Simbel

There is interesting evidence about the level of knowledge in Antiquity, such as the illustration showing the use of precision scales in Fig. 3.4a, which is part of a relief from the year 1250 BC. Another example is the jar in Fig. 3.4b, showing an interesting drawing of a loom.

On the Development of Ingenious Mechanisms

One of the most relevant incentives for developing mechanisms in ancient cultures was the need for measuring time for several reasons, both with secular and religious aims. Another purpose was to make devices for games and recreation for a sector of society that had time for leisure.

Most of the mechanisms examined are mere curiosities without any apparent usefulness. The ownership of those mechanisms was used to show social prestige so that they even became artistic objects that could additionally produce surprising movements or melodic sounds.

The craftsmen enhanced their ingenuity to supply the market with these luxury goods for top society. Sometimes, the experience that was accumulated from making these automatons was later used to design and build machines for practical uses. The automatons can be considered to be initial experimental prototypes of devices for practical purposes.

Fig. 3.3 Evidence of the use of drilling tools, from a relief in the Egyptian Museum, Cairo

Fig. 3.4 (**a**) Scales in an Egyptian relief, 1250 BC. (**b**) Jar showing a loom, 430 BC [33]

There is proof of the existence of very simple Egyptian water clocks, like the clepsydra in Fig. 3.5, which measured time by using the flow of water from a tiny hole with a constant cross-section. According to the reconstruction by the Jesuit

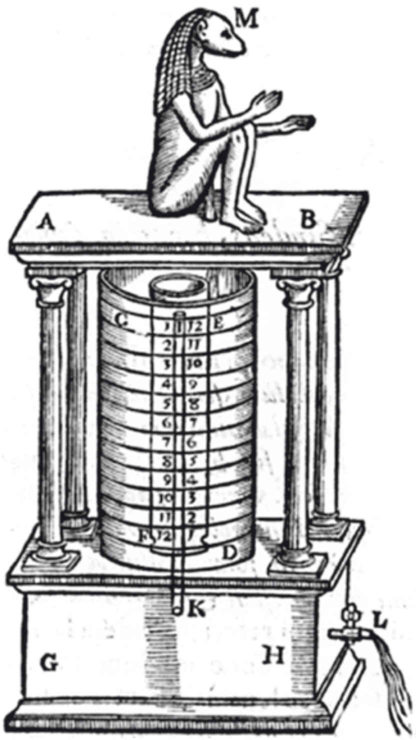

Fig. 3.5 A reconstruction of an Egyptian water clock (Form the work, Oedipus Aegyptiacus, 1652–1654)

priest Athanasius Kircher, in his work Oedipus Aegyptiacus in 1652–1654, it had a graduated scale of hours and a dog-faced humanoid on the top as an ornament.

Giving continuity to the technological progress, the Greco-Roman civilisation continued to develop time-measuring instruments by using water as the power source.

During the third or second century BC, several devices were invented that are attributed to Ctesibius, like the water clock or clepsydra in Fig. 3.6a, according to Vitruvius's opinion that was also reported in the book by Abraham Rees "Clocks, Watches and Chronometers", in 1819. The Ctesibius clock was powered by water falling from a full tank through a pipe to an open cylinder. The cylinder had a floating piston with a rack that moved a pinion with a hand-shaped indicator that turned and pointed to the hour signs.

Ctesibius's main improvement over previous water clocks was his adaptation to Egyptian hours, which were of a different duration according to whether it was day or night. This adaptation was achieved by a cone-shaped device to limit the flow to the cylinder, together with a pipe for discarding excess water. The disadvantage of the system was that the clock needed two manual adjustments every day, namely one in the morning and one in the evening.

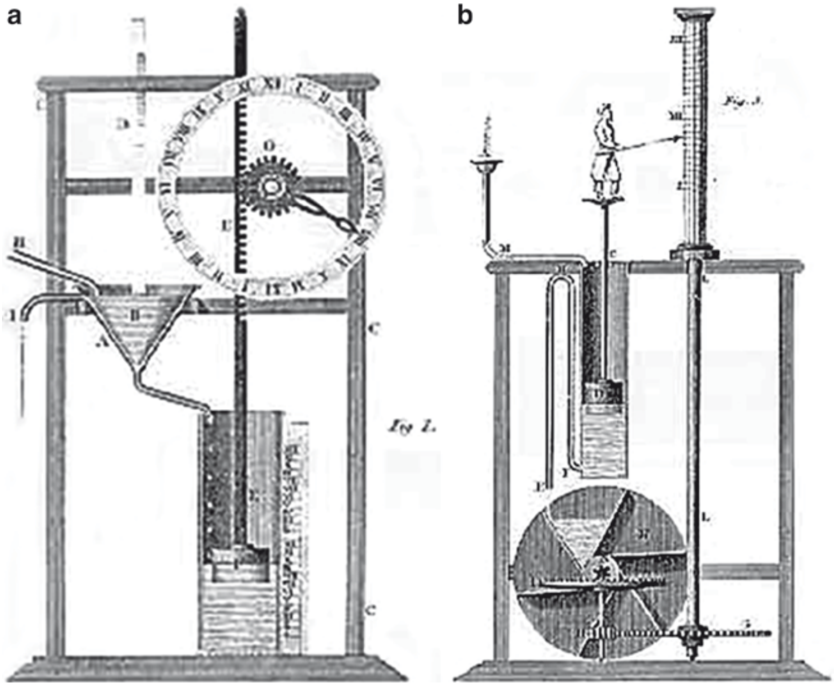

Fig. 3.6 Reconstructions of Ctesibius's clocks according to Rees [96]: (**a**) water clock. (**b**) Improved version

Figure 3.6b shows an improvement of the previous clock that was again attributed to Ctesibius. The clock is decorated with a human figure pointing to the hours on a column. The level of water in the cylinder moves a float up or down, together with the human figure. From the cylinder, the water passed through a U-shaped pipe and fell into a drum that was divided into compartments. When a compartment became full, the drum rotated slowly together with the column marking the hours. This rotation was produced by a gear transmission using several gears with several speed reduction ratios.

Ctesibius used to decorate his machines with moving figures, like automatons. This was also typical of other personalities from the School of Alexandria, such as Hero.

Another very popular machine of the time of the School of Alexandria was Ctesibius's organ that is shown in Fig. 3.7a. According to Dr. Richard Pettigrew, in 1992 Greek archaeologists recovered the fragments and reconstructed an organ that can be dated from the first century B.C.

