Technology and Autonomous Mechanisms in the Mediterranean - From Ancient Greece to Byzantium

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The idea to write this article originated from presentations made at the panel on "*Early History of Autonomous Mechanisms*" that took place during the *Mediterranean Conference on Control and Automation* and the *IEEE International Symposium on Intelligent Control*, in Limassol, Cyprus, June 27-29, 2005 [1]. The rationale behind organizing this panel was to explore the origins of technology and first autonomous mechanisms as well as shed light to the question "Is Feedback Control a Mediterranean Invention?" The panel included the following presentations by the panelists: "Sketching the Ancient Mediterranean Map of Science and Technology: A snapshot of the Ancient Quest for Autonomy," P. Antsaklis, Department of EE, University of Notre Dame; "The study of Ancient Technology", V. Kassianidou and G. Papasavvas, Archaeological Research Unit, University of Cyprus; "An Introduction to the Technology of the Ancient World," H. Doumanides, Department of Mechanical and Manufacturing Engineering, University of Cyprus and N. Fourlingas, Harvard Medical School; "The Roots of our Profession: Antiquity's Contributions to Engineering and Automatic Control", G. Vachtsevanos, Department of ECE, Georgia Tech, and Kimon P. Valavanis Department of CSE, University of South Florida. Sketching a map of, and through a journey around the Ancient Mediterranean World, reveals overwhelming evidence of major achievements in Science, Technology and 'making of Automation' (from the Greek word *Αυτοματοποιητική*) that even if it does not answer authoritatively the posed question, it does point towards that direction. Regardless, that part of the World has been, without any doubt, the birthplace of today's Western Science and Technology.

INTRODUCTION

All through craft history and technological progress, humankind has attempted to build 'devices' that could function by themselves under minimum or no human supervision, as well as 'devices' that looked and behaved as humans do (now known as humanoid robots). This '*quest for autonomy*' and the evolution of such automatic devices, called *automata* by the Greeks (Greek word *αυτόματα*), find their origins in Greek Mythology and poetry, where such 'devices' reflected the everlasting human desire: i) to relieve humans from the burden of heavy and repeated labor; ii) to protect humans, and iii) for amusement and wonder. For example, myths refer to god Hephaestus as the owner and builder of automated mechanisms, called *golden women*, who helped him in his machine shop and who were able to talk; Hephaestus also built a series of tables with three legs and wheels - Homer's *Iliad* refers to those mechanical devices as the *gold tripods* of Hephaestus, otherwise known as the *golden slaves* (see Figure 1a) - that helped him walk but also served wine and food to the 12 Gods of Mount Olympus [23]. In addition, Hephaestus is known to have designed a *chair – trap* in which he trapped his mother Hera and blackmailed her to reveal to him who was his father (the myth says that his father was Zeus). Homer's *Odyssey* also mentions the ships of the Phoenicians that were moving by themselves as if there were an internal force pushing them. Greek Mythology refers to the giant Talus shown in Figure 1b (in Greek *Τάλος* or *Τάλως*), made of brass, built by Hephaestus and offered as a wedding gift to Europe when she married Zeus. Zeus gave Talus to King Minos of Crete, who used the giant to convey his messages and laws all over the island running back and forth three times a day, but also to protect the island against intruders by throwing at their ships rocks and melted lava from huge pots. According to [23], Hephaestus was helped by Daidalus (who designed wings for him and his son Icarus in an attempt to fly over the Aegean Sea) to build Talus. Talus is considered the first humanoid robot with characteristics similar to today's humanoids: endless repeatability, no fatigue, ability for heavy labor, multi tasking ability, serving humans, and with huge power. What is amazing is that after the mythical Talus, it was not before the 16th century where the Italian Hieronymus Fabrikius (1537-1619 A.D.), a famous anatomist and embryologist of his time, attempted to build the first ever mechanical man shown in Figure 1c using surgical tools [23].

There exists a long list of descriptions of mechanisms, many of them having autonomous functions, from the inventions of Archimedes (287-212 B.C.), to those of Heron of Alexandria (circa 60 A.D.), to modern times. Many of these autonomous devices were built to amaze and entertain royalty, but also to demonstrate their creator's skills as applied to a specific design. They typically relied on some clockwork mechanism and worked without feedback, open loop; once started they followed a prescribed set of steps in sequence to complete a series of tasks. Such devices could be described and modeled accurately today by using Automata Theory or Petri Nets. From 1500 A.D. on, well known creations in automatic mechanisms include: the figure of a girl playing a lute (1540, Gianello della Tore, Kunsthistoriches Museum, Vienna), two mechanical dolls called the scribe and the musician playing a piano (1770 and 1773, Henri-Louis Jaquet-Droz, Musee d' Art et Historie, Neuchatel), the talking machine (1778, Wolfgang von Kempelen), the Philadelphia doll (a writing mechanism built before 1812 (Les Maillardet, Franklin Institute, Philadelphia)), the steam man (walker powered by a gas-fired boiler, 1893, George Moore), and the electromagnetic chess-playing machine (the first decision-making machine, 1912, Leonardo Tores Quevedo) [3], [4].

Focusing on the discipline of Feedback Control, it is customary to consider James Watt's Flyball Governor (1769) as one of the earliest feedback control devices of the modern era. This device was used to regulate the rotational speed in steam locomotives and became very useful during Europe's Industrial Revolution in the 1800's. As demands on the device grew, the flyball governor was required to work in new operating regions where it was exhibiting undesirable oscillations for unexplained reasons at that time. It was J.C. Maxwell (1868) who first used differential equations to model and explain this phenomenon, and this event marked the beginning of the introduction of mathematical rigor into the study of feedback control devices, together with the work of Routh (1877) and Lyapunov (1890) [5], [6], [7], [8], [9], [10], [11], [12], [13].

However, the discipline of Feedback Control has a very long history dating back not 2 centuries but over 20 centuries. Looking back, one finds that automatic feedback control devices appeared first in the work of Ktesibius (or Ctesibius) of Alexandria (circa 270 B.C.) as reported by Vitruvius (circa 25 A.D.), Heron (or Hero) of Alexandria (circa 60 A.D.) and Philon of Byzantium (circa 230 B.C.). In fact, the first feedback control device on historical record is the water clock of Ktesibius [5], [6]. Indeed, the roots of automation, automated mechanisms, and feedback control are found about 3,000 years ago, and they are centered in the Ancient Greek World that developed in the Mediterranean region.

It is important to note that as presented in [24, pp: 473-478] the term 'machine' (in Greek *μηχανή*) with its current meaning was used by Aeschylus (5th century B.C.) to describe the theater stage mechanism built to 'bring' Ancient Greek tragedy heroes on stage. This term is known in Latin as *Deus ex machina* introduced by Vitruvius. Those mechanisms consisted of beams, wheels and ropes that could raise weights up to one ton, and move back and forth violently to depict space travel, as the play demanded. The same term, machine, is found in Homer's Iliad with a different meaning – that of political dealing or political manipulation.

Further, in an attempt to capture as best as possible the thought process in the Ancient Greek World and offer more justifications, it is deemed essential to connect the concept and meaning of the term 'machine' with the term 'system' (from the Greek word *σύστημα*). As presented and documented in detail in [28], the meaning of the term 'system' varied according to sources such as geometry, numbers, philosophy, music, and medicine; but the basic notion that the whole is made from parts and that the whole appear with properties not always attributed to the individual parts was common to all domains. Although some understanding of the 'system' notion is due to Plato, Aristotle and Hippocrates, its origin is credited to the Pre-Socratic philosophers and their effort to comprehend the unknown physical world. The first explicit definition of 'system' is attributed to the Lakonian and Pythagorean Kallicratides in his work "On the Happiness of Family" (in Greek *Περί οίκων ευδαιμονίας*) where he explains what is a ‘system’ in terms of three examples: the system of dance in the singing societies; the system of the crew in a ship; the system of the family, where the people are next of kin: “*Any system consists of contrary and dissimilar elements, which unite under one optimum and return to the common purpose”*. Kallicratides’s definition indicates that the system could be considered not as a simple open system, but as a closed loop control system consisting of opposite parts, united to the optimum (controller aiming at optimization) and returning to the common target (embodying feedback).

