



Cesare Rossi  
Flavio Russo

# Ancient Engineers' Inventions

Precursors of the Present

*Second Edition*

# **History of Mechanism and Machine Science**

Volume 33

## **Series editor**

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Precursors of the Present

Second Edition



Springer

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# Preface to the Second Edition

According to the authors, writing about History of Mechanism and Machine Science not only consists of examining gears, pulleys and mechanical parts in general. It also means, to investigate devices that were born in a specific historical period, made to increase production or to alleviate fatigue. These purposes were achieved by using natural energies or optimizing muscular energy, certainly making use of gears and drivelines, but on a rational basis. With the advent of the Roman Empire much knowledge was acquired from the scientific and technical knowledge of India was acquired, and was followed up in Mesopotamia and Egypt during the epic of Alexander the Great when wide disclosure and use was found.

From them the Romans were able to tap into real opportunities, avoiding testing themselves on abstract problems; so that the Romans, although they were not good mathematicians, became among the best engineers of antiquity.

The term engineer in English clearly comes from engine while in Italian and Latin languages it derives from the Latin *ingenium* (= inventiveness, ability, talent), suggesting a speculative faculty. However, the root of the Latin word may be derived from the Sanskrit *gen* (= give birth, produce, woman). The engineer therefore was never only a scientist but a prolific ‘parent’ of new devices. Thus, despite the Roman’s learning limits, little inclination for science and propensity for the only practical use of scientific discoveries, the osmosis between the Hellenistic and Roman technology was widespread, stimulated by military and commercial needs.

With regard to the word “technique”, the ancient Greek word *techné* was used to indicate every professional skill, but catching up further back, we find the root *tak*, *tak-s* in Sanskrit, having the generic meaning of to make, manufacture, produce, build. The technology is therefore the discipline that studies all the professional abilities and artisan skills: ultimately, the sum of the competences behind all productions.

Mechanics, then, in turn derives from the ancient Greek *mèchané* that can be translated as tool to do; the oldest root is still in the Sanskrit *mahate* that means increase, make it big. In other words, an artificial entity capable of increasing the strength, production, growth. Concept that, in broad terms, is well suited to

machines and to our mechanics in general, while in antiquity included also the meaning of cunning and guile. Persons like Odysseus were able to devise *mechanai* (devices) to resolve critical situations; his horse had, in fact, already all the characteristics of the nascent mechanics, being the outcome of a rational assembly of more pieces.

The following pages attempt to provide an overview of the most remote engineering and related mechanics, thus suggesting how much of our disciplines are directly derived from those distant premises.

For this second edition, the book has been increased with many of the results of our research in the last 8 years.

In addition, some entirely new topics were added and paragraphs of especially engineering interest were also added. In some of the latter the work provided by men, animals, wind engines, water wheels and torsion engines for throwing machines are evaluated; models of machines such as siege towers and throwing machines are also proposed. For the throwing machines some examples of performance and projectile trajectories are also reported.

Finally, many unpublished figures by the authors have been added.

Naples, Italy  
Torre del Greco, Italy  
March 2016

Cesare Rossi  
Flavio Russo

# Preface to the First Edition

We live in an age in which one can easily think that our generation has invented and discovered almost everything; but the truth is quite the opposite. Progress cannot be considered as sudden unexpected spurts of individual brains; such a genius, the inventor of everything, has never existed in the history of humanity. What did exist was a limitless procession of experiments made by men who did not waver when faced with defeat but were inspired by the rare successes that have led to our modern comfortable reality. And that continue to do so with the same enthusiasm.

The study of the History of Engineering is valuable for many reasons, not the least of which is the fact that it can help us to understand the genius of the scientists, engineers and craftsmen who existed centuries and millenniums before us; who solved problems using the devices of their era, making machinery and equipment whose concept is of such a surprising modernity that we must rethink our image of the past.

But there is an even more important reason to study the History of Engineering: the authors believe that it is impossible to have a true technical culture if the ideas and the work of those who came before us are ignored. Culture, in whichever field, consists of understanding and not simply in know-how. For this reason it is essential to learn how a certain phenomenon was understood and how the application of that knowledge evolved through the centuries. For the same reason it is important that the scientists of our generation transmit an interest in and taste for the accomplishments of ancient engineers. Young engineers should be familiar with the knowledge of the past if they are to understand the present and perceive the future. Moreover, engineering must be considered that discipline that tries to give to man the possibility to outperform his body's limits.

This book describes the inventions and designs of ancient engineers that are the precursors of the present. The period ranges mainly from 300 BC to 1600 DC with some exceptions belonging to ages before and after these years.

As for the very ancient inventions, in the book there are descriptions of inventions (documented by archaeological finds mainly from Pompei, Hercolaneum and Stabia) of which often very little is known.

Some of the inventions are in the military field since (unfortunately) many inventions and technological innovations were conceived starting from military applications.

In this volume the authors have considered several important fields of engineering; in each of these fields, they highlight the first examples of the inventions (and workings) accomplished by scientists and engineers.

Although many of these inventions are extremely old, the ones presented in this book are the precursors of the knowledge and inventions of our era. In addition, many of them often reveal a surprising modernity in their conception, in their scientific and technical design and even in their shape and function.

The book is divided into five parts.

The first four parts pertain to definite fields and present inventions conceived up to the late Roman Empire. Inventions that are representative of the engineering genius of the ancients and that may be considered as milestones, each in their respective field.

The fifth part also refers to separate fields of engineering innovations (such as textiles and automation), but concentrates on more recent centuries.

The last chapter (16th) deals with building construction techniques and not devices. These building techniques, in the authors' opinion, can also represent inventions.

For each of the inventions presented, even the ancient ones of many centuries past, the authors provide three elements of research and reference:

Written documents (the classics)

Iconic references (coins, bas-reliefs, etc.)

Archaeological findings.

The only exception is when an exhaustive and detailed treatise by the inventor himself is available (e.g. Vitruvius).

Many devices and building constructions described in the book pertain to the age of the Roman Empire; it could be presumed that this is so because the authors are Italians, but this is not the reason. Undoubtedly, the Roman Empire represents something of very great (and probably not yet completely understood) in many fields of science, technology and law; it started within the Italian peninsula but it does not belong to the Italians alone. First of all, most of the inventions and technology of the Roman Empire were not invented by Latin inventors; in fact, one of the merits of the Romans consisted of recognizing, appreciating and using the intellectual abilities of other peoples. In addition, the quality of the organization and the "sense of the State" has been retained more by the German and Anglo-Saxon peoples than from the Latin ones; hence the heritage of the Roman Empire, today, belongs to the ones that study and appreciate those ages and those men. Moreover, living in Italy, the authors have had more chance to see and investigate roman relics. However, certainly a large number of the inventions that are precursors of the present were developed at that age.

Based on a wide reading of many references, the authors concluded that a first industrial revolution started during the Roman Empire. Many aspects suggest this hypothesis: the Romans made a large use of unification and standardization in the

productions of goods. At certain periods, the Roman Armed Forces had up to 500000 men; this means that it was necessary to equip such a number of men with everything they needed to live, wear clothes and fight. An army needs, necessarily, unified and interchangeable equipment also because a military unit can be sent anywhere; this means that something like an industrial and unified production had been certainly necessary for the army's needs.

The standardization, that probably was fashioned specifically for military use, was certainly extended to civil applications: many of the components used in various systems like hydraulic valves and pipes (see Chapter 8), cart wheels and gauge (see Chapter 10) and so on had standardized dimensions and were interchangeable all over the Empire. This was clearly written by Vitruvius, the most famous Roman engineer.

Finally, the authors did not write this book for engineers only; hence they describe all the devices without assuming wide technical knowledge. The authors' main aim is to try to communicate their enthusiasm for the inventions and inventors of the past and, possibly, to make their contribution to the fascinating study of the History of Engineering.

Napoli  
November 2008

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# Chapter 1

## Representing and Measuring the Environment

**Abstract** This chapter represents a sort of introduction to the ancient technology. All started with a design, so the early techniques used to represent what had to be built. Examples of planimetries and the relative building, starting from the IV Millennium B.C. are presented. Finally tables containing almost all the ancient Greek and Roman units are reported.