According to the reconstruction in Fig. 3.7b, it consisted of a series of pipes that were installed on a platform under which there was a pipe for compressed air. The air was compressed by a pedal pump. In order to keep the air pressure constant,

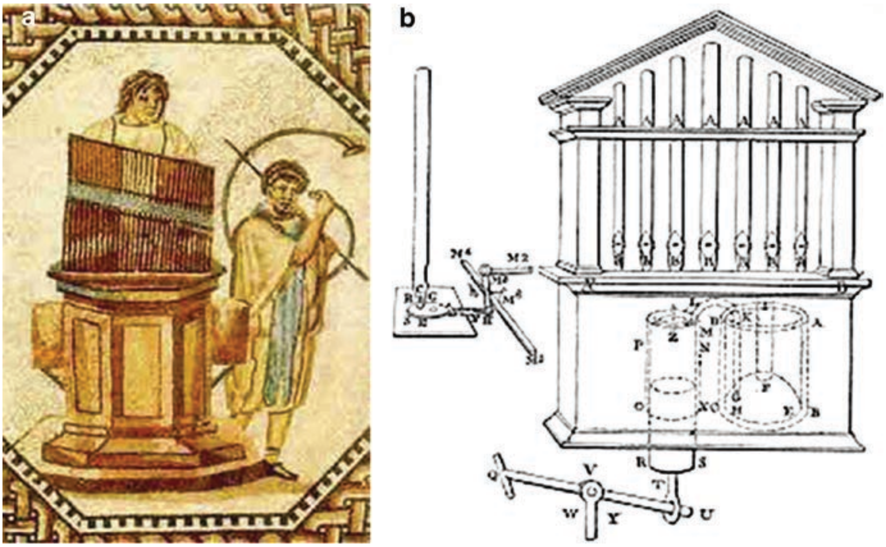

Fig. 3.7 The organ by Ctesibius: (**a**) in an ancient mosaic; (**b**) a reconstruction showing how the keys work (From B. Woodcroft's translation of "Pneumatics" [137])

a tank was submerged in a water container. When air was pumped into the tank, the water passed to an outer container.

Under each pipe was a perforated wooden board. When one of the keys was pressed, an articulated mechanism was lined up with the hole by giving the compressed air in the pipe the possibility to produce a note, as can be noted in Fig. 3.7b. This diagram is taken from the translation of Hero's "Pneumatics" by Woodcroft in 1851. In addition, Woodcroft's work shows continuing technical and historical interest in the machines of Antiquity, which began in the Renaissance and persists to the present yet.

In another version of this organ, the pump did not require manpower, but the operating mechanism is similar to that in a windmill. In this alternative version that is shown in Fig. 3.8, the wind moves a sail, the shaft of which has a wheel with four spokes projecting from it. This shaft moves the vertical piston that pushes the air into the compression chamber. The piston's own weight compresses the air that has entered during the intake stage.

It is remarkable to note the change in the drive energy. The invention of the windmill has been attributed to the Arabs, although they were only really responsible for its spread to the West from its Persian origins, according to the testimony of Hero, who describes windmills already used in that country for milling and water pumping in the seventh century BC. Their use gradually extended to Europe and North Africa via the Arabs and the Crusades. The first reference to the existence of windmills in Europe is due to Ibn Abd el Munim, who made reference to a windmill that was installed in Tarragona in the twelfth century.

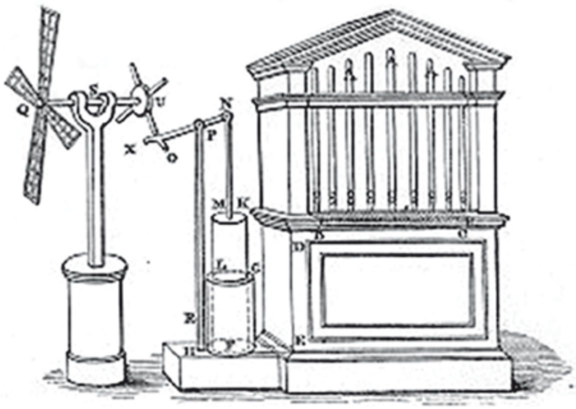

Fig. 3.8 The air-powered organ of Ctesibius (From B. Woodcroft's translation of "Pneumatics" [137])

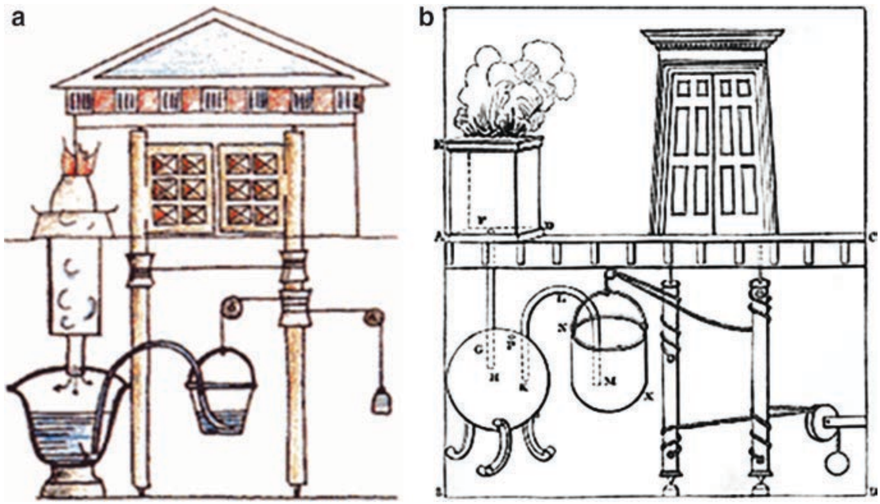

Fig. 3.9 Reconstructions of the automatic opening and closing of doors in a temple: (**a**) colour sketch; (**b**) (From Bennet Woodcroft's translation of "Pneumatics" [137])

Evolving the organ in Fig. 3.8 from a recreational automaton to an industrial use of wind energy was obviously only a matter of scale which, without any doubt, occurred in the West during the Greco-Roman civilisation.