It is the objective of this paper to present documented historical evidence of achievements in Science, Technology and the making of Automation in the Ancient Greek World, until the era of Byzantium. To do so, it is essential to observe that in the history of humankind and regardless of time frame, technological innovation evolved always through three important steps: i) invention of tools like the spear and the sickle that prolonged a man’s arms and enhanced human power; ii) invention of machines functioning through external means of power, such as animal or wind power, and put under human control as in the case of chariots or ships; iii) invention of automatic devices moving by themselves without requiring any human force.

Moreover, it is at least equally important to understand that the main driving force behind Greek Science [14], [15], [16] has been *curiosity*, the desire for knowledge for its own sake, followed by the study of *nature*. The three main branches of investigation concerning nature in Ancient Greece were Natural Philosophy (including Physics and Cosmology), Mathematics and Astronomy, Biology and Medicine. The term Philosophy in the Ancient

Greek World (in Greek *Φιλοσοφία* – love of wisdom) had a more general meaning and encompassed the study of natural phenomena. Besides philosophers and mathematicians who thrived during that time, there were also doctors, architects and engineers who recognized the practical importance of their theoretical inquiries. But the idea that the study of nature would be of practical use, while not totally absent, took second place to the idea that it contributed to knowledge and understanding. On the other hand, it is interesting to note that an architect like Vitruvius, whose books are primary sources for automation in the Ancient World [17], did more than design buildings, squares and other public spaces; an architect was also a designer of machines of war, like catapults, and so was well versed in mechanical devices.

This vast amount of information about Science and Technology in the Mediterranean region and the Ancient Greek World available today, perhaps beyond imagination, has come from archaeological research (*Archaeology* is defined as the study of ancient material culture - that is the study of human artifacts) [1]. Excavations of ancient workshops and mines have revealed materials and tools that shed light into the extraction process and the various steps in technological processes. Wall paintings have also revealed useful information about tools and processes. In addition, among the writings and text that have survived (3rd – 1st millennium B.C.) over the years, there are many of technological content; for example, texts from Ancient Mesopotamia dating back to the 2nd millennium B.C. contain recipes to make glass and copper alloys. Additional information is gathered through *Ethnoarchaeology*, a rather new field studying contemporary communities that live and use a technology that has not changed much since antiquity, for example pottery making. Issues have also been addressed by experimental Archaeology by creating, for example, exact replicas of ancient ships and numerous mechanisms with the intent to study them but also to showcase the achievements of the ancient world. The study of ancient technology has been enhanced by *Archaeometry*, the application of physical sciences to the study of ancient artifacts to pin point their exact time of appearance and reconstruct ancient trading networks [1].

In order to put things in perspective and in context, it is best to provide first a foundation by sketching the map of the Mediterranean region and the Ancient Greek World in terms of Science and Technology, as well as its major contributors. This is given in Section II in terms of a set of Tables that provide major chronological divisions, key contributions and important events. Details of achievements during each period are provided in Section III, followed by accomplishments in automatic control and the transition from the Ancient Greek World to the Greco-Roman era and the Byzantium. Conclusions and discussion are finally offered.

BACKGROUND: CHRONOLOGICAL MAP OF SCIENCE AND TECHNOLOGY

It is worth noting that there was an initial phase of imported influences in the development of Ancient Greek technology that reached the Greek states from the East (Persia, Babylon and Mesopotamia) and practiced by the Greeks up until the 6th century B.C. It was at the time of Thales of Miletus (circa 585 B.C.), when a very significant change occurred. A new and exclusively Greek activity began to dominate any inherited technology, *Science* (from the Greek word *Επιστήμη*). As a result, in subsequent centuries, technology itself became more productive, and technological innovations surfaced through synergies between science and technology. New measuring instruments, geometrical concepts, engineering, mechanics, musical instruments, etc., influenced important application domains like metallurgy, construction projects, architecture, military tactics and machines, among others [14], [15], [16].

One of the first inventions of the 5th century B.C. - not widely known but very important - was the starting mechanism in ancient stadiums, built to prevent untimely starts in races, called 'hysplex' (in Greek *ύσπληξ*), shown in Figure 2. Quoting from [24, pages 465-472], "The system consisted of two horizontal ropes stretched in front of the waist and the knees of the runners. The ends of the ropes were tied at the peaks of vertical wooden posts implanted in mechanisms near the two ends of the starting threshold. The mechanisms were controlled by the starter, who, standing at the back of the runners, could let at the appropriate moment the ropes to fall down, thus permitting all the runners to start simultaneously." A reconstruction of a full-size model of the hysplex was made possible at the UC Berkeley, and it was tested successfully in Greece after 2,330 years, on July 1, 1996, at an international track and field meeting called Nemean Games [27]. The hysplex worked for 52 consecutive times!

However, in terms of chronological accomplishments and breakthroughs, it is convenient to divide the era of Ancient Greek Science into four periods [14]:

- The pre-Socratic period from 600 B.C. to about 400 B.C;
- 4th century B.C. (400-300) with main representatives Plato, Aristotle, the Epicureans and Stoic philosophers;
- The Hellenistic (in Greek *Ελληνιστική*) period, 300-100 B.C., where there was direct interaction with the remains of older cultures, with main representatives Euclid,

Archimedes, Apollonius. This has been coined as the *Golden Era* of Science and Technology. It was the period that followed the death of Alexander the Great, 323 B.C., where Alexander's successors ruled most of the Old World. During that period more direct interaction took place between the Greek and remnants of older cultures.

- 100 B.C. – 600 A.D. where Greek science was influenced by spiritual and non-rational currents that were partially responsible for the rise of Christianity. It was during that period that Greek Science that was passed later on to the Arabs and through them to the Latin West was epitomized, reorganized and subjected to extensive commentaries.

Table 1 presents a non exhaustive list of major contributors and important events that influenced Ancient Greek Science and Technology, establishing a timeline of major achievements.

Mathematics as a discipline was tightly coupled with technological achievements. Over the years, there have been questions of when and how Mathematics was used in the study of physical problems and the role of experiments in Ancient Greek Science. Mathematics was used not only as a theoretical discipline but also as a tool; mathematics was behind a wide range of applications and the means to engineering designs. It is no coincidence that Thales, Pythagoras, Euclid, Archimedes, and Apollonius were mathematicians at first. Archimedes was the first one to utilize mathematics in a completely mature fashion for the treatment of a physical problem. Furthermore, the tradition of formal mechanical treatises, including theoretical and applied mechanics, as distinct domains from the almost completely theoretical mechanics of Archimedes continued in the 3rd century B.C. by Ktesibius whose work, although lost, is known only through the references of Vitruvius and by Philon of Byzantium. The most comprehensive of the extant mechanical treatises is that of Heron of Alexandria, a recognized mathematician and an excellent mechanic.

In order to provide a reference point related to Mathematics as a distinct discipline, Table 2 provides a general division in four distinct units [17] each marking an important era, followed by Table 3 with representatives of the Hellenistic period.

The next section concentrates on specific accomplishments.

THE JOURNEY THROUGH GREEK SCIENCE AND TECHNOLOGY

There were three main institutions in the Ancient Greek World that contributed to Science and Technology: *Plato's Academy*, *Aristotle's Lyceum*, and *The Library of Alexandria*.

Plato's Academy and Aristotle's Lyceum were focusing more on Science; they were very influential institutions operating as Schools or Universities charging tuition, and financially self sustained. The Museum and Library of Alexandria established around 300 B.C. exerted long lasting influence over many centuries; it was operating more like a research laboratory than a University and it was financially dependent on the rulers of Egypt [14], [15], [16], [19].

Among the earliest contributors to Ancient Greek Science and Technology were the members of the Miletian School and particularly Thales of Miletus. The main contributions of the Miletian School were considered to be the distinction between the *Natural* and the *Supernatural* and the introduction of rational criticism and debate. Achievements of the period between Thales and Aristotle were the advances in factual knowledge (anatomy, zoology), the problem formulation (Aristotle's biological problems of reproduction and heredity), the application of Mathematics to the understanding of natural phenomena (Pythagoreans and Plato) and the notion of undertaking empirical research (Hippocrates and Aristotle).