### A Premise: It All Started with a Drawing

The portrayal of any structure in remote antiquity was not very different from the more generic representations of the surrounding animate or inanimate objects. In general, they were first limited to drawing a simple outline, something that could coincide with a backlit contour, a sort of shadow projected onto a normal or vertical surface. Later they began to look for greater similarity, endowing the Figure with a quasi three-dimensional form by using a *sfumato* coloring to simulate curvatures and size.

But the depiction remained that of an outline, a profile, as this was the easiest to draw and identify. Thus the origin of technical drawings cannot be considered as part of the evolution of design or drawing, understood as the portrayal of reality, tangible or imaginary as it may be, even though both make use of a graphic sign on a surface of a different color. The technical drawing can, in a certain sense, be equated to the writing of chemical formulas; written in a conventional and symbolic manner, they are very different from actual writing even though they make use of the same letters of the alphabet, thus their development in no way coincides with the invention of writing.

Like the chemical formula that can describe or anticipate a resulting reaction, a technical drawing can also describe an existing structure, in which case it is called a ‘survey’ drawing, or it can define the characteristics of one to be constructed, in which case it is called a ‘plan’. A procedure that, following the same criteria, gradually evolved into the planning and design of machines. In both cases the basis is the proportional ratio between the drawing and the reality it represents, one that required the probable existence of a geometric support, without doubt a rudimentary one, to designate the outline of existing buildings or to transfer to the ground those that were designed.

According to current graphic convention any object can be represented using three projections: plan, side elevation and front elevation. Three drawings perpendicular to the three ideal axes of space, which, because of their constant proportion with reality, the scale, become a universal language understood everywhere without the need for interpreters or vocabularies. Like writing, that system of drawing initiated a technological evolution, the foundation and prerequisite of modern civilization, providing a way to record and circulate ideas that was even more effective than writing and to allow for their universal understanding. In effect, its adoption replaced representation by similarity of outline with representation in scale.

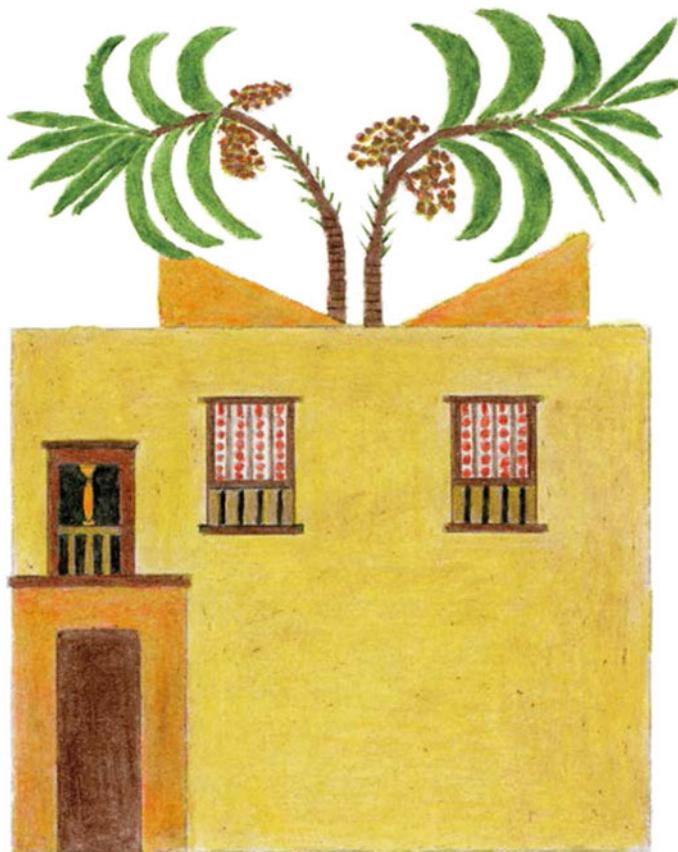
The precondition for the establishment of the scale was the existence of a pair of orthogonal straight lines upon which to base measurements, an orthogonal intersection attributed to Descartes but that is actually much older. The plane between the vertical and the horizontal will become, using the most varied of materials—stone, clay, wood, papyrus—the space upon which it will be possible to trace a design.

The real difference in the survey or drawing of antiquity compared to modern practice lies in the lack of any correlation between the Plan and the Elevation, as the two appeared at very different times, thus it was only in sporadic and relatively recent periods that we could associate the floor plan to the elevation.

From a chronological aspect the first projection to be used was Elevation, followed at a significant distance by the Plan, called Imprint by Vitruvius, and finally by the Vertical Section.

## 1.1 Elevations, Plan and Sections

The drawing of the side elevation, as mentioned, appeared in the oldest depictions on stone, wood and later ceramics, more than 20,000 years ago. Adherence to the truth that was first reserved only to animals, in the dawn of time, was extended to representation of buildings, becoming progressively more coherent, especially after the emergence of ornamental decoration. On the papyri of the III millennium B.C. there were perspectives of houses that were perfectly in proportion and delineated in every detail. The singular graphic designs of profiles adopted by Egyptians, transforming every portrayal of a residence into a front view, induces us to place those that were certainly intentional, that is in rigid proportion, in the Hellenic Era. It is more difficult on the other hand to determine the chronology of the plan and especially its origin (Fig. 1.1).



**Fig. 1.1** Front elevation of an Egyptian home of the II millennium B.C.; illustration by authors of the drawing from Nakhte's Book of the Dead, end of the XVII dynasty, 1550–1070 B.C.

The plan, or more accurately, the planimetry, is a horizontal section of a building, what one would see from a higher position, infinitely far, if an imaginary plane parallel to the ground cut it at a given height. In effect no one perceives the plan, even of a house in which one lives, and if he did see it, it would mean that the house had been razed to the ground by a catastrophic event leaving only a hand's width of the walls above the ground. And perhaps it was because of some traumatic event, especially related to war, that the technique of the plan developed. Among the many methods of destruction resulting from war one of the most radical was the rather frequent method of razing all buildings to the ground leaving only a few centimeters of wall standing, thus coinciding with its ground plan. The representation over the centuries of similar images indicates that it was those walls, in reduced proportions, that were the most reliable outline of a building and the most appropriate drawing to allow for its construction (Fig. 1.2).

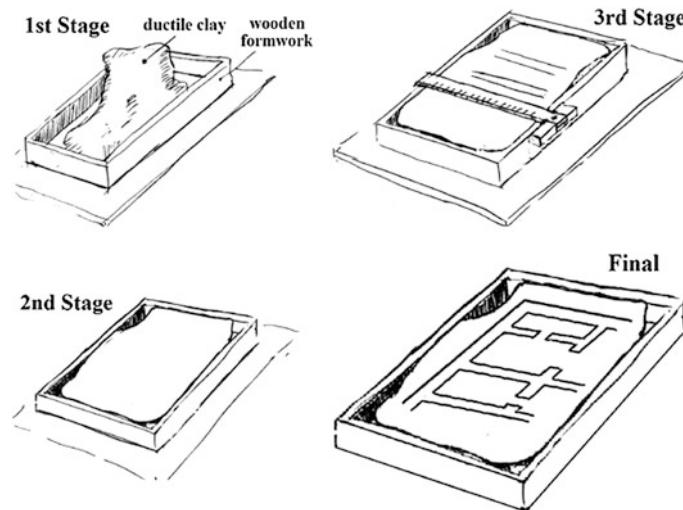


**Fig. 1.2** Aerial view of the Prysg Field Barracks at Caerleon (Wales); remains of the barracks for the Legio II Augusta—kind permission © Crown copyright (2015) Cadw

## 1.2 Protohistoric Drafting Machine for the Clay Tablets Engraving

To draw in scale on a stone plate or a wood plank required accuracy and an unhurried determination, perhaps starting with an initial tracing of the outline that the engraving device would then etch, a procedure that allowed for an intermediate verification. The process was completely different for incisions on plastic clay, unquestionably easy to engrave once it was levelled, but requiring extreme precision from the very beginning of the work as it would be impossible to have a simply graphic preparation, similar to the previous one. In observing the Sumerian tablets containing blueprints very similar to modern ones as early as the III millennium B.C., the great precision of the lines, perfectly straight, accurately parallel and perpendicular to each other is obvious, almost as if they had been traced by an ancient drafting machine.