The altar in Fig. 3.9 can be ascribed to Hero, who was a successor of Ctesibius. The altar is described in his work "Pneumática", as an application for automatic doors in the holy precinct of a temple that can be opened and closed automatically. It was provided with a torch to make an offering of fire to the gods. The fire heated the air in a container that was partially filled with water. As the air expanded, the pressure in the container increased by forcing the water to pass through a siphon to a second container.

The container was hung from a pulley that let it fall down to pull a rope operating the rollers that automatically opened the doors. When the fire was extinguished, the process was reversed and the doors automatically closed again. This mechanism is recognised as a significant forerunner of the steam engine. It represents an innovation for the source of drive energy. Its size lets it be called a machine and, more exactly, a heat machine, although its purely liturgical use relegates it to be classified as an automaton or mechanical curiosity.

Without an abundance of slave labour, the Greco-Roman civilisation would probably have developed heat machines at the beginning of our time.

Figure 3.10a shows a reconstruction of Hero's mechanism known as the "divine box" by Bennet Woodcroft. An ingenious mechanism makes the bird at the top turn and to sing by manually turning a wheel. The bird is connected to an upright shaft with a toothed wheel. Movement is transmitted to this shaft by a wheel that is located on the same shaft as the drive wheel. At the same time, this shaft also has a pulley with a bell hanging from it with a chimney. When the bell is submerged into the water, the air flows up to the chimney by making a whistle blow.

Further evidence of Hero's creativity is the "singing birds" machine that is based on the same principle as the "divine box". In Bennet Woodcroft's 1851 reconstruction in Fig. 3.10b, it can be seen that the water spouts out from an angel's mouth and falls through a hole into a large covered container, forcing the air out of it through some pipes with whistles at their ends. When the water in the tank reaches a certain level, it overflows to a second container via a siphon where a floating link

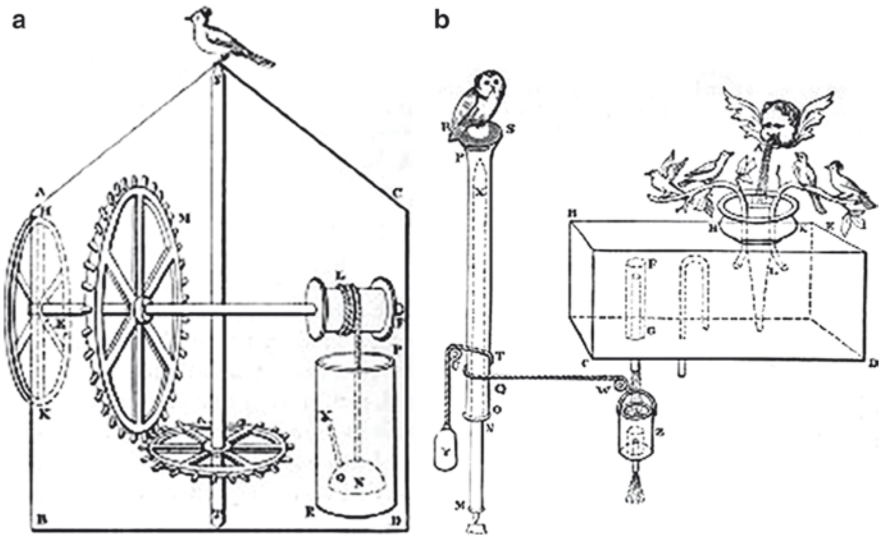

Fig. 3.10 Automatic machines by Hero (From Bennet Woodcroft's translation of "Pneumatics" [137]): (**a**) Hero's "Divine box". (**b**) Hero's "Singing birds"

attached to a rope and counterweight, turns a column with an owl on the top. There is an overflow pipe in this tank that let the owl return to its original position.

On Gears and Screws

The previous illustrations show practically all the elementary mechanisms still used today, namely shafts, couplings, joints, cams, gearwheels, flexible transmissions, hydraulics, and pneumatics.

These were brilliant machine parts for their time, since they were very simply made through rudimentary manufacturing processes. Figure 3.8 is an example where a four-spoke wheel acts as a cam. Figure 3.10a shows another example where the teeth can be understood as primitive teeth of gears.

The amazing Greek developments in theoretical geometry were always applied to both practical and theoretical mechanics. To a large extent, geometry has been also considered as a science of motion and therefore it was applicable for building mechanisms and machines.

Spiral motion was known in Ancient Greece since the time of Archimedes (287–212 BC), who designed the spiral screw for raising water via the gaps between the screw and the outer casing. These machines were widely used and illustrated by the Romans. Renaissance texts include one of the first illustrations of an Archimedes screw, like that in Fig. 3.11a by Honrad Kyeser from his work "Bellifortis", at the beginning of the fifteenth century. Figure 3.11b shows another Renaissance reproduction by Daniele Barbaro.

The construction of gears and particularly interconnecting sections bears a close relation to geometry.

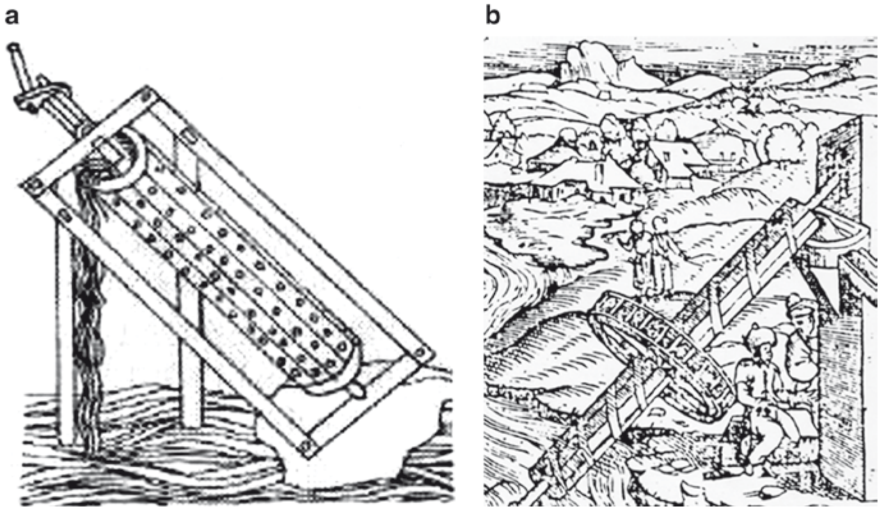

Fig. 3.11 Archimedes' screw pump: (**a**) Kyeser's illustration; (**b**) a drawing by Daniele Barbaro [15]