Thales is mostly known as the first person who studied *geometric objects*, circles, lines, triangles. He was the first who thought of the *angle* as a separate, distinct and autonomous mathematical entity, and he established it as the fourth geometric element complementing the other three, *length*, *surface*, *volume*. Thales' contribution to Science is that his work never referred to calculations and results obtained for a specific example or case study (as the Egyptians and the Babylonians did), but rather, it was very general; he is considered to be the first theoretician in the field of mathematics with theorem proving abilities.

Focusing on mechanisms, technological innovation was either related to invention of machines functioning using external means such as, animal or wind power, or related to invention of automatic devices moving by themselves without requiring any human force; such were the inventions of Heron of Alexandria as detailed below.

One of the oldest mechanisms chronicled around the 6th century B.C., 580 B.C., depicting an oil press operated by the weight of stones was found by Fouque in 1879 in Therassia, a small island opposite Thera (Santorini). Figure 3 is the only evidence found on an Ancient Greek design on exhibit at the British museum in London.

It is documented that the first major breakthrough contribution to autonomous mechanisms occurred during the era of Pythagoras (who was Thales' student for a few years). It is attributed to the Pythagoreans and in particular to Archytas from the city of Tarantas (in south Italy), known as *Archytas the Tarantine* (also referred to as Leonardo da Vinci of the Ancient World). Archytas was not only the inventor of the number 'one', 1 (*the father of 1*) in number theory, but he also was the *first engineer*. By applying a series of geometric notions and observations to the study of structures, links and joints, he created *Mechanics* (in Greek *Μηχανική*)! Not only he was drawing mechanisms, he was also building them. As such, in 425 B.C. *he created the first Unmanned Aerial Vehicle of all times* by building a mechanical bird, a pigeon (in Greek *περιστέρι*) that could fly by moving its wings getting energy from a mechanism in its stomach, see Figure 4. This flying machine flew about 200 meters. However, once all energy was used, the pigeon fell, landed, on earth and could not fly, take off, again. Archytas was also a politician elected seven times as General of the city of Tarantas.

The introduction of catapults changed the art of war. The first catapults appeared in Syracuse, during the time of the tyrant Dionysius the Elder (Dionysius of Syracuse, 430 – 367

B.C.), who created the first ever Scientific Research Center [23]. The widest and most well known use of catapults occurred during the reign of Philip of Macedonia and his son Alexander the Great who perfected the use of catapults to gain advantage in battles against their enemies. Perfection was the elaboration of mathematical formulas that related the size of the catapults' components to the weight of the projectiles or the size of the bolts that were about to shoot by the Alexandrian mechanics [24, pp: 545-548]. Figure 5 illustrates two types of catapult that subverted martial tactics and dominated for many centuries the battlefield; Figure 6 depicts other types of catapults also used in battlefields, while Figure 7 shows recent reproductions of other battlefield mechanisms.

Several inventions are attributed to Archimedes, who, according to Drachmann, was "…the greatest mathematical and engineering genius of ancient times" [24], [25], [26]. He was perhaps the first to use mathematics to solve physical problems. They include the steam gun (Figure 8) and the endless screw (Figure 9), among other inventions such as cranes and solar mirrors. The steam gun created the foundation for the theory of hydrodynamics. Information about the steam gun is due to the Italian Petrarca (1304-1374 A.D.), but it was Leonardo da Vinci who explained its operation and stated that it could through a bullet weighted 1 *τάλαντο* about 1,100 meters away.

Another invention attributed to Archimedes is the *water clock*, shown in Figure 10 that stood tall more than 4 meters (although there are researchers claiming that it was invented by Heron or Philon, and others). There are three sources [26] from Vitruvius, Pappos the Alexandrian and an Arabic document that provide evidence regarding this invention by

Archimedes, shown in Figure 10, as reproduced by the German scientists Wiedemann and Hauser. A complete detailed description of how it works may be found in [26]. It is important to state that it looks like there was progress in this area before Ktesibius invented his water clock (see below) without knowing exactly when it started. But since Archimedes (287-212 B.C.) and Ktesibius (285-222 B.C.) lived almost at the same time, it may be that either Ktesibius improved Archimedes' clock, or the two invented it independently of each other.

Next in sequence is contributions made by the School of Alexandria. This entity is treated separately due to its importance as a link between the Ancient Greek World, the Greco-Roman era and Byzantium.

The School of Alexandria

During the golden era of the School of Alexandria [19], Greek thought evolved towards what Newton called much later *Natural Philosophy*. Instead of interpreting the world from *outside-in*, the world was explored from *inside–out*. This turn of Greek thought culminates in the search for observation, measurements, design and construction.

The School of Alexandria is directly linked with three Greek engineers of the Hellenistic world: Ktesibius (or Ctesibius), Philon of Byzantine and Heron of Alexandria who lived in the second century B.C. through the first century A.D. Their pioneering contributions influenced the western science and technology and their writings were reprinted until the 16th century A.D.

Ktesibius (circa 270 B.C.) was the son of a barber. He was a Greek physicist and inventor, the first great figure of the ancient engineering tradition of the School of Alexandria. The discovery of the elasticity of air is attributed to him, as is the invention of several devices using compressed air, including force pumps and an air-powered catapult. His most famous invention, however, was an improvement of the clepsydra (in Greek *κλεψύδρα*), or water clock, in which water dripping at a constant rate raised a float that held a pointer to mark time - the passage of hours. Another notable invention was a ‘hydraulis’, or water organ, in which air was forced through the organ pipes by the weight of water rather than by falling lead weights [16], [17], [20]. Unfortunately, Ktesibius' writings have not survived, and his inventions are known only from references by Vitruvius [17] and Heron of Alexandria. Figures 11 to 13 illustrate inventions made by Ktesibius. Ktesibius’ water clock, shown in Figure 12, incorporated a feedback mechanism that used a floating device as both a sensor and actuator that kept the water level approximately constant and ensured constant flow of water and so accurate time keeping [5], [6]. This device was so successful that they were still making it in Baghdad in 1200 A.D. when the Mongols conquered the city!

Philon of Byzantium (circa 230 B.C.) authored several books (most of which have survived) on levers, water clocks, pneumatic mechanisms and military machines, among others. His major contribution relates to the subject of *spur gears* (in Greek *οδοντοτοί τροχοί*). The transfer of mechanical power and the multiplying or dividing effect of circular motion machines are based on such gears. Philon’s treatise *Pneumatica* is addressing key physical properties of liquids and gases supported by a plethora of experiments. He also had advanced knowledge of metallurgy. Philon explained thoroughly Ktesibius' contention regarding the replacement of animal fibers with thermally treated metal leaves. In essence, Philon advanced further the Alexandrian School's developments in automatic mechanisms started by Ktesibius. The Arabic translation of Philon's *Pneumatica* is a thesaurus of such automatic devices based on properties of air, liquids, fire, floaters and gears. They offer a rich foundation for a new technology, *automation*. Although he did not complete his work, he laid the groundwork for the European technological developments for the next 1500 years [16], [20].

Eight hundred years of tradition in Ancient Greek Science and Technology culminated with the enormous work of Heron who was a scientist of great breadth. Heron of Alexandria (circa 60 A.D.) taught at the Museum of Alexandria and presented in his books *About Pneumatica* and *About Automation* (in Greek *Αυτοματοποιητική*) the up until then known knowledge of automation technologies. Among his surviving writings, his book on Automation (*Αυτοματοποιητική*) according to historians, lays the foundation of modern automatic control and it is the oldest known document that describes mechanical automatic systems capable of performing programmed movements. [16], [20], [21]. *Αυτοματοποιητική* refers to automatic machines that operate and move without human intervention by capitalizing on properties of steam, liquid and gaseous matter, and involve complex mechanical systems and ingenious programming of movements. Every mechanical device was broken down to its constituent components which, in turn, refer to levers with a basic geometric interpretation. Therefore, a methodology was pursued although the ultimate objective of Heron's books was applications.

Heron’s two books, *About Pneumatica*, introduced steam as a major driving force. He did not invent Watt's steam engine, but he presented basic notions such as the lifting and driving force of steam as well as its properties under compression and expansion. These two books are the oldest preserved in their original Greek manuscripts that describe applications of pneumatic and hydraulic control systems; they comprise a systematic collection of machines dating before and during his lifetime. These machines moved with water, air or steam pressure, produced sounds and were intended to decorate public places and to amaze or serve the practical needs of the spectators.