Such accuracy is in contrast with the rapidity required by clay and even more so by the use of a simple straightedge, certainly effective to etch straight lines but useless in making them parallel or perpendicular to each other. It is obvious at this point that they must have used some drawing instrument that, independent of the



**Fig. 1.3** Possible method of drawing on clay. Sketch by authors

border of the tablet, always uncertain and curvilinear, could guide the incisions in a parallel and orthogonal direction to each other, requiring only that the surface be precisely flat.

The least improbable solution leads us to envision a small frame, consisting of a rectangular box, with no bottom or lid, similar to the forms used to make bricks, in which was placed the plastic clay, levelling it by sliding a stick or rolling pin over the two side axes of equal height (Fig. 1.3).

Once they had a flat and smooth horizontal surface, they could use a hinged square, passing it over the larger and smaller sides, tracing lines parallel or perpendicular to each other. These could be cancelled by passing a spatula over any incorrect lines. The gradation on the straightedge of the square would allow them to make any necessary evaluations of length and width.

The drawing made by the Sumerians in this manner is easily comprehensible and can be interpreted and used by any modern designer to build the structure drawn, allowing for some graphic conventions regarding elevation, even after 5000 years. There remains only one reservation: any survey or project design was difficult to transport and could easily break either in the archives or in the construction site, an irreparable damage as there would only be one drawing. However, the etchings could be made in several copies by a sort of ‘frottage’: a light sheet of papyrus or sheep skin was placed on the tablet, then by rubbing an ‘inked’ swab over the tablet, using coal, the original acted much like our transparencies of the previous century.

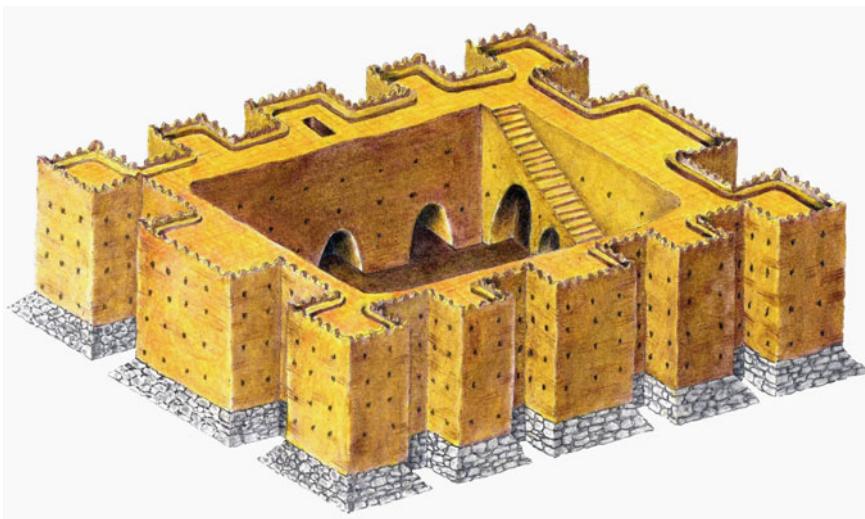
### 1.3 Examples of Planimetries from the IV Millennium B.C. to the 1st Century A.D.

#### 1.3.1 *Plan of Egyptian Fortress, IV Millennium B.C.*

Egyptian civilization developed along a slim strip of land crossed by the Nile, from the territory of the Suda up to the Mediterranean, fertilized by the seasonal floods of the river. The union of the two kingdoms of Upper and Lower Egypt into a single nation took place around the end of the IV millennium B.C. and was achieved, according to tradition, under Pharaoh Narmer. He is portrayed intent on defeating the Nubians on the “Narmer Palette”, which also contains the oldest drawn plan of which we are aware: a turreted fortress.

The palette, dating to 3200 B.C. was found around the end of the 1800 s in the course of excavations conducted in ancient Nekhen. It is a single plate of siltstone in the shape of a shield, measuring 64 cm by 42, 2.5 cm thick. Both sides of the palette are etched with inscriptions. Of great interest is the scene depicting Narmer, towering over two enemies he has killed, one of whom is surmounted by the plan of a fortress. In Fig. 1.4 a pictorial reconstruction by Authors of the fortress is shown.

It is interesting to determine when they began to build houses with rectangular spaces, the only ones that could be surveyed and traced graphically, with moderate precision, and the only ones that could conform to a drawing in orthogonal lines. One of the first urban aggregates with houses having a rectangular plan is in the Jericho of 7000 B.C.



**Fig. 1.4** Pictorial reconstruction by authors of the fortress the plan of which is engraved on the “Narmer Palette”

The rectangular layout however cannot be considered as coinciding with the advent of technical drawing but only as its precursor: indeed the ruins certify its systematic use starting from the end of the IV millennium B.C. Thus the revolutionary debut of technical drawing should be placed between these two dates. But what exactly is a technical drawing?

Chronologically the technical drawing was the only method used to survey or design architectural works, thus it originated and developed in order to establish the characteristics and connotations of a building in an objective manner, encompassing its formal and structural features.

An architectural survey design is one that is inherent to an existing original of which it must maintain the proportions and thus be, even if only implicitly, in scale: by the word scale we intend the relationship that links the real dimensions to the graphic ones.

A project design on the other hand, which graphically does not differ from a survey design, is a drawing that must provide all the information necessary to build what it represents.

To enclose within an urban circle the residences, temples, royal palace, food storage sites, troop lodgings, shops and markets, required a more prudent exploitation of the interior surface and a less spontaneous construction of roads and buildings, a method implemented in the Sumerian area between the IV and III millennium, leading to the first proto-cities of antiquity, such as Uruk, Ur and Nippur. This is a very significant period because the excavation of the ruins indicates the presence of the aforementioned road network and buildings that already had systematic orthogonal walls and parallel extrados and intrados produced by the determined and constant thickness present along the entire floor. Not incidentally starting from the 3rd century B.C. the plans for those buildings will be traced on clay tablets, in exact scale and duly sized. Rarer, though of identical conception, and perhaps a product of those tablets, were the blueprints etched on stone tablets, most likely commemorative rather than merely projectual.

### ***1.3.2 Plan View, Front View and Sections: Inventions Over the Time***

It is interesting to determine when they began to build houses with rectangular spaces, the only ones that could be surveyed and traced graphically, with moderate precision, and the only ones that could conform to a drawing in orthogonal lines. One of the first urban aggregates with houses having a rectangular plan is in the Jericho of 7000 B.C. The Figure below is of the ruins of Jericho.

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### ***1.3.3 Planimetries on Sumerian Tablets of the III Millennium B.C.***

Girsu, an ancient Sumerian city located about 20 km north-west of Lagash, corresponds to the current Telloh, in the province of Dhi Qar, Iraq. Around the end of the II millennium B.C., about 2140 B.C., during the reign of Gudea, Girsu was probably the principal religious center and perhaps even the capital of Lagash, which during the time of the original city state had expanded to include an area of approximately 1600 km<sup>2</sup> and well over 17 large cities, in addition to a considerable number of villages. In the course of archeological excavations numerous clay tablets came to light, enriching the more than 30,000 similar ones of the same era found in Lagash. Among these was a tablet measuring approximately 11 × 9 × 2 cm, on which was carved, with great accuracy and precision, clear and complete even regarding elevations, the plan for a six room residence, all noticeably long and narrow, as can be seen below.

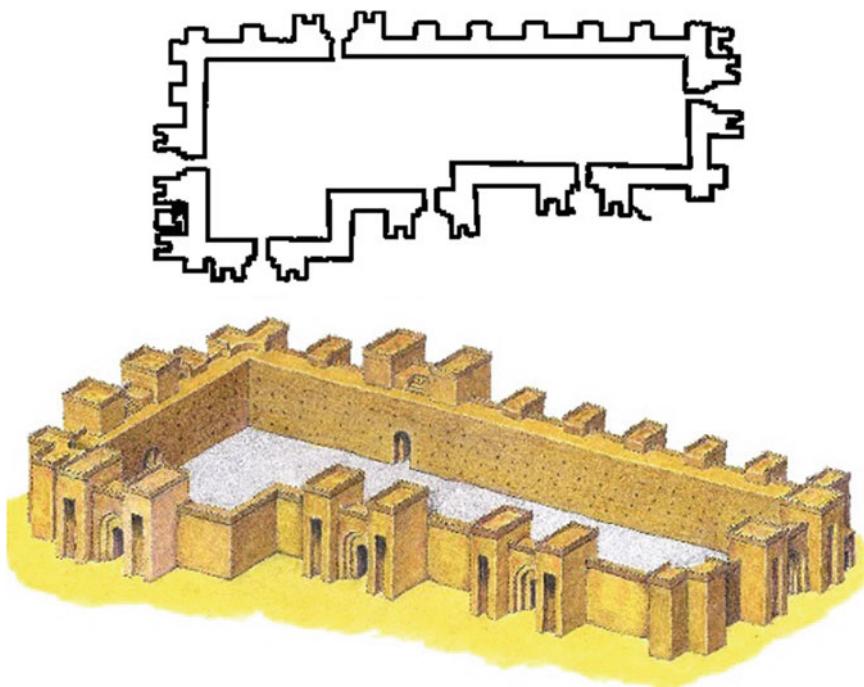


**Fig. 1.5** Terracotta model and two graphic reconstructions by the authors

Several factors indicate that this was the ground floor of a small two floor house, similar in architectural dimensions to the many funerary models found. In Fig. 1.5 the terracotta model and two graphic reconstructions by the authors are shown.