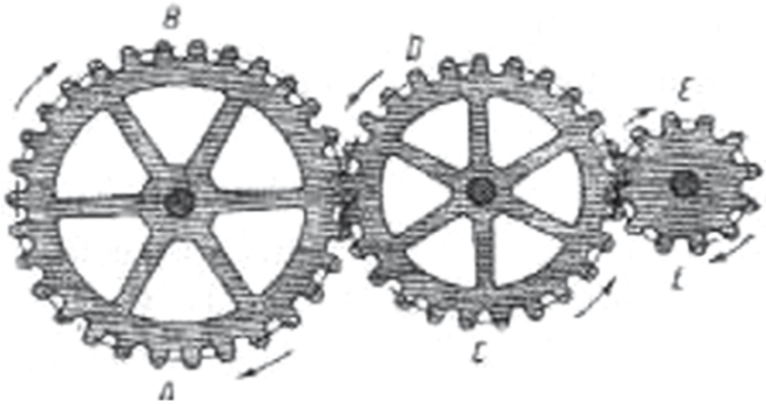

Fig. 3.12 Gear wheels described by Aristotle as in Milonov Ju.K's reconstruction [129]

In the fourth century BC, Aristotle described the transmission of movements by using iron or metal gearwheels. Figure 3.12 shows a reconstruction by Milonov Ju.K. in 1936.

An example of Greek expertise in constructing gear assemblies is the astronomical instrument in Fig. 3.13. It is a front view (Fig. 3.13a) of a mechanical gear assembly from the first century BC, found in the wreck of a Greek vessel in Antikythera (Greece). The reconstruction (Fig. 3.13b) was made by M.T. Wright in 2005.

Combining a gear wheel and a screw led to the worm gear, which required considerable geometric and technical problems to be overcome if it was to work properly.

According to Sigvard Strandh's reconstruction in Fig. 3.14a, Hero's odometer is an example of how such a complex mechanism was used. Figure 3.14b corresponds to one of Leonardo da Vinci's Renaissance machines designed for the same purpose.

It is an instrument for measuring the distance travelled by a vehicle. Movement is transmitted by the lower part via a pinion and has numerous stages of worm-type gear speed-reduction until it reaches the last upright shaft. This shaft moves very slowly and has a container full of balls at top.

The ball container has a hole that lets the balls drop down a motionless vertical tube every time the hole coincides with the hole in the tube. Thus, the speed of the vehicle can be related to the number of balls dropping to the bottom. It is to be noted that, unlike Leonardo's odometer, Hero's allowed greater distances be dealt with and precisely measured due to the use of a worm gear.

On the Way to Mechanical Engineering

Throughout several centuries, mechanical knowledge became systematically applied to devices that supplied considerable force and consumed considerable power. Those devices were real machines.

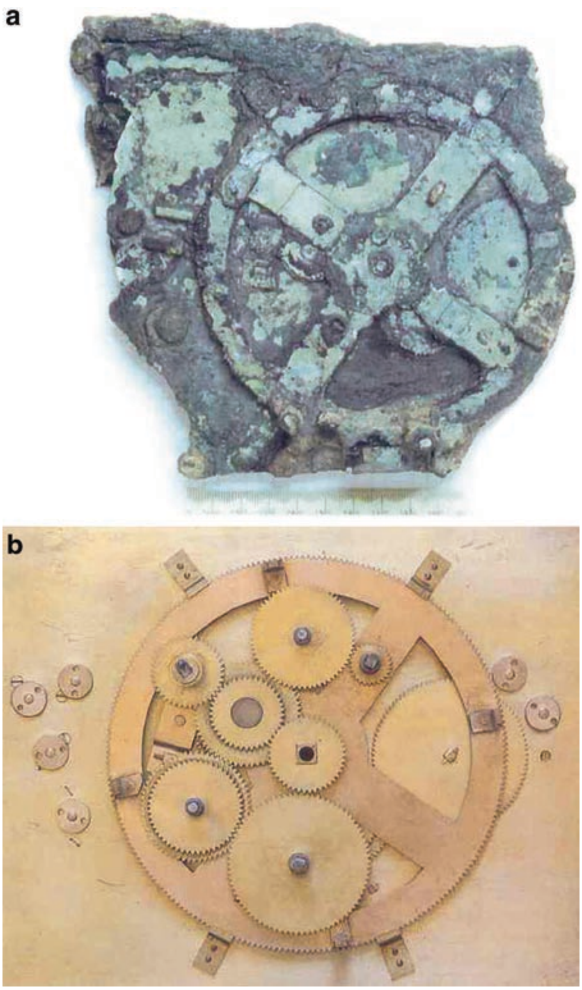

Fig. 3.13 Antikythera mechanism: (**a**) Mechanical gear assembly constructed from the remains, front view. (**b**) M.T. Wright's reconstruction

The activities of military forces during these centuries also stimulated the development of more efficient war machines. Even entertaining events that were attended by large crowds of citizens needed machines whose dimensions required the support of mechanical designs. Mining activity reached proportions that made manual labour unfeasible and therefore it was necessary to pump water from the galleries in amounts that would be described today as on an industrial scale.

All the civilisations coming together under the Greco-Roman world undertook large-scale public works requiring appropriate machinery, even though there was an enormous amount of slave labour. Mechanical engineering gradually became consolidated as a profession that designed, built, and operated machinery.

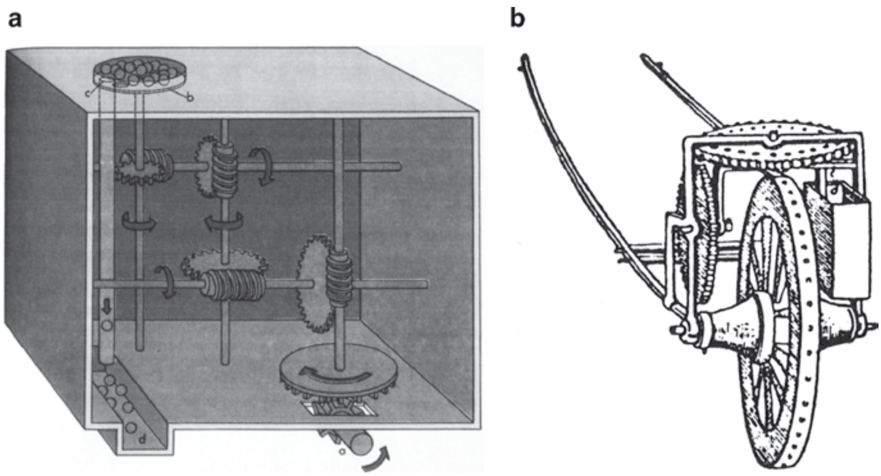

Fig. 3.14 Odometer machine: (**a**) Sigvard Strandh's reproduction of Hero's odometer. (**b**) Leonardo da Vinci's odometer drawn during the Renaissance [119]