Although in his books he describes a menagerie of mechanical devices, or ‘toys’ like singing birds, puppets, coin-operated machines, a fire engine, and a water organ, his most famous invention is the first steam-powered engine. This is of special significance to the science of automation because he presented automatic means necessary to control steam supply. This device consists of a sphere mounted on a boiler and supported by an axial shaft with two canted nozzles that produce a rotary motion as steam escapes (Greek word *ατμοστρόβιλος*); it constitutes a revolutionary entry into the field of today’s Automatic Control.

Among Heron’s inventions are the *automatic theaters*, capable of conducting an entire theatrical performance with automatic portals, changing automatically the stage props, and moving puppets that performed a myth. For these mechanical automata, Heron wrote *"A prop is placed on a pylon depicting a theatrical scene with portals that open and close automatically. Therefore, it allows several scenes of a play to be enacted in sequence and the* *puppets are able to move, act, and speak or produce sounds like live characters. In addition, fires are lit automatically and new puppets appear on the stage until the end of the story".*

Heron's book *The Belopoeica* (Engines of War) purports to be based on a work by Ktesibius. His three books on *Mechanics* (in Greek *Μηχανική*) survived in a somewhat altered Arabic translation. Mechanics is closely based on the work of Archimedes, presenting a wide range of engineering principles, including a theory of motion, a theory of balance, methods of lifting and transporting heavy objects with mechanical devices, and how to calculate the center of gravity for various simple shapes. Both books include Heron's solution to the problem of two mean proportionals i.e., two quantities, x and y that satisfy $a/x = x/y = y/b$, with a, b known. This may be used to solve the problem of constructing a cube with double the volume of a given one.

A catalogue of 60 mechanical devices is attributed to Heron, not mythical but historical and indeed functional, as proven by their modern reproductions. The function of his devices was based on scientific observations of nature. But unlike pure science that involves theoretical understanding of the environment but often lacks immediate implementation, his observations were applied science brought to use. Heron himself, however, explained that some of these devices were not meant to cover any practical use but they were created only for aesthetic pleasure. Heron's devices were explored and reproduced by Romans, Arabs and Byzantines and served as the link that united the Ancient Greek and the European technologies of the Renaissance that marks the beginning of the technological advances of Western Civilization. Figures 14 to 18 illustrate a sample of Heron's creations.

Mechanical achievements during those centuries were very significant. The world had one of the greatest geniuses, Archimedes, who devised remarkable weapons to protect his native Syracuse from the Roman invasion and applied his powerful mind to such basic mechanical devices as the screw, the pulley, and the lever. Alexandrian engineers, such as Ktesibius and Heron, invented a wealth of ingenious mechanical contrivances including pumps, wind and hydraulic organs, compressed-air engines, and screw-cutting machines. They also devised toys and automata that may be regarded as the first successful steam turbine.

Little practical use was found for these inventions, but the Alexandrian school marks an important transition from very simple mechanisms to the more complex devices that properly deserve to be considered “machines.” In a sense, the School of Alexandria provided a starting point for modern mechanical practice.

THE GRECO-ROMAN PERIOD AND TRANSITION TO BYZANTIUM

The Roman Empire became the dominant force in the greater Mediterranean region starting at 100 B.C.

The Romans were responsible, through the application and development of available machines, for an important technological transformation: *the widespread introduction of rotary motion*. This was exemplified in the use of the treadmill for powering cranes and other heavy lifting operations, the introduction of rotary water-raising devices for irrigation works (a scoop wheel powered by a treadmill), and the development of the waterwheel as a prime mover. Vitruvius, a Roman engineer gave an account of watermills, and by the end of the Roman era many were in operation.

The Roman Empire was split in two parts around 350 A.D. with Rome being the capital of the Western part and Byzantium, later called Constantinople (today's Istanbul), the capital of the Eastern Roman Empire. The Eastern Roman Empire also called Byzantine Empire became distinctly Greek as opposed to its Western Roman counterpart. The level of knowledge declined much more rapidly in the Roman West than in the Greek East. Inventions in Byzantium derive from Heron's era as shown in Figure 19 that depicts mechanical animals and birds of the Byzantine throne.

In the West, what survived was mostly contained in handbooks as collections of known facts. Notable examples are Pliny's Natural History (75 A.D.), Aulus Gellius Attic Nights (2nd century A.D.), Slinus' Collection of Remarkable Facts (3rd or 4th century A.D.).

In the East, by contrast, much more of the Greek Science was preserved. The tradition of scholarship kept knowledge alive from the ancient scientific texts-via scholarly discussions and the publication of commentaries in addition to original texts- even when the scholarly commentators themselves did not attempt to engage in original scientific research on their own account. Much of what is known today about Greek Science is due to this tradition.

By the year 600 A.D. preliminary efforts had already been made to turn part of the Greek corpus of scientific learning into Latin in the West and into Syrian in the East. Greek science was converted first into the Arabic tongue in the 9th and 10th centuries and then once again from Arabic and Greek into Latin in the 12th and 13th centuries. Although the Greek corpus received major additions and modifications at the hands of Arab and Latin authors, it was still essentially the Greek learning that made its way to the Latin West.

After the fall of Alexandria to the Arabs (642 A.D.), knowledge of medicine, biology, astronomy and mathematics spread through the Arab world and from about the middle of the 9th century, the Arabs produced scholars like the astronomer and geometer Thabit ben Qurra and the polymath Al Kindi [16], [22].

DISCUSSION AND CONCLUDING REMARKS

The central objective of this study was to provide justifications and evidence related to technology and autonomous mechanisms in the Mediterranean region and the Ancient Greek World. Indeed, it has been shown that the Mediterranean region was the hub from where the foundations of modern western Science and Technology were laid.

The foundations were very strong based not only on ingenious solutions to specific problems but also drawing from first principles that govern natural phenomena and from powerful mathematical concepts also developed in the same geographical area during the same time frame.

It should not be overlooked that this paper touched only upon mechanisms as mostly related to the discipline of (feedback) control, without even making an attempt to state accomplishments is other areas. However, there is documented evidence and proof of major inventions in areas like Architecture, Metallurgy, Marine Engineering and ship building, Hydraulics and hydraulic projects, construction engineering, music instruments, everyday life, mechanisms using series of bolts and spur gears, to name a few [23], [29].

Moving away from the discipline of control, it is worth mentioning just one additional example of a major breakthrough related to communications: the so called *hydraulic telegraph mechanism* of Aineias [29], a modern reproduction of which is shown in Figure 20. A description of this instrument is found in the (now lost) book by Aineias (in Greek *Αινείας ο Τακτικός*), *Πολιορκητικά*, 4th Century B.C. its name is due to E. Stamatis. The operation of the hydraulic telegraph mechanism required two units that should be synchronized to transmit a message / signal. Within a cylinder full of water there was a floater with a series of marked lines each corresponding to a message. There was a valve at the bottom of the cylinder that opened manually to 'empty' the cylinder up to a certain level corresponding to a specific marked line. Once a message was about to be transmitted, the 'transmitter' was lighting a torch, so that the 'receiver' was opening the valve at the receiving side. Once the water level reached the 'message' line/level to be transmitted, the torch was put off and the valve in the receiving side was closed. In this way, both floaters were at the same level and the transmitted message was received and read!

Therefore, as it has been demonstrated, Ancient Greek technology was rather complex but also very dominant and did not lack contributions to society. It is very misleading to claim that Greeks contributed only to Philosophy, Arts and Sciences excluding Technology. Perhaps this erroneous statement was partially because of Plato, his fight against Archytas the Tarantine as well as his passion for Science (*Επιστήμη*) and not 'technology' with the meaning of learning how to do or fix something (in Greek *τέχνη*) [29].

It is also true that most of such inventions originated in areas away from Athens, but it is the Athenian Philosophers who eventually recognized and supported the need for technology in parallel and in addition to Philosophy, Arts and Sciences.

As evidence and references continue to mount in quantity, it will not be before long that there is a complete picture of what was accomplished and invented during that time. Regardless, those were exciting times indeed!

ACKNOWLEDGEMENTS

We gratefully acknowledge the sources of the schematics and pictures used in this article. They include [5], [21], [23], and [24].