#### **1.3.4 *Plan of a Sumerian Retaining Wall, on Stone, 2150 B.C. Time***

Gudea, whom we have already mentioned, was one of the rulers of Lagash, reigning from 2144 to 2124 B.C. He appears to have been responsible for the construction of numerous temples and channels, as well the founding of several cities. 27 statues of this ruler have come down to us, all basically similar, the oldest made of limestone while later ones were made of diorite.



**Fig. 1.6** Detail of the plan of the Sumerian retaining wall engraved on the Gudea statue and authors' pictorial reconstruction

One of the most important of these portrays him seated regally while holding on his knees a tablet upon which is engraved a very clear and precise plan for a large complex. This detail is represented in Fig. 1.6 along with the pictorial reconstruction by the authors.

This was most likely the enclosure for a temple, a theory supported by the great number of doors, excessive for a fortification. If so it could be the temple of Ningirsu, in Girsu, Lagash, as Ningirsu was the highest divinity adored by Gudea, to whom he dedicated the reconstruction and construction of numerous temples. According to the inscription, the details of the planimetry came to him in a sort of oneiric vision, were soon transformed into executive design and rapidly built as soon as an appropriate site outside of the city was identified.

### 1.3.5 *Plan for the Mausoleum of a Rural Roman Home, I c. A.D.*

A singular Roman marble headstone, dating to the 1st century A.D. contains engravings of three different plans, each with its own graphic scale. Together they

form the blueprint for a small funerary property composed of a burial monument, including an underground crypt, and an annexed rural building, a sort of farmhouse used for the maintenance of its custodians.

A legend engraved on four lines of the stone, two above and two below the plans, tells us that the buildings, mausoleum and farmhouse, are the legacy of Claudia Peloris, the freedwoman of Octavia and Claudius Eutuchus, probably the procurator for Claudius and Nero, thus providing a precise chronological date, between 54 and 61 A.D. The legend reads:

CLAVDIA OCTAVIAE DIVI CLAVDI F(iliae) LIB(erta) PELORIS  
 ET TI(berius) CLAVDIVS AVG(usti) LIB(ertus) EVTYCHUS PROC(urator)  
 AVGVSTOR(um)  
 SORORIBVS ET LIB(ertis) LIBERTABVSQ(ue) POSTERISQ(ue) EORVM  
 FORMAS AEDIFICI CVSTODIAE ET MONVMENTI RELIQVERRVN[T].

In spite of the perfect legibility of the epigraphs and planimetries, we have no historical knowledge of the tablet nor its exact origin, but it is clear from the etching on the left and top center that it represents the ground floor and the upper floor of the farmhouse, with the orchard in front, respectively in scale 1/140 and 1/230; the third depiction, to the right, is the mausoleum in scale 1/84.

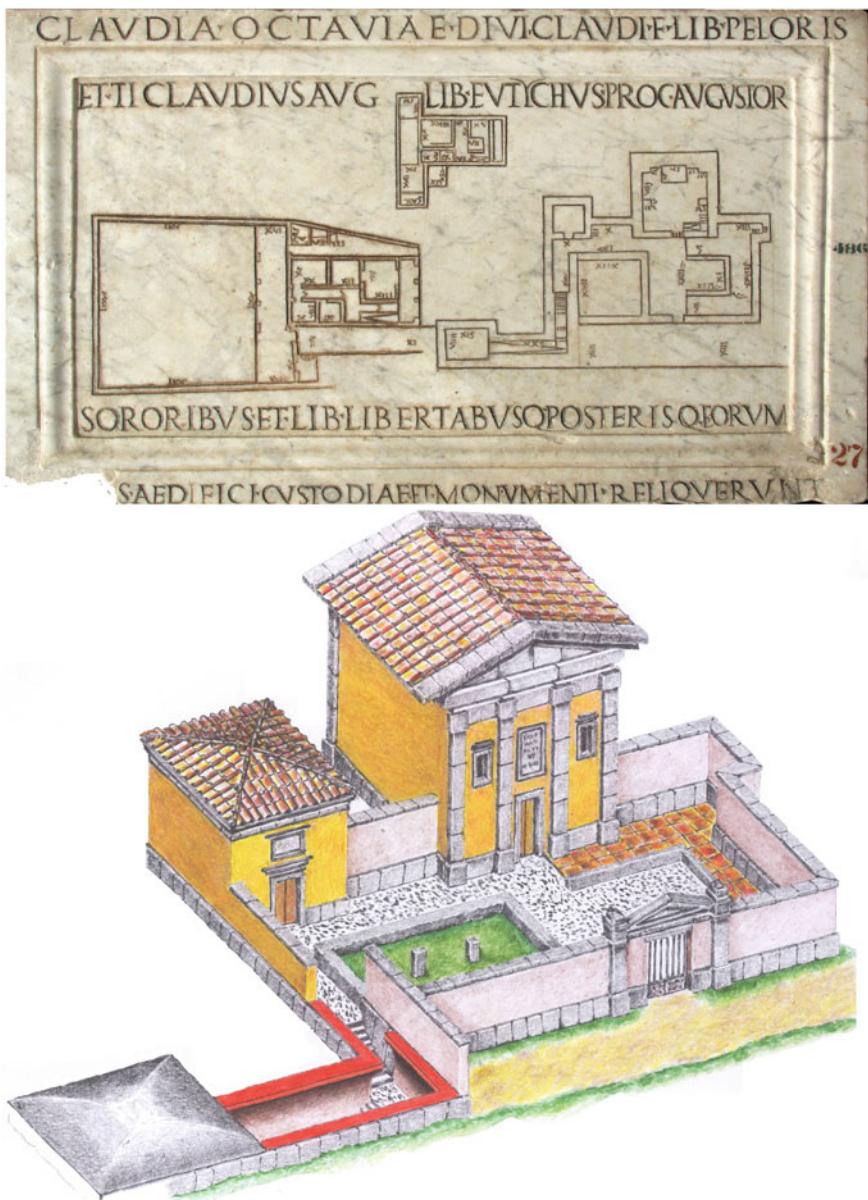
From a technical aspect, apart from the adoption of a triple scale that highlights how the decrease in height of the construction also decreases the related scale, it is an absolute novelty to find the plans for two separate floors of the same building in a single drawing.

In Fig. 1.7 the tablet and a pictorial reconstruction by the authors are shown.

### ***1.3.6 Anthropometric and Mathematical Units of Measurement***

It has by now been confirmed that man began to count even before numbers were invented, which in turn conceptually led to writing. All they needed to do was to use fingers and make as many notches on a cane as required. On the other hand it was more complex to determine length and make it standard and mandatory inside the same city state. The oldest unit of measurement found so far dates to 2600 B.C.: this is the sacred sample of a cubit rod, equal to approximately 52 cm, considered to be the average length between the elbow and the tip of the index finger.

More recent, but still relative to the certified example, is the Sumerian unit of measurement that assigned a slightly different value to the cubit. Considering the progress of the ancient world it is easy to surmise that the appearance of units of measurement coincided with the advent of the city, though a bit more time was required for their standardization. It should also be noted that since other anthropometric linear units of measurement were not exact multiples of themselves,—thumb, finger, palm, span, cubit, arm, foot and step—the tracing of a design in



**Fig. 1.7** Plan for the Mausoleum of a Rural Roman home and authors' pictorial reconstruction

proportion required the use of straightedges a cubit long, with palm and finger scales etched upon them. Thus, in order to measure an object, contrary to modern methods that use decimal metric system, the amount was reached by seeing how many cubits it included, how many feet were contained in the residual fraction, and how many fingers in the remaining part.