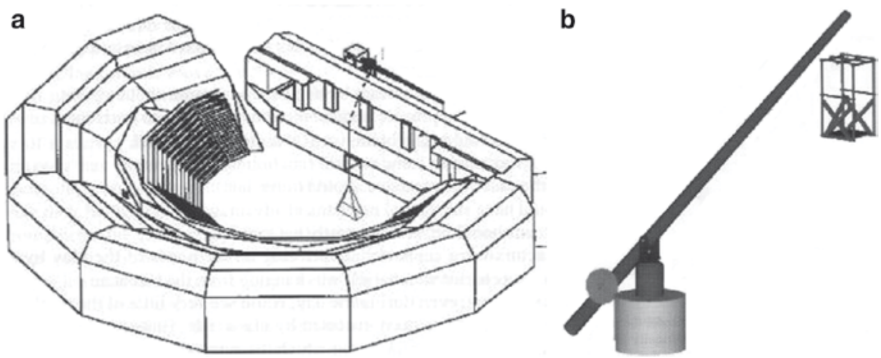

Fig. 3.15 The Mecano mechanism in Greek theatre according to Chondros in 2004 [129]: (**a**) Reconstruction of a fifth century BC Greek theatre. (**b**) Reconstruction of a Mecano

Greek theatre reached its splendour in the fifth century BC. Evidence can be found in classical texts of this period on the existence of mechanisms that were used in theatre, although we have no illustrations. T.G. Chondros's 2004 reconstruction shows an elevator of the period called a Mecano, which is thought to have been able to lift over 500 kg. Figure 3.15 shows a three-dimensional drawing of the ancient theatre in Athens with a Mecano and a description of its parts.

Elevators like those in Fig. 3.16 were also employed in Ancient Egypt, and operated by several people using a rope and pulley. Milonov Ju.K's 1936 reconstruction can be appreciated in this figure.

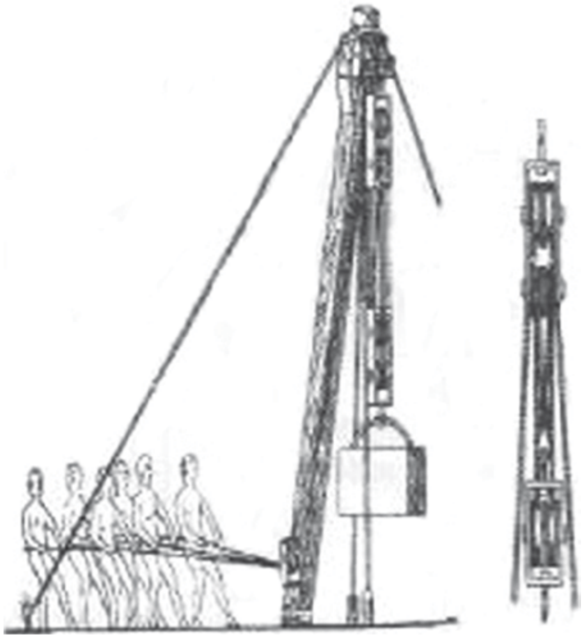

Fig. 3.16 Elevator used in Ancient Egypt, reconstruction by Milonov Ju.K. [129]

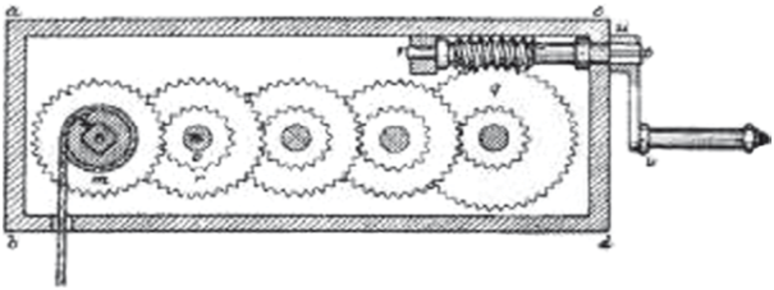

Fig. 3.17 Mechanism designed for raising loads, according to Hero's works. Reconstruction by Milonov Ju.K. [129]

Regarding the same machines, Hero presented a mechanism for lifting loads, whose reconstruction is shown in Fig. 3.17 according to Milonov Ju.K. (1936). This figure shows a worm gear that was designed to obtain a considerable reduction in speed of operation and to multiply the force in lifting operations.

Also relevant are hydraulic machines like Ctesibius's famous suction pump that was described in detail by Hero. The discovery of this kind of pump among Roman remains in Huelva is proof that it was extensively used. It is shown in Fig. 3.18a.

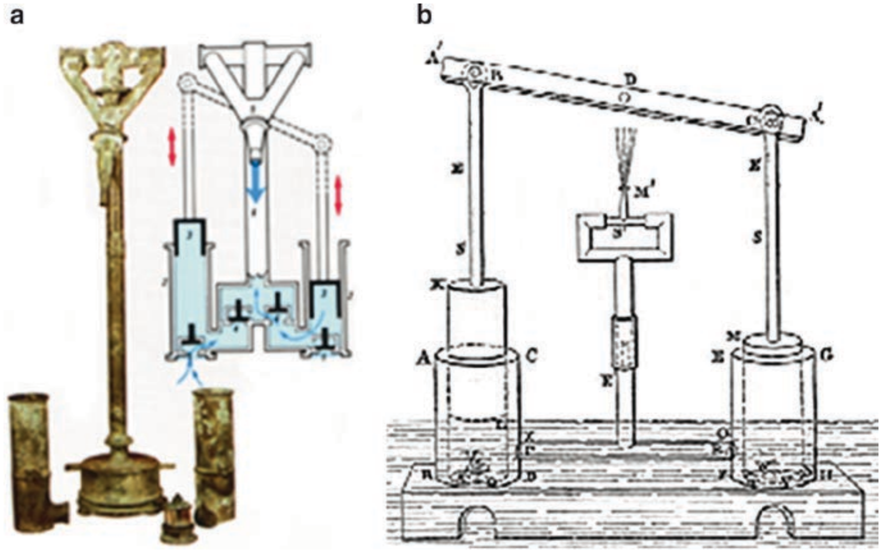

Fig. 3.18 Mechanism design in pump machines: (**a**) Remains of a Roman pump from the Valverde mine in Huelva, Spain. (**b**) Reconstruction of Ctesibius's pump as described by Hero from the translation of "Pneumatics" by Bennet Woodcroft [137]

The pump is operated by a lever mechanism that moves the pistons in two cylinders in order to pressurize water for several purposes like drainage, fountains feeding, fires extinction, etc. As can be noted in Fig. 3.18b, the cylinders were interconnected by mean of valves and through a common vertical pipe for the output of the water.