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(a) (b) (c)

Figure 1: a) Hephaestus, mechanic and creator of the golden slaves; b) Talus; c) The first mechanical man

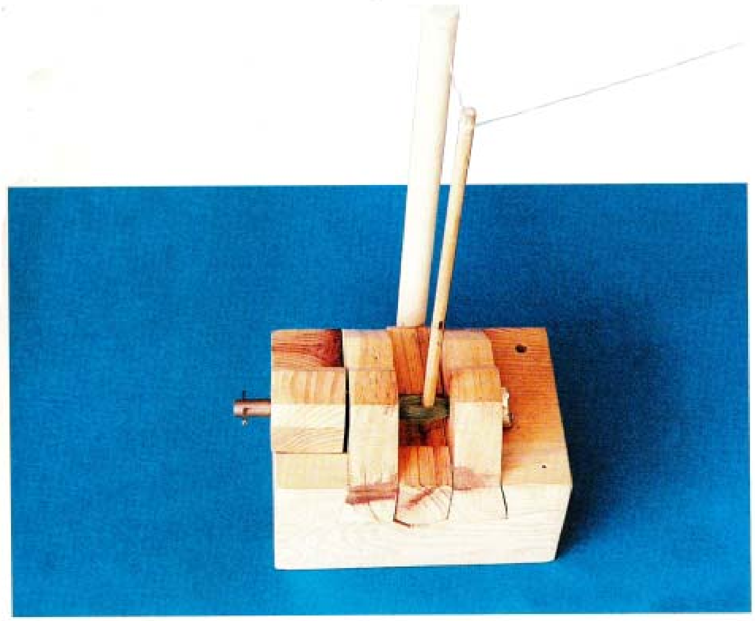


Figure 2: Model of one of the two parts of the hysplex

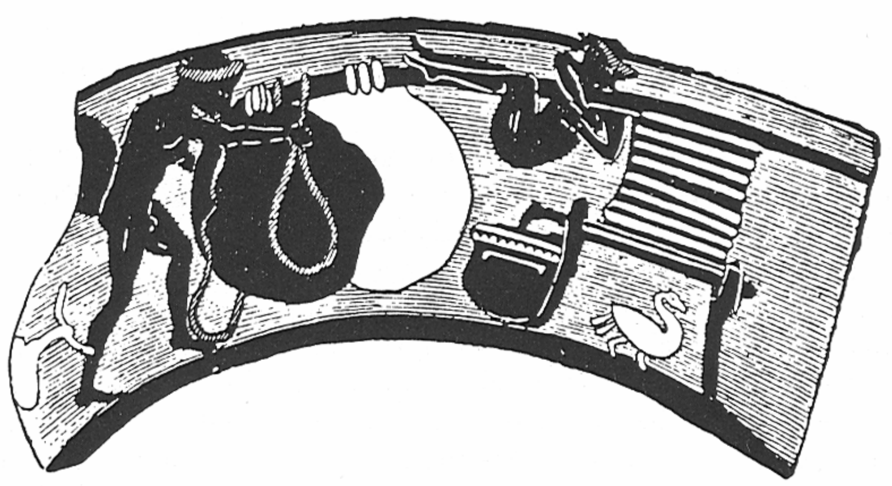
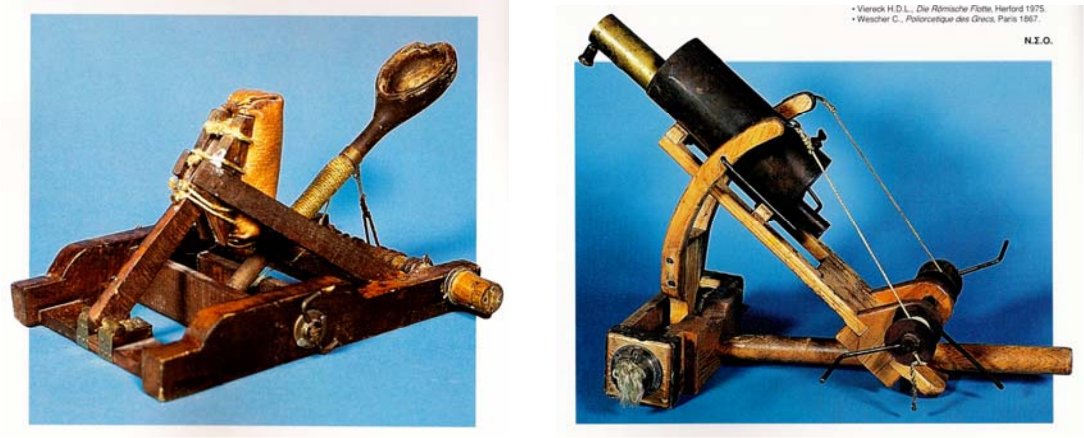


Figure 3: Oil press, 6th century B.C.

Figure 4: Archytas' pigeon reminding us of modern airplanes

Figure 5: Catapults used by Philip and Alexander the Great



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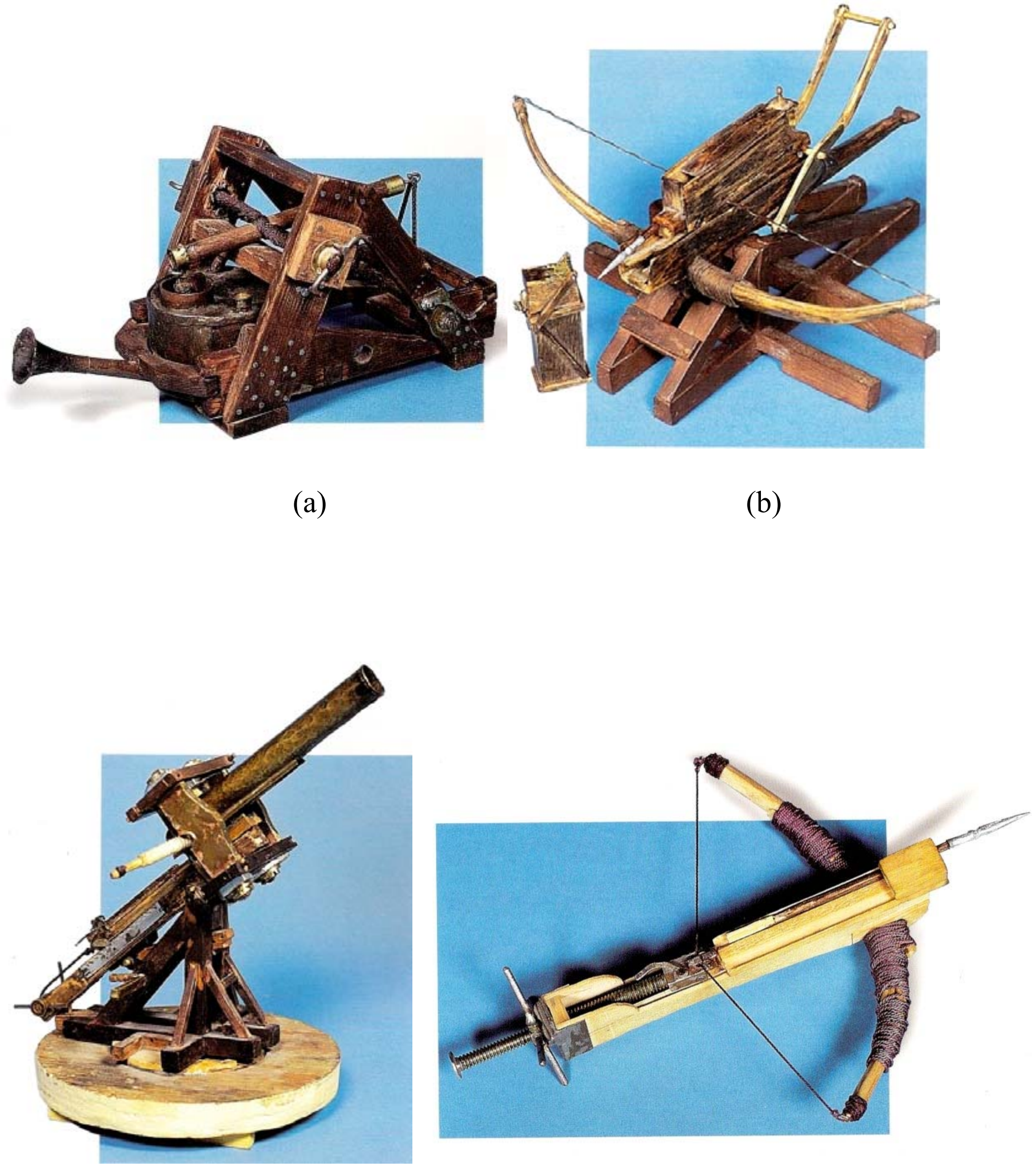
(a) (b)