The sum of all three forming the total, or measurement—an extremely laborious process. Which, in light of the great number of measurements required for the commerce of the era, suggests the existence of special straightedges able to graphically reduce a known size to a smaller or larger one, as occurs for example with a pantograph. A normal scissors would provide similar results as the distance between the two points were proportional to the distance between the eyelets. Babylonian mathematics, based (as was all Babylonian culture) on the Sumerian tradition, adopted operational criteria that we still use today, such as:

- Positional notion, introduced in Europe only in the Middle Ages, extended also to fractional values allowing for infinite precision calculations
- Base-60 numbering, currently used to measure time and degrees
- Pythagorean theorem
- Use of algorithms, of which the most famous takes its name from Newton to calculate the square root
- Use of logarithmic tables.

The first part of this book is divided into four chapters and mainly pertains to the measurements. In the first three chapters measures and measurement devices are presented, in the fourth are reported the first computing devices that were developed before the invention of the computing machines.

The first step towards science was the measuring of the environment and, in this field, the first step was the measure unit establishment; this demand was certainly due to trades but the measure units are obviously indispensable for any scientist, inventor and engineer to his studies and to describe his designs.

Probably, as far as we know, the first measure unit systems were established in the East in Mesopotamia, Persia and India, then in Egypt and Greece and later in Rome.

## 1.4 Ancient Units

Most of the oldest inventions reported in this book were made by Greek-Roman inventors who, in their original writings, describe their device using Greek units or in Roman units; furthermore, at that time, these last measure units were used all over the Roman Empire. For this reason the authors think it is useful to report these units in the tables that follow.

**Table 1.1** Greek length units

Greek name	Latin alphabet	English name	Value (dactyloī)	S.I. Equivalence
δάκτυλος	dàctylos	Finger	1	≈19.3 mm
κόνδυλος	còndylos	Middle joint of finger	2	
παλαιστή, δῶρον	Palaiste or doron	Palm	4	
διχάς, ἡμιπόδιον	Dichas or hemipodium	Half foot	8	
λιχάς	lichàs	Span of thumb	10	
ὁρθόδωρον	orthòdoron		11	
σπιθαμή	spithamè	Span of all fingers	12	
ποῦς	pous	Foot	16	≈308.3 mm Attic ≈ 296 mm
πυγμή	pygmè	Elbow to base of fingers	18	
πυγών	pygòn		20	
πῆχυς	pèchys	Cubit	24	
πῆχυς βασιλήιος	pèchys basilèios	Royal cubit	27	

### 1.4.1 Ancient Greek Units

#### Length Units

In Tables 1.1 and 1.2 the ancient Greek length units are reported. For small lengths the unit was the dactylos (pl. dactyloī) that means finger; for longer lengths the unit was the pous (pl. podes) that means foot.

#### Area Units

The main unit of surface was the square plethron; traditionally it was the amount of land a yoke of oxen could plough in one day and, more specifically, it was any area equal to the area of a square whose sides are 100 podes (1 plethron) in length; submultiples were the aroura (1/4 of plethron) and the sixth (1/6 of plethron).

#### Volume Units

In Tables 1.3 and 1.4 the ancient Greek volume units are reported, for liquid and solid respectively.

#### Weight/Mass Units

In Table 1.5 the ancient Greek weight/mass units are reported. It has to be pointed out that in ancient times (and until just a few centuries ago), conceptually the differences between force (weight) and mass units was not very well defined. For this reason, in the fourth column of the following table, the S.I. equivalents are

**Table 1.2** Greek length units

Greek name	Latin alphabet	English name	Value (ft)	S.I. Equivalence
ποῦς	pus	Foot	1	≈308.3 mm Attic ≈ 296 mm
ἀπλοῦν βῆμα	aploun bema	Single pace	2.5	≈0.75 m
διπλοῦν βῆμα	diploun bema	Double pace	5	≈1.5 m
όργινά	orguià	Fathom or stretch of both arms	6	≈1.8 m
ἄκαινα	ákaina	[2]	10	≈3 m
πλέθρον	plèthon	Breadth of Greek acre	100	≈30 m
στάδιον	stádion	Stadium	600	Attic ≈ 177.6 m Olympic ≈ 192.27 Walking ≈ 157.5 m
δίσυλος	diàulos		2 stadia	≈355.2 m
ἵππικόν	hippikòn		4 stadia	≈710.4 m
δόλιχος	dòlichos		12 stadia	≈2.131 km
παρασάγγες	parasànghes		30 stadia	
σχοινός	schoinòs		40 stadia	

**Table 1.3** Greek volume units, liquid

Greek name	Latin alphabet	English name	Value (cotylai)	S.I. Equivalence $m^3 \times 10^{-3}$ (=litre)
κύαθος	kýathos		1/6	≈0.046
οξυναφόν	oxynafon		1/4	
ημίκοτύλη	emikotýle		1/2	
κοτύλη	cotýla	Cup	1	≈0.275
ημίχους	emichous	Half jug	6	
χοῦς	choùs	Jug	12	≈3.3
μετρητής	metretès		144 ≈ 1 amphora wine	≈39.4

**Table 1.4** Greek volume units, solid

Greek name	Latin alphabet	English name	Value (cotylai)	S.I. Equivalence $m^3 \times 10^{-3}$ (=litre)
κοτύλη	cotýla	Cup	1	≈ 0.275
χοῖνιξ	choìnix		4	
έκτεύς	hecteús		8	
μέδιμνος	mèdimnos		6	

**Table 1.5** Greek weight/mass units, solid

Greek name	Latin alphabet	English name	Value (obola)	S.I. Equivalence (g) Attic/Euboic	S.I. Equivalence (g) Aeginetic
ὀβολός	obolòs	Obol		0.72	1.05
δραχμή	drachmè	Drachma	6	4.31	6.3
μνα	mna	Mina	600	431	630
τάλαντον	tálanton	Talent	60 minas	25.86 kg	37.8 kg

**Table 1.6** Roman length units

Latin name	English name	Value (ft)	S.I. Equivalence
Digitus	Digit	1/16	18.5 mm
Uncia	Inch	1/12	24.6 mm
Palmus	Palm	1/4	74 mm
Pes	Foot	1	296 mm
Cubitus	Cubit	1 + 1/2	444 mm
Gradus	Step	2 + 1/2	0.74 m
Passus	Pace	5	1.48 m
Pertica	Perch	10	2.96 m
Actus	Arpent	120	35.5 m
Stadium	Stadium	625	185 m
Milliarium	Mile	5000 ft = 1000 pace	1.48 km
Leuga	League	7500	2.22 km

given for the masses; obviously, the S.I. equivalents for the forces are obtained in Newton by multiplying the masses by 9.81.

### 1.4.2 Ancient Roman Units

#### Length Units

In Table 1.6 the roman length units are reported

#### Area Units

In Table 1.7 the roman area units are reported

#### Volume Units

The roman volume units are reported in Tables 1.8 (liquid) and 1.9 (solid).