At the bottom of the cylinders there were connecting valves with a tank. The lever mechanism operated in such a way that when it guided a cylinder to rise, the other cylinder descends. The rising cylinder takes in water through the valve at the bottom and the descending cylinder pushes out the water into the upward vertical pipe, while the water pressure closes the other valves.

Figure 3.19 shows two examples of water-powered machines from Antiquity. They were used for several purposes, such as raising water, mills, etc. Figure 3.19a shows a sophisticated water wheel that is attributed to Philon, as in the reconstruction in the book "A History of the Machine" by Sigvard Strandh. It consisted of a water wheel driving a chain that gives a rotation motion to an upper shaft of a triangular drum. The chain is provided with suitable buckets. As the shaft rotates, the buckets are filled with water from the bottom flow and then they are poured out into a pipe at the top.

The machine in Fig. 3.19b is a gear mill that is described by Vitruvius and is shown as in the book "A History of the Machine" by Sigvard Strandh.

Many other machines implemented a knowledge of the screw and examples can be outlined from different kinds of presses that were described by Hero. Sigvard Strandh's reconstructions show examples for crushing fruit. In Fig. 3.20a, the screw

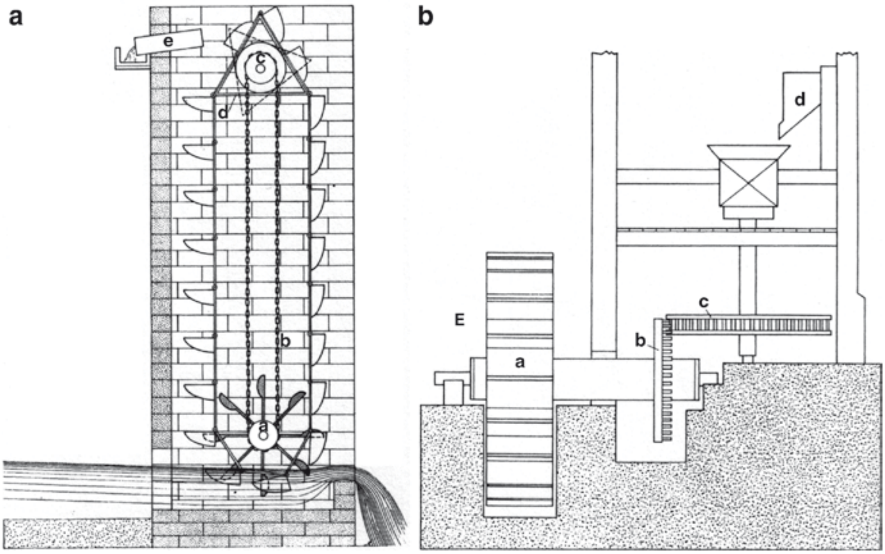

Fig. 3.19 Water-powered machines according to reconstructions by Sigvard Strandh [119]: (**a**) Philon's water wheel. (**b**) Vitruvius' gear mill

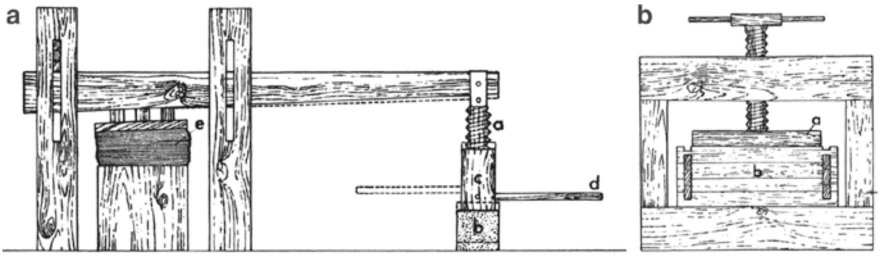

Fig. 3.20 Hero's press; reconstructions by Sigvard Strandh. (**a**) Beam press. (**b**) Direct press [119]

operates a crossbeam for compression by moving the beam vertically. Figure 3.20b shows a direct screw press. This type of press, with some innovations, was found during the Renaissance and during the Iberian Empire.

Among war machines at the beginning of the second century AD, the role of Apollodorus of Damascus is remarkable. His work on siege machines was later reinterpreted in Byzantium. More detailed drawings were outlined with the figures of persons to give some idea of the size of the machines. Figure 3.21 shows a siege tower from a sixteenth century Italian copy of a drawing taken from an eleventh century Greek manuscript by a Byzantine author who, under the pseudonym of Hero of Byzantium, based his work on Apollodorus's manual.

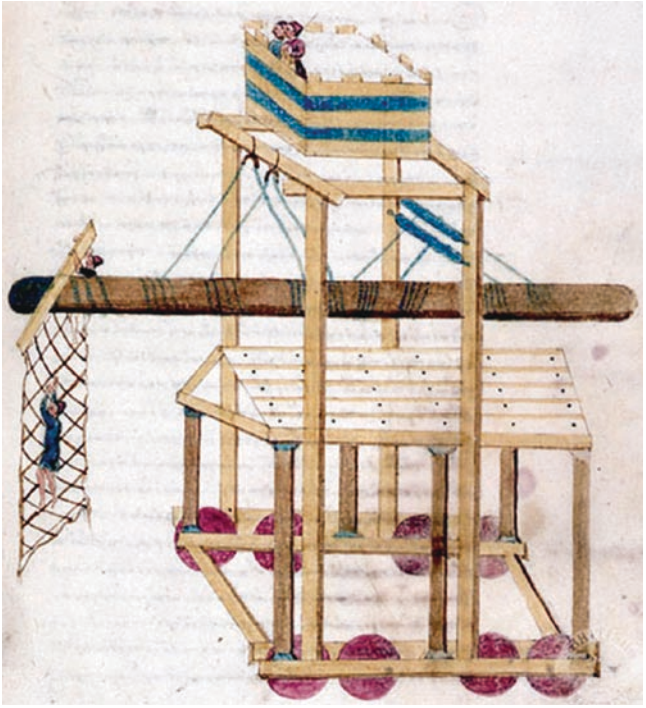

Fig. 3.21 An Apollodorus war machine as redrawn several centuries later

On Vitruvius's Influence

The Roman Empire acquired and improved this development of mechanical engineering during the millennium of the Empire.