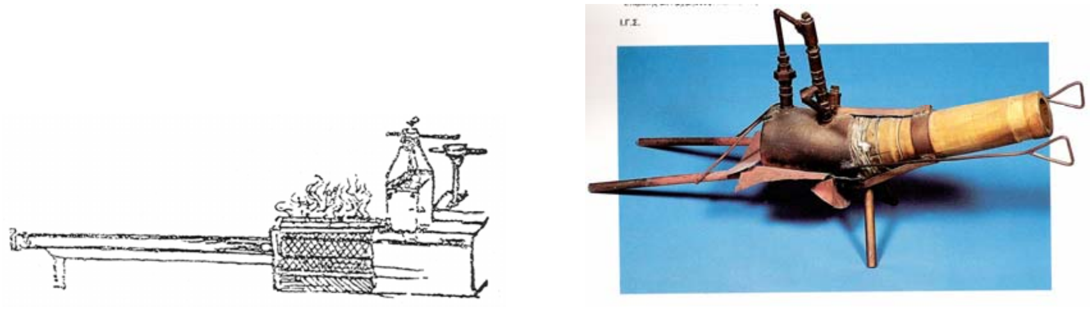
Figure 6: [From reference 29, design and model reproduced by N. Orfanoudakis]; a) catapult used to throw 'Greek fire' (in Greek *υγρόν πυρ*); b) theoretical design of a portable mechanism to throw 'Greek fire', composed of pipes coupled with a tormentum serving as a power source – its range was about 22 meters



(a) (b)

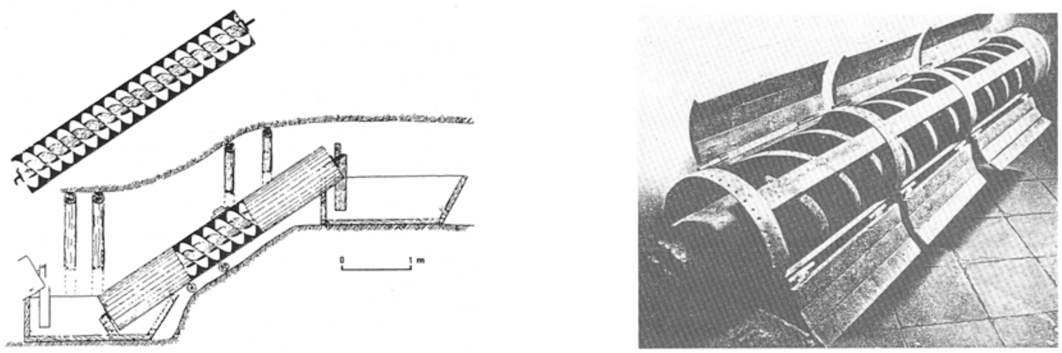
(c) (d)

Figure 7: [Reference 29, design by N. Orfanoudakis], a) mechanism composed of a catapult and Heron’s pump to throw Greek fire at a distance of about 30 meters; b) repetitive multi arrow catapult with range of about 100 meters; c) another catapult used to throw Greek fire; d) ballista throwing two – arrows simultaneously.



(a) (b)

Figure 8: a) Leonardo da Vinci’s drawing for the ‘architronito’, steam gun invented by Archimedes; b) Reproduction by J. G. Sakas in 1981 [Reference 29].



(a) (b)

Figure 9: a) Representation of the endless screw installation from Los Linares (Rep. Palmer 1926 -27); b) Reconstruction in Liverpool, 1930 - model was in use inside a mine in Sotiel Coronada

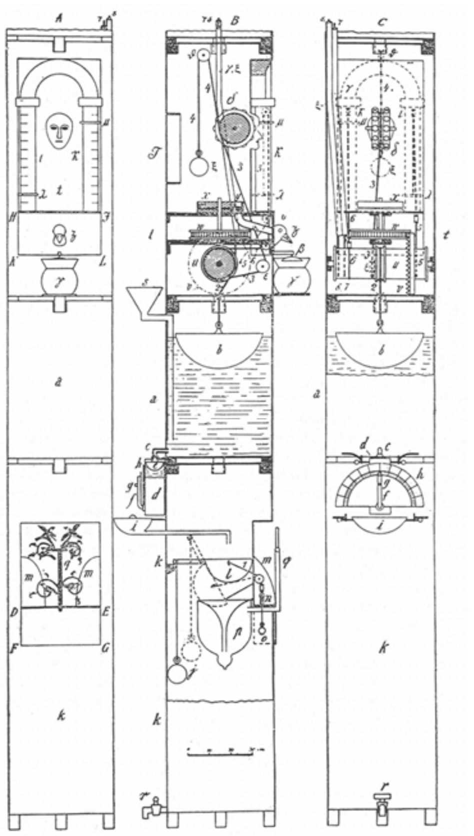


Figure 10: Façade (A), cross section (B) and back view (C) of the water clock of Archimedes