**Table 1.7** Roman area units

Latin name	English name	Value (acres)	S.I. Equivalence
Pes quadratus	Square foot	1/14400	$\sim 876 \text{ cm}^2$
Scripulum	Square perch	1/144	$\sim 8.76 \text{ m}^2$
Actus minimus	Aune of furrows	1/30	$\sim 42 \text{ m}^2$
Slima	Rood	1/4	$\sim 315 \text{ m}^2$
Actus quadratus (acnua)	Acre	1	$\sim 1260 \text{ m}^2$
Iugerum	Yoke	2	$\sim 2520 \text{ m}^2$
Heredium	Morn	4	$\sim 5040 \text{ m}^2$
Centurium	Centurie	400	$\sim 504000 \text{ m}^2$

**Table 1.8** Roman volume units, liquid

Latin name	English name	Value (sesters)	S.I. Equivalence $\text{m}^3 \times 10^{-3}$ (=litre)
Ligula	Spoonful	1/48	$\sim 0.01125$
Cyathus	Dose	1/12	$\sim 0.045$
Sextans	Sixth-sester	1/6	$\sim 0.09$
Triens	Third-sester	1/3	$\sim 0.18$
Hemina	Half-sester	1/2	$\sim 0.27$
Choenix	Double third-sester	2/3	$\sim 0.36$
Sextarius	Sester	1	$\sim 0.54$
Congius	Congius	6	$\sim 3.25$
Urna	Urn	24	$\sim 13$
Amphora	Jar	48	$\sim 26$
Culleus	Hose	960	$\sim 520$

**Table 1.9** Roman volume units, solid

Latin name	English name	Value (pecks)	S.I. Equivalence $\text{m}^3 \times 10^{-3}$ (=litre)
Acetabulum	Drawing-spoon	1/128	$\sim 0.0675$
Quartarius	Quarter-sester	1/64	$\sim 0.0135$
Hemina	Half-sester	1/32	$\sim 0.27$
Sextarius	Sester	1/16	$\sim 0.54$
Semodius	Gallon	1/2	$\sim 4.33$
Modius	Peck	1	$\sim 8.66$
Quadrantal	Bushel	3	$\sim 26$

**Table 1.10** Roman weight/mass units

Latin name	English name	Value (drachmae)	S.I. Equivalence
Chalcus	Chalcus	1/48	~ 71 mg
Siliqua	Siliqua	1/18	~ 189.33 mg
Obolus	Obolus	1/6	~ 0.568 g
Scrupulum	Scruple	1/3	~ 1.136 g
Drachma	Drachm	1	~ 3.408 g
Sicilicus	Shekel	2	~ 6.816 g
Uncia	Ounce	8	~ 27.264 g
Libra	Pound	96	~ 327.168 g
Mina	Mine	128	~ 436.224 g

### Weight/Mass Units

In Table 1.10 the roman weight/mass units are reported; as for the S.I. equivalences, the same observations made about ancient Greek weight/mass units must be made.

# Chapter 2

## Measuring Mass

**Abstract** Measuring mass was a very important task, essentially due to the trades. In this chapter some ancient device to measure the mass are reported. Examples of balance scales from the Egyptians and of Roman steelyards balances are shown.

### Introduction

Measuring mass and force, together with the measuring of the linear dimensions that will be exposed in the next chapter, represent the first step in the developing of science and technology. Examples of balance scales from Mesopotamia and Egypt are dated to the V millennium B.C. but their use became common in nearly all the populations.

Speaking about devices, probably those designed to measure the mass were the first ones since a yarn with some knots to measure a length can not be considered a real device. The input to design mass measuring devices were, quite certainly, the trades.

It is interesting to consider that, by the Egyptians, the balance scales was already considered a symbol of justice, even for after death life. The god Anubis, in fact, was also the guardian of the scale balance that was used to measure the weight the soul; if the soul was not heavier than a feather, she was given to Osiris; otherwise it was eaten by Maat. In Fig. 2.1 is reported an Egyptian paint showing the god Anubis and a balance scale.

Ancient balance scales were built in two shapes: one has two arms having equal length, the other had arms having different lengths; the first will be indicated simply as “balance scale” while the second will be indicated as “pendulum scale”.

### 2.1 The Balance Scale

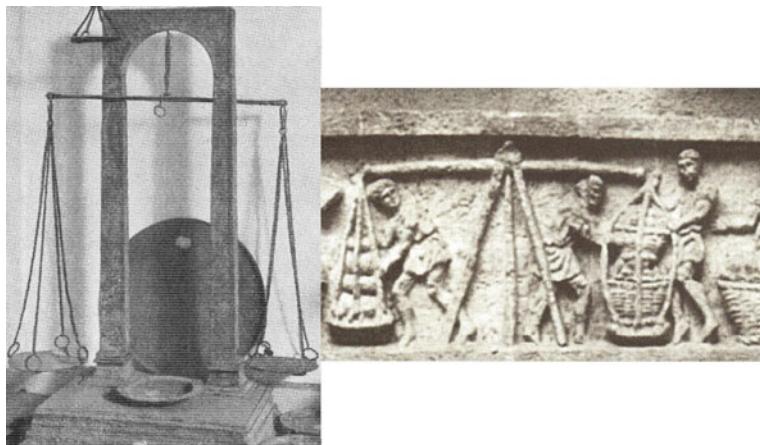
The word balance (that is similar in many languages) comes from the Latin “*bilanx*” that means double pan. The balance scale essentially consists in a couple of pans suspended from a yoke; the latter is suspended in the middle point between the points in which the dishes are suspended. The use is very easy and well-known: the



**Fig. 2.1** Balance scale and god Anubis

object that has to be weighed is located on a pan while on the other pan are located weights having known value, until the yoke is horizontal. When the yoke is balanced, since its arms have equal length, the weights (and the masses) on both the pans are equal, hence the object's mass is given by the sum of the known weights on the other pan. Such a type of balance scale is common all-over the world and has been used for thousands of years by a great number of civilizations. In Fig. 2.2 are reported a roman balance scale now at the Museo Nazionale, Naples, Italy (on the left) and a detail of a Roman bas-relief showing a large balance scale.

The mathematic theory of the balance scale is not very simple (and certainly was formulated 1000 years after the first balance scales had been built), but it is possible to briefly summarize the main aspects. The precision of a balance scale depends on the quality of its components (mainly the yoke and the suspension pins) and the



**Fig. 2.2** Roman balance scales

accuracy of the weights; the sensibility mainly depends on the yoke's weight and length hence on the balance size. For thousands of years balance scales have been built in a wide range of sizes, the big ones to measure the mass of large objects and the small ones to compare the weight (hence the value) of the coins.

## 2.2 The Steelyard Balance

The steelyard is also known as Roman balance because it was invented by the Romans around the 4th century B.C. and was called “statera”. In about the same period, about 3th century B.C., similar devices appeared in China. The working principle is shown in Fig. 2.3.

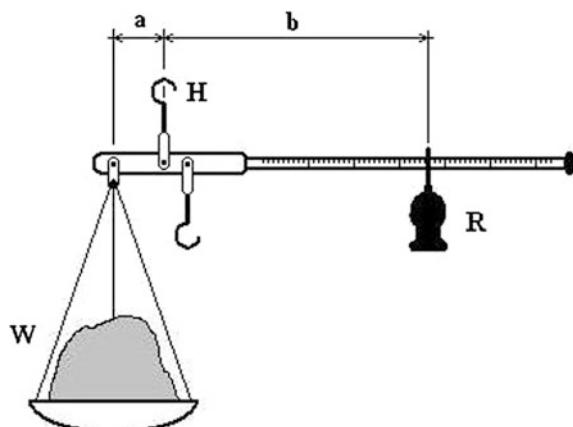
The steelyard has two arms having different lengths; to the shorter one is linked a pan on which is located the unknown mass  $W$ , a known (and calibrated) counter-weight  $R$  can slide on the longer arm that is graduated. When hung from the hook  $H$ , obviously the equilibrium is reached if both the momentums of  $W$  and  $R$  are equal respect the pivot of the suspension hook  $H$ :

$$W \cdot a = R \cdot b \Rightarrow W = a \cdot R/b \quad (2.1)$$

Since the counterweight  $R$  and the arm's length  $a$  are constant,  $W$  is a function only of the distance  $b$ . To weigh an object it is only necessary to move the counterweight  $R$  along the arm till the steelyard is horizontal and then to read the weight on the graduation of the long arm. This device is generally less precise than the balance scale but it is very easy to handle and to carry since it does not require a set of known weights.

A very good description of the steelyard is given by Marcus Vitruvius Pollio (1st century B.C.), who was a Roman writer, architect and military engineer that will be widely mentioned in the following chapters of this book, in his famous

**Fig. 2.3** Scheme of a steelyard balance



treatise “De Architectura”. It is interesting that Vitruvius, in his description, uses the term “momentum” with the same meaning of the English word in mechanics.

In Fig. 2.4 is reported an ancient steelyard found at Hercolaneum.

A later description of the steelyard is given by Saint Isidore of Seville (Spanish name: San Isidro or San Isidoro de Sevilla, Latin name: Isidorus Hispalensis ~560–636 B.C.) who was Archbishop of Seville and one of the most educated man of that age; he wrote about liberal arts, law, medicine, natural science, theology. In his treatise “De ponderibus et mensuris” (On the weights and measures), he calls statera the scale balance while the steelyard is called “Campana” after the name of the Italian region Campania where, according to him, the first example of this device was found. Really the word “campana” does not appear in the classic Latin literature but only in the later one.