When he was young, Marcus Vitruvius worked as an engineer for Julius Caesar, and then he focused his attention on civil architecture in his masterpiece work "De Architectura", which is a compilation of architectural knowledge that also devotes several sections to machines for building activity.

Later, in his work "De aquaeductu urbis Romae", Frontino gathered together the techniques for supplying and distributing water to the capital of the Empire.

In the next centuries, mechanical engineering languished as a professional activity and was relegated to specific spheres, until it was once boosted because of new economic and social conditions. An indicator of the extraordinary level that was reached in the Greco-Roman period was the enormous value that was credited to Vitruvius's work centuries later when, during the Renaissance, society once again began to approach similar technological problems.

There is evidence that the work of Vitruvius was studied by Iocundo in 1511, with a folio edition containing 136 illustrations. There were many translations and

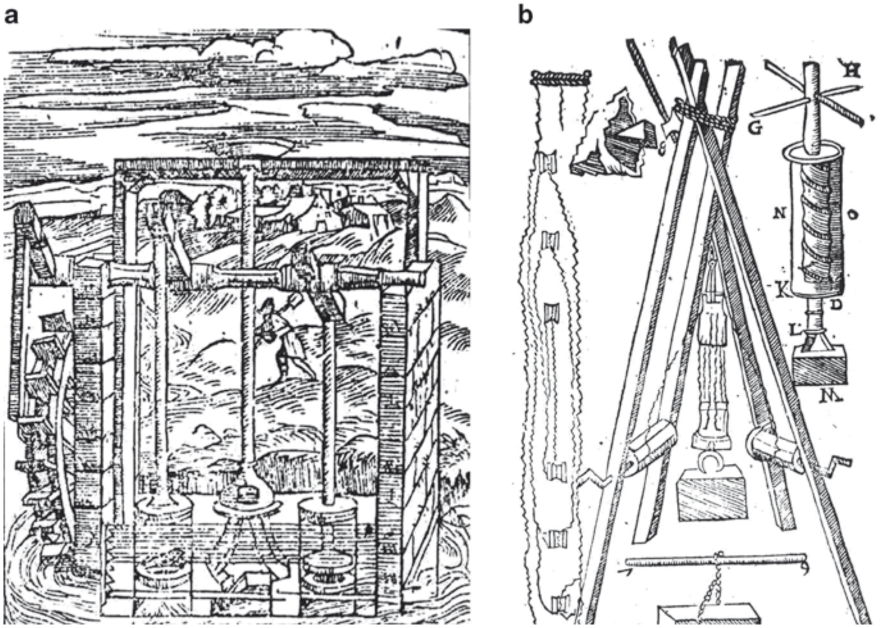

Fig. 3.22 Vitruvius's reconstructions of machines by Danielle Barbaro [15,135]: (**a**) Suction mill; (**b**) Crane

interpretations during the Renaissance and later periods. These Vitruvius editions were published with a wealth of magnificent engravings, like in Danielle Barbaro's work in 1584. Figure 3.22a, b show a water pump and a crane.

Two hundred years later, a machine treatise was published on Vitruvius machines and then it was translated from the Latin and commented on in Madrid in 1787 by Joseph Ortiz y Sanz, who was a priest in the service of the King. This publication includes some more thorough reconstructions of the water raising machines described by Vitruvius, such as tympanums and water wheels or screws by Archimedes, as shown in Fig. 3.23. It can be noted that Ortiz y Sanz also provided some schematic-type drawings for building this screw.

The great works of Roman architecture required the use of several machines and elevators for construction work. These machines were different in the way weights were lifted and in the number of men required to operate them. The machines make use of mechanical parts such as pulleys, winches, ropes, and wheels, with a place for a person to work inside. Outstanding examples are shown in Figs. 3.24 and 3.25.

On Harmony in Machines

The Greco-Roman world had a profound sense of beauty and harmony, which was reflected in its works, even in machines.

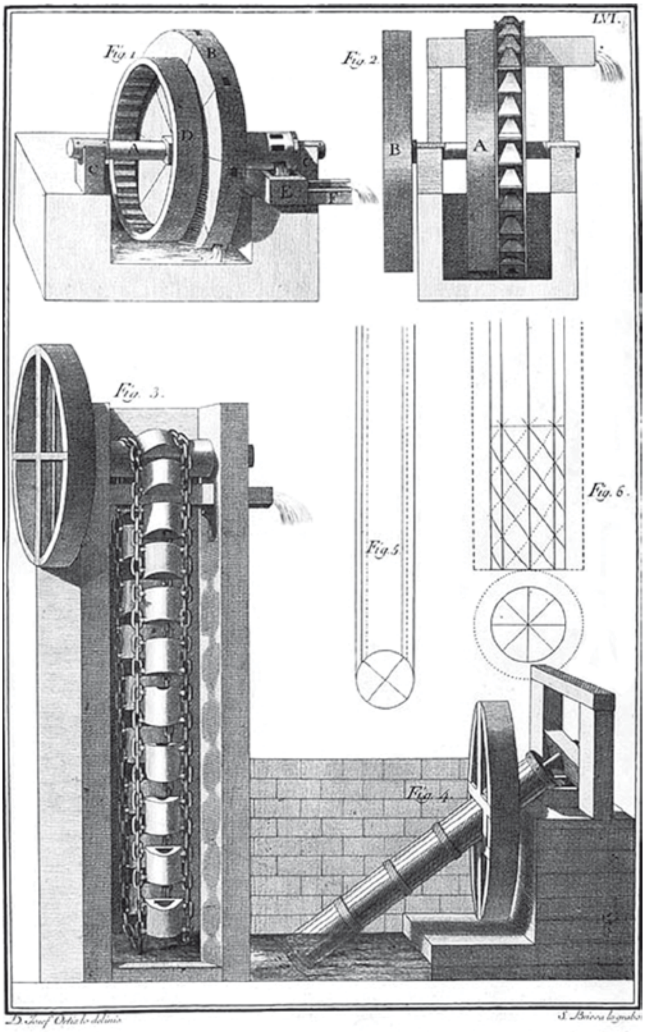

Fig. 3.23 A reconstruction of Vitruvius's machine for raising water in engraving VI by Joseph Ortiz y Sanz [135]

Harmony with the universe, with the nearby surroundings, and between the parts composing a machine. All this was considered, even in the design aspects. But apart from aesthetic considerations, this harmony was aimed at efficient operation of whole. Something in harmony will more likely achieve this purpose.