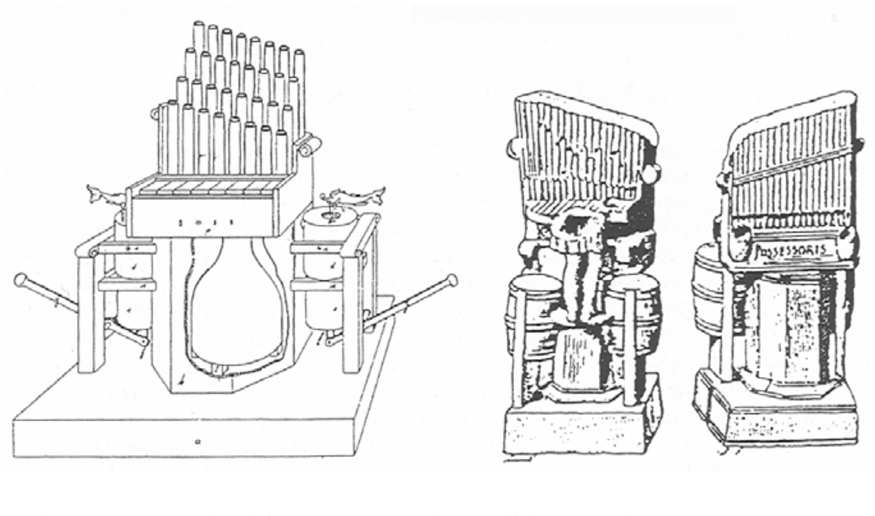


Figure 11: The water musical instrument of Ktesibius, and rare terracotta model

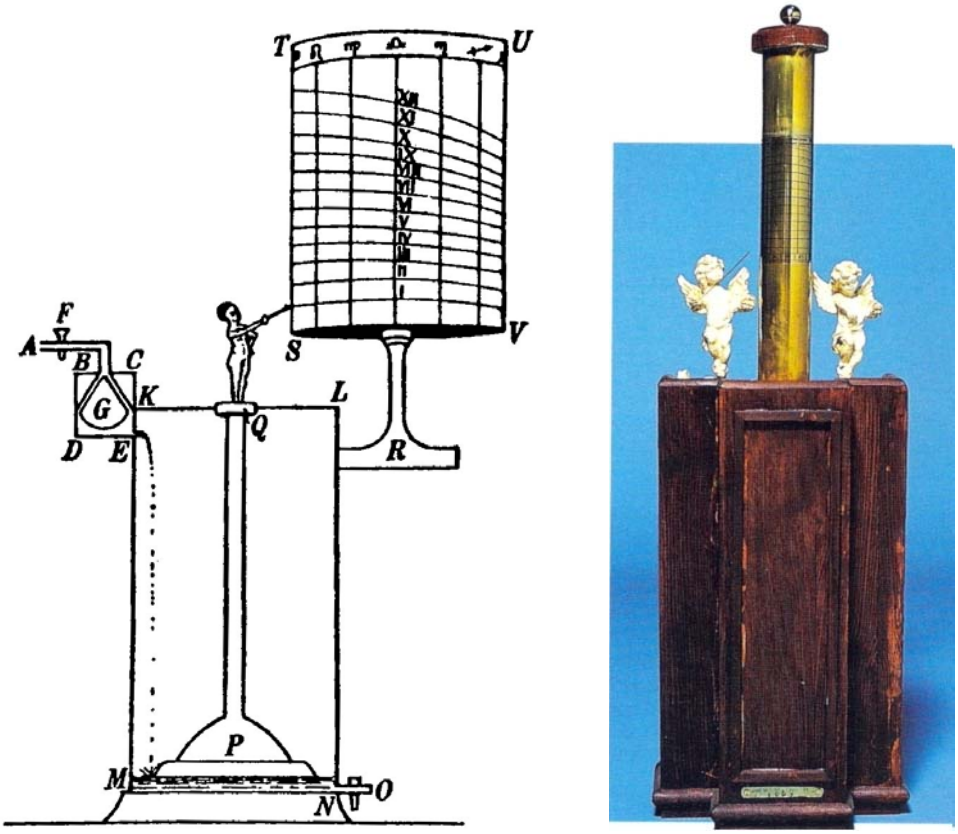


Figure 12: The water clock of Ktesibius and reproduction by D. Kriaris [Reference 29]

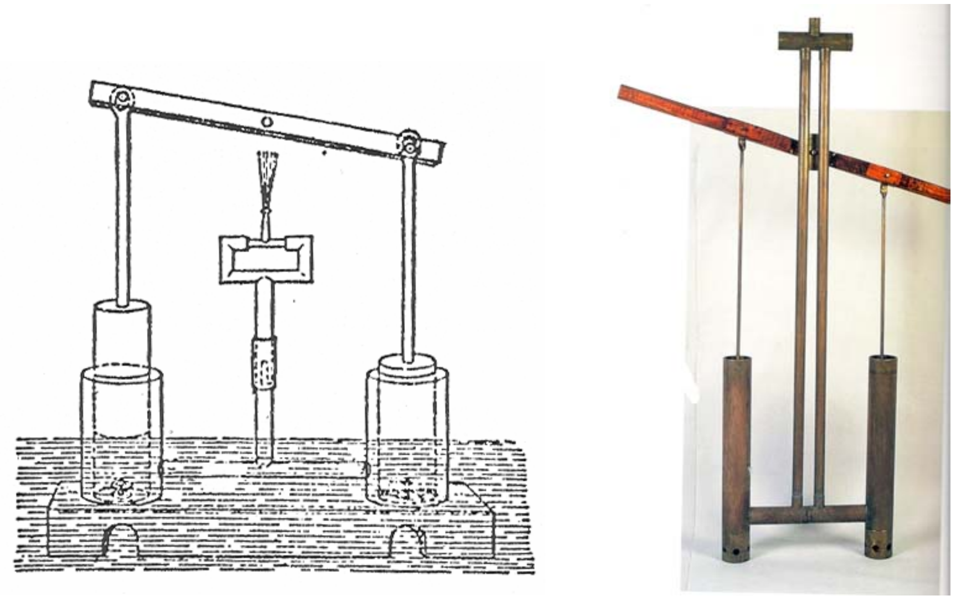


Figure 13: The force pump of Ktesibius and modern reproduction by D. Kriaris [Reference 29]

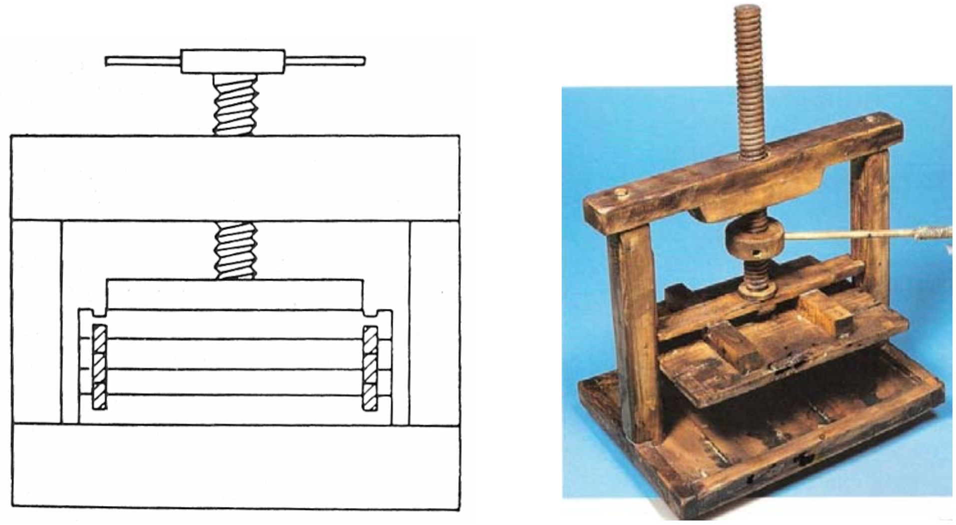


Figure 14: Representation of the oil press operated by an endless screw, and modern reproduction by D. Kriaris [Reference 29]

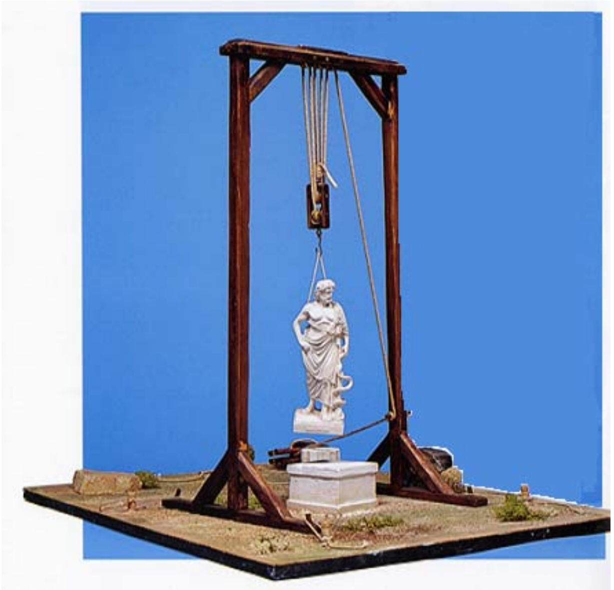


Figure 15: Hoisting machines: monokolos

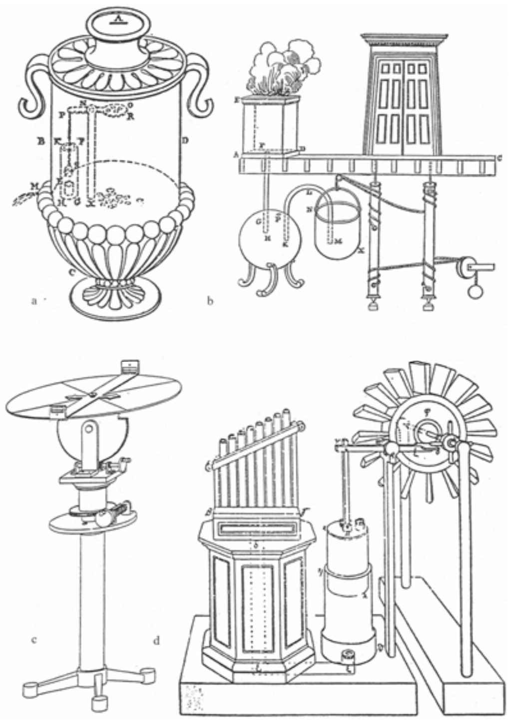


Figure 16: Four famed structures by Heron: the agiasterion, which supplied an amount of holy water by throwing a coin (a), the water mechanism for the automatic opening of the gate of a temple (b), the dioptra, mechanism useful in geodesics (c) the armonio, musical instrument operated by air pressure (d)