### Observations

Balance scales having, substantially, the same shape of those built thousands of years ago, have been built up until the present day and have been the only device to make accurate measures of weight till the very recent invention of electronic dynamometers. Some of those balance scales, built for laboratory use, have a sensibility of 0.1 mg in a range from 0 to 200 g.

Balance scales and steelyard measure the mass because the measurement is made by comparing the gravitational force acting on two masses; the authors think that ancient force measuring devices could have existed but they have not found any proof of this.

Also steelyards are still used; until a few years ago these devices were used in most country markets. Some modern steelyards are still built in small size to weigh the gunpowder charge to load the cartridges; these devices generally have a sensibility of 0.1 grain (=0.0065 g).

**Fig. 2.4** Steelyard found at Hercolaneum



It is interesting to report a legend, told by Vitruvius, that demonstrates that, in ancient times, also the concepts of specific weight and density were well-known: when Hieron I became tyrant of Syracuse in Sicily (from 278 to 267 B.C.), he wanted to offer a votive crown made of solid gold to a temple; so, he gave the necessary amount of gold to a goldsmith. Once the crown was made, Hieron was doubtful that the goldsmith could have made the crown by substituting some gold with silver and so asked Archimedes, the well-known ancient scientist (Syracuse ~287–212 B.C.), to discover whether the crown had been made only by gold or not. Archimedes operated as follows:

- (1) He weighed the crown;
- (2) then he got an equal mass of gold and an equal mass of silver;
- (3) finally, he took a container full of water, put the gold mass in it and measured the water that spurted from the container that obviously represents the volume of that mass of gold.
- (4) The same was done with the silver mass and with the crown.

The volume of water that spurted from the container when the crown was immersed was lower than the water that spurted with the silver mass but more than the water that spurted with the gold mass; from this Archimedes concluded that the crown was not made of pure gold but of a gold with silver alloy.

Vitruvius does not tell us if Archimedes computed the gold amount that was substituted by silver but, on the bases of the described procedure the computation is very easy:

$$\frac{\text{Gold mass}}{\text{Silver mass}} = \frac{\text{Silver volume} - \text{Crown volume}}{\text{Crown volume} - \text{Gold volume}} \quad (2.2)$$

A very simple equation that that such a mathematician, as Archimedes was, could have probably used.

According to the procedure described by Vitruvius, Archimedes did not use any balance scale.

The same legend was told later but the procedure credited to Archimedes was different: on one of the pans of a balance scale was put the crown and on the other pan some gold having the same mass of the crown; in this way, the yoke of the balance was obviously horizontal. Then the balance scale was put into water: since the pan containing the pure gold went down, Archimedes concluded that the crown was not made by pure gold but contained silver.

The second procedure is more plausible because to a certain amount of silver in the crown could have corresponded to a very little difference of volume that could have been hardly measured in that age. In any case, both procedures show that those concepts were known by scientists and engineers in those ages.

# **Chapter 3**

## **Measuring Distance and Slope**

**Abstract** In this chapter the ancient device to measure slopes and distances are presented. Most of them belong to the Greek-Roman era. These devices, despite their simplicity, were surprisingly accurate; in fact, they permitted to realize the surprising roads, bridges, tunnels, aqueducts, buildings etc. of the antiquity. Then the astrolabe is also briefly described. Some examples of how did these devices work are also presented.

### **Introduction**

As already mentioned in the previous chapter, the measuring of distance (together with the measuring of mass and force) represent the first step in the developing of science and technology. In addition, the first western scientists and engineers (e.g. Thales, Pitagoras, Archimedes etc.) were very deeply interested in the study of geometry.

It is also well-known that in building temples and towns an accurate measuring of distances is also essential. An impulse in this field of knowledge was given during the Roman Empire.

As everybody knows, the Roman Empire was one of the widest empires ever to exist in the human history. On the other hand, most people believe that, at that age, technology and science were quite primitive and the study of them almost neglected. The study of the History of Engineering gives a great help to recognise that, on the contrary, mechanical knowledge was rather advanced and also to recognize the function and the meaning of some archaeological finds and their way of working. In particular by common efforts of Archaeologists and Engineers it was possible to understand that many devices of present day common use were invented and built about twenty centuries ago.

In such a wide empire as the Roman one the measurements of distances, both on land and on the sea, played certainly a very important role. One of the most important buildings the Roman built in Europe is, in fact, represented by a wide road system. Most of those road paths are still in use today. In addition, since sextant and marine chronograph were not yet invented the only way to know distances on the sea was to measure the space run by a ship.

### 3.1 Jacob's Staff

When it was not possible to measure distances directly, because there was a deep gorge, wide river or sea inlet, a rudimentary range finder was used: *Jacob's staff*, also called *baculum* or *cross-staff* or *radius*. The precision of the instrument depended a great deal on the skill of the user, which was still scarce. Historically, the *baculum* was first used by the Egyptians, then the Jews and later the Arabs. It reached Europe during the Middle Ages, perhaps brought by the mathematician Levi ben Gerson (1288–1344). The oldest model consisted of a simple graduated rod along which slid a smaller cross shaped one: the estimate was based on the similarity of right angled triangles. The primitive nature of the instrument made it very approximate, even though it is the relative criteria at the basis of modern optical telemeters. According to some scholars, the *baculum* was the precursor of the *Latin radius*, a completion of the *Greek radius*, also called *Jacob's staff*.

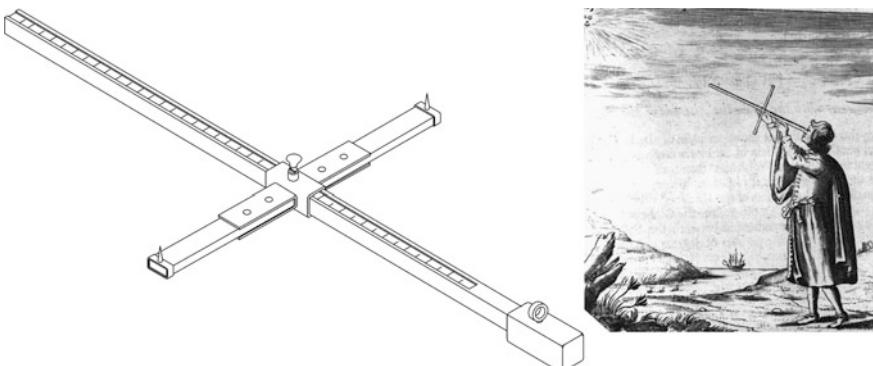
In Fig. 3.1 a schematic reconstruction of a roman era staff or baculum is reported, with a medieval print illustrating the use of a staff or baculum.

### 3.2 Range Finders

In this paragraph are reported those ancient devices which made possible the development of topography.

#### 3.2.1 *Groma*

It would be difficult to determine when the groma, a land surveyor's instrument was first invented: it may have originated in Mesopotamia, where it may have been



**Fig. 3.1** Jacob's staff

**Fig. 3.2** Groma

taken from the Greeks around the 4th century B.C., renaming it gnomona or little star. The Etruscans then brought it to Rome, calling it cranema or ferramentum. It consisted of an iron or bronze cross from whose arms descended four plumb lines. Looking through the opposing pairs, the surveyor could identify two perpendicular directions, which allowed him to subdivide the land into orthogonal alignments.

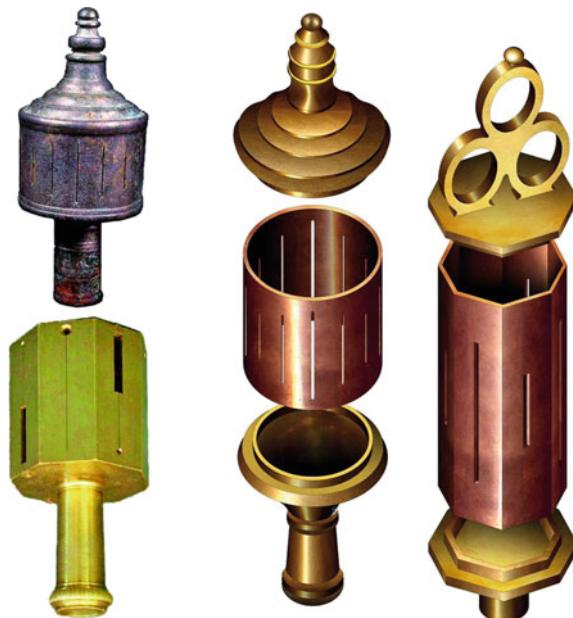
In spite of the fact that this instrument goes back to very ancient times, it was in common use even centuries later. Proof is found in the remains of a groma discovered in Pompeii and its illustration on several funerary steles. As far as we can tell, the approximately 2 m long rod supported the cross well above the eye level of the user, who could therefore look freely through the plumb lines. The real limitation of the instrument was revealed when there was even a weak wind as this caused the lines to oscillate and prevented a correct line of sight.