Geometric criteria of harmony were applied to machines which had to be built in the right proportions. A proportion is made up of ratios and a ratio is a comparison between two sizes, quantities, qualities, or similar concepts, and it is expressed by the formula *a/b*. Therefore, a ratio consists of the measurement of a difference; a difference to which at least one of our sensorial faculties can respond. The world

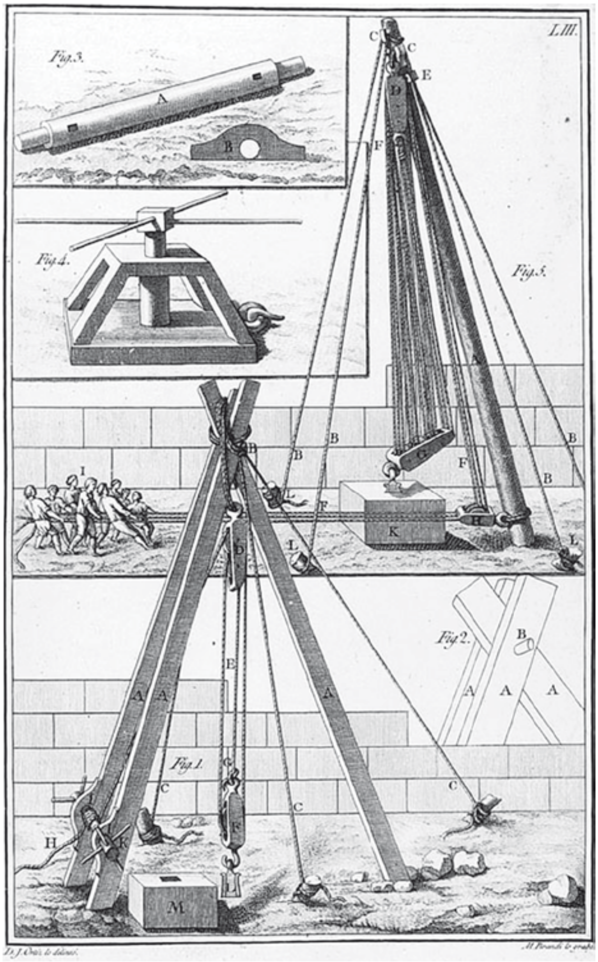

Fig. 3.24 A reconstruction of Vitruvius's machine for lifting loads in engraving III by Joseph Ortiz y Sanz [135]

we perceive is made up of intricate inter-related patterns which Gregory Bateson calls "differences that make a difference".

The golden proportion (usually denoted Φ) is a constant ratio that is derived from a geometric relationship, which like π and other constants, is "irrational" in numerical terms. In one sense, the golden proportion may be deemed supra-rational or transcendental. For this reason, for the Greeks it was a proportion that was the foundation of the experience of knowledge *(logos)*.

It may be said that wherever function is intensified or where there is a special beauty or harmony of form, the golden number will be found.

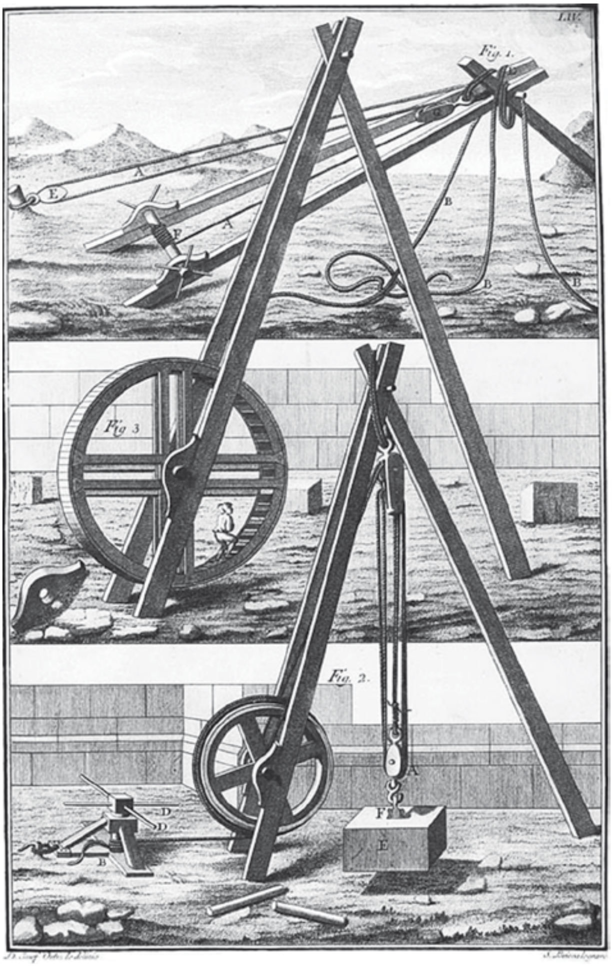

Fig. 3.25 A reconstruction of Vitruvius's machine for lifting loads in engraving IV by Joseph Ortiz y Sanz [135]

However, it is in the human body where the metaphysical meaning of Φ, can be discovered, as expressed by Heraclites' aphorism: "Man is the measure of all things". According to the different traditions which identify a human model, that is a definition of the average ideal proportions of the body, the body is divided by the navel, according to the golden section (Fig. 3.26).

The parts composing Greco-Roman machines also abided by this concept of proportion. Machines, man, and the firmaments had to be one of the same harmony.

Fig. 3.26 Division of the human body according to the golden section