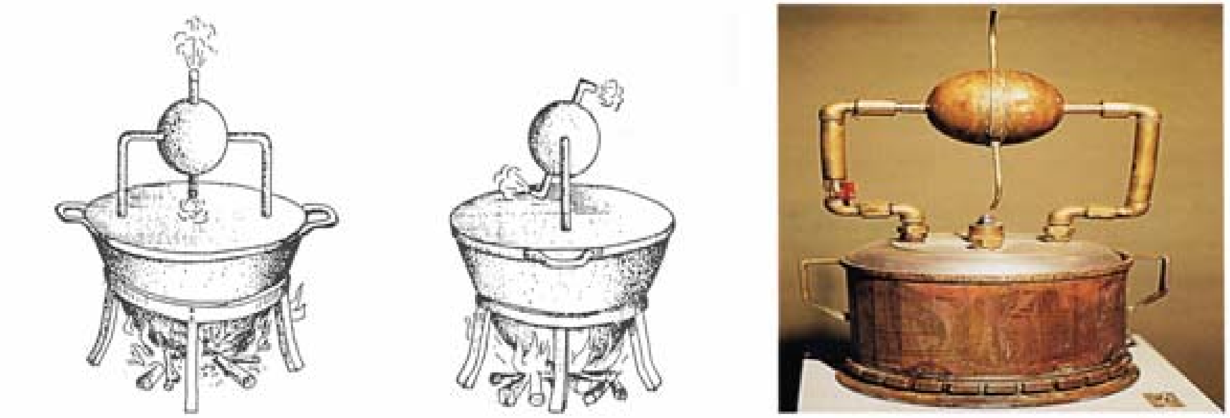
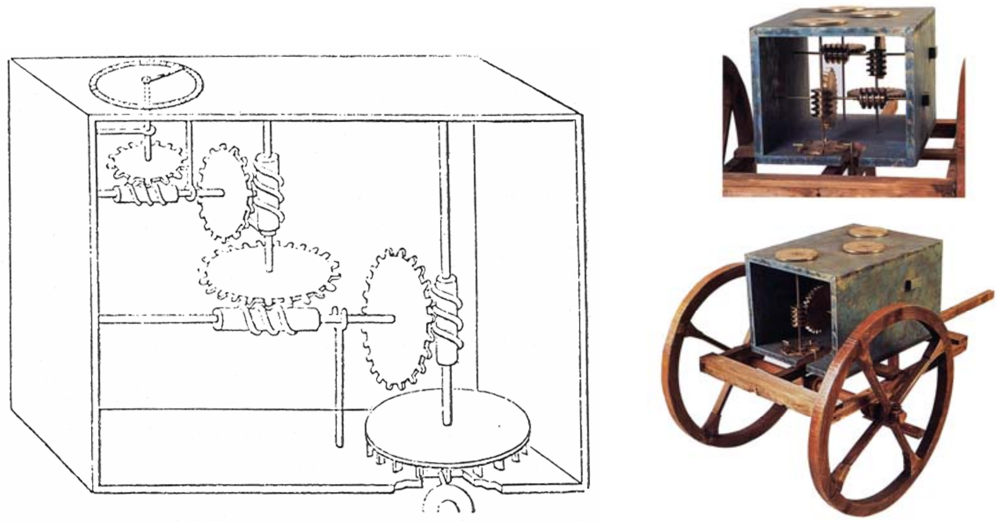


Figure 17: Two representations of the steam boiler: a) A schematic from Heron's writings and b) a physical reconstruction of the device.



(a) (b)

Figure 18: a) Representation of the odometer and b) reconstructions of the odometer by Woodcraft

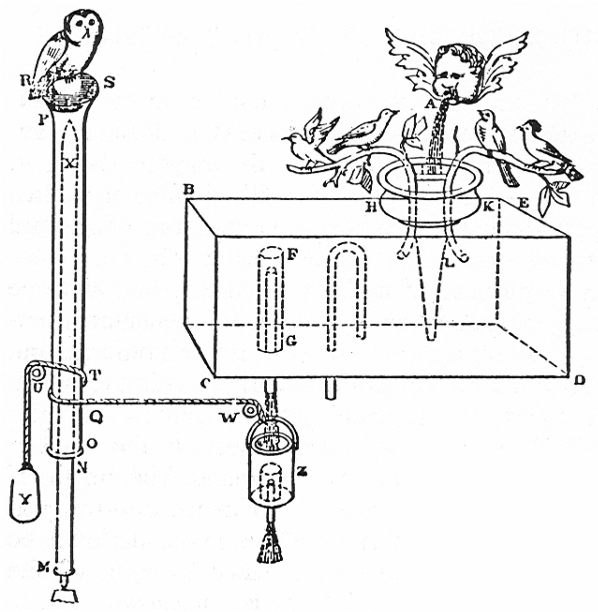


Figure 19: The mechanical animals and birds of the Byzantine throne are based on Heron's inventions

Figure 20: Hydraulic telegraph mechanism

SIDEBAR

Today's Athens still offers evidence of ancient accomplishments. The visitor will not miss, without doubt, a large (42 feet high by 26 feet in diameter) octagonal marble structure located in Plaka, under the shadow of the Parthenon on the Acropolis. It is called the *Tower of the Winds* and also *Horologium* (from the Greek word *Ωρολόγιο*), 'Timepiece'. It was built around 100–50 B.C. by Andronicus for measuring time. The building's eight sides, which face points of the compass, are decorated with a frieze of figures in relief representing the winds; below it, on the sides facing the sun, are the lines of a sundial. The Horologium was surmounted by a weathervane in the form of a bronze Triton and contained a water clock (clepsydra) to record the time when the sun was not shining. The Figure depicts an artist's rendition of the *Tower of the Winds.*

Artist's rendition of the Tower of the Winds

Measuring time was very important in antiquity as much as it is today. Measuring accurately long periods of time was particularly challenging. It was important however to calculate when the next crops should be planted, when the next Olympic Games will be held, and for how long a particular politician should stay in office! The earliest calendars were based on the lunar month and the later ones on the solar year. The main challenges come from the fact that neither the solar year nor the lunar month contains an integer number of days. Rather inconveniently, the lunar month is approximately 29.5306 days long, while the (tropical) solar year currently is 365.24219 days long. The study of lunar and solar calendars is a fascinating exercise, and has kept astronomers, mathematicians and engineers busy through the centuries.

Table 1: Major contributors and key events in Greek Science and Technology

Thales of Miletus	Circa 585 B.C.
Pythagoras of Samos	Circa 525 B.C.
Hippocrates of Cos	Circa 425 B.C.
Peloponnesian War	431-404 B.C.
Death of Socrates	399 B.C.
Plato of Athens	Circa 365 B.C.
Aristotle of Stagira	384-322 B.C.
Death of Philip	336 B.C.
Death of Alexander the Great	323 B.C.
Epicurus of Athens	341-270 B.C.
Euclid	Circa 300 B.C.
Archimedes of Syracuse	287-212 B.C.
Apollonius of Perga	Circa 210 B.C.
Ktesibius of Alexandria	Circa 270 B.C.
Philon of Byzantium	Circa 230 B.C.
Vitruvius	Circa 25 A.D.
Heron of Alexandria	Circa 60 A.D.
Galen of Pergamum	Circa 160 A.D.

Table 2: Distinct Periods in Mathematics over the Years

1st Period:	Hellenistic Period Mathematics
2nd Period:	Mathematics in the Arab World, 9th -15th century
3rd Period:	Mathematics in the West after 1400
4th Period:	Mathematics in the 20th century

Table 3: The Hellenistic Period of Mathematics

Period	**Representatives**
6th century B.C.	Thales (Geometry). Pythagoras (Arithmetic).
5th century B.C.	The Pythagoreans; Pythagoras' school in Croton (south Italy) that lasted about 150 years and had 218 Pythagoreans, not all mathematicians.
4th century B.C.	The Athenian school; Plato and Plato's Academy; Aristotle (Logic); Archytas (Pythagorean).
3rd century B.C.	The Golden Age of Mathematics; Euclid (*Elements*) and Apollonius (*Conics*) in Alexandria, and Archimedes. Eratosthenes, the first director of the Library of Alexandria, mathematician, astrologer and geographer, the first who measured earth's diameter.
2nd century B.C.	Ipparchos (Trigonometry) and Theodosius an astronomer
1st century B.C.	Heron of Alexandria.
2nd century A.D.	Claudius Ptolemy, Theon from Smyrna (Number Theory)
3rd century A.D.	Diofantos (Algebra).
4th century A.D.	Theon from Alexandria (Geometry) and his daughter Ypatia the only woman mathematician in the Ancient World.
5th century A.D.	The era of the 'critics' who criticize Math of the Hellenistic Period.