In Fig. 3.2 are reported a virtual reconstruction of a groma and a bas-relief from the roman imperial era representing a groma.

### 3.2.2 Surveyor's Cross

This little deficiency of the groma was overcome with the surveyor's cross, either the drum or case version. In Fig. 3.3 is shown a find and an authors' virtual reconstruction of this device.

**Fig. 3.3** Surveyor's cross:  
find and virtual reconstruction



The function of the lines was carried out by thin slits, made at regular intervals, along the side of a cylindrical drum. In most models, these were placed at  $90^\circ$  intervals, decreasing to  $45^\circ$  in the more accurate ones. For more important uses requiring more than simple squaring, the distance was further decreased as low as  $22^\circ 30'$ . By looking through the slit to its corresponding opposite, the surveyor could determine the correct direction; by holding the instrument stable, again looking through the slit at  $90^\circ$ , he could identify the direction orthogonal to the preceding one. Finally, looking through the slit at  $45^\circ$  he would determine the diagonal and its bisecting line from the line placed at  $22^\circ 30'$ , allowing the user to trace geometric Figures with 8 or 16 sides, with great precision.

The crosshead was inserted into the tapered upper extremity of a wooden rod, which had an iron tip at the bottom to fix into the ground. Before proceeding with collimation, the surveyor first had to ensure the perfect verticality of the rod, using a plumb line. We know neither the era nor area of origin of the surveyor's cross nor, obviously, its inventor. The unearthing of an undamaged specimen in Koblenz dispelled any doubt: this particular finding was an octagonal prism shell case, with a slit on every facet placed at  $45^\circ$ . Lost during the last conflict, it was replaced in 1997 by a second exemplar discovered in Spain, during the excavation of the ruins of a Roman villa from the 3rd century A.D.

This later discovery consisted of a cylindrical bronze drum, approximately 19 cm high and 6 cm in diameter, with 16 slits located vertically every  $22^\circ 30'$ , each one half millimetre wide. Perfectly identical to the models of the eighteen hundreds, upon further study it was revealed that at a distance of 50 m the visual field of one of its slits did not exceed 40 cm, with a maximal angular error of  $30'$ .

### 3.2.3 *Chorobate*

The need to contain the maximum inclination of roads within 3 % and within 0.1/1000 for aqueducts, spurred the invention of effective precision levelling instruments, later correctly called levels. Contrary to the ones used for carpentry work and construction, these tools had to allow for altimetric mapping along very long extensions, often for hundreds of kilometres. They were indispensable in providing sight estimates at a moderate distance and could assess the horizontal direction not of a slab but of a general course that extended for dozens of meters. By studying the water's ability to maintain an always perfectly flat surface, in whatever container and at whatever inclination, they devised numerous tools but the best known and most reliable result was the Roman *chorobate*, still in use during the Renaissance.

According to Vitruvius the *chorobate* is a sort of wooden plank, a bit less than 1 m high and about 6 m long. Along the upper axis there is longitudinal groove about one and one half meter long and a couple of centimetres deep and wide. Before using, it was completely filled with water. When the *chorobate* rested perfectly level, the water touched the borders of the grooves; when it was not level, it would leak out of one side. They would then place pads under the corresponding extremity until the water once again met the entire borders. At that point, looking directly through along the surface of the water, with the instrument placed at a significant distance from the site, and perhaps also using a surveyor's pole, they could obtain a horizontal reference.

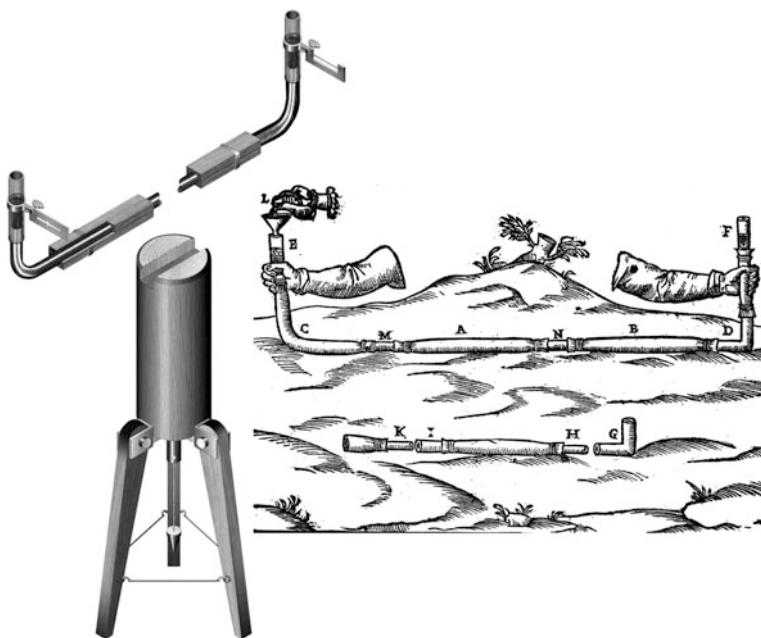
In Fig. 3.4 a virtual reconstruction of Heron's level, using communicating pipes and optical sights is reported with the table XXXIX from Giovanni Branca "Macchine", Rome 1629, showing a similar device.

## 3.3 The Astrolabe

The astrolabe is an instrument typical of the Middle Ages; its Latin name is astrolabium and the Arabic word is asturlâh. The origin of the astrolabe dates back to Eudoxus of Cnidus (408–355 B.C.) or of Apollonius (265–170 B.C.), or to the Babylonians.

It began as an astronomical instrument to solve problems regarding the calendar; these application outcomes explain the great commitment of medieval scholars, both Arab and Christian, to improve the instrument as well as the projective theory upon which it is based.

The astrolabe, an instrument destined to have wide use and that will remain practically identical for many centuries is composed of several superimposed discs: the upper disc, called *araneus* or *rete* is perforated and has the positions of the brightest stars; underneath this disc is a solid disc called *tympan* or *climate* upon which is engraved the system of celestial coordinates for a specific latitude.



**Fig. 3.4** Virtual reconstruction of Heron's level and tab. XXXIX from G. Branca

In order to measure the height of a building one must observe it in a vertical position, moving the alidade up and sighting it in order to read, on the appropriate graduated scale of the instrument, the height of the point being observed with respect to the horizontal line of reference.

### 3.4 The Dioptre by Heron

Obviously a topographic instrument 6 m long, even though precise, was too cumbersome to transport during a campaign. There was also the possibility that rain and wind could prevent its use. The real step forward was made when Hero succeeded in constructing a dioptre fitted with a special accessory in lieu of the alidade, transforming it into a high precision level. In many ways this is the forerunner of the theodolite. Etymologically, *dioptre* in Greek comes from two words: *dià* = through and *opteuo* = observe: *observe or look through*, a definition suitable for all sighting instruments used to identify a direction; these sights will soon be replaced by the telescope.

Hero left us a very detailed description in his *Treatise on Dioptrics*, translated from the Greek by Giambattista Venturi in 1804. The instrument was intended to take angular measurements using an alidade or dioptre that could rotate both

horizontally and vertically. Two semi-cogged wheels used two worm screws with knobs to rotate in the horizontal and in the vertical direction. In this manner, they could achieve a line of sight with target rods to get the azimuth or elevation. By using a crosswire applied to the ends of the dioptr, they were able to improve precision apparently up to 30'. A small tripod column, rather like our trestle, was used to support the instrument and a plumb line or bob along its side ensured perfect verticality.

Venturi theorised that, in addition to the goniometric plate to measure the azimuths, there must also have been a vertical semi-disk to measure elevation. In effect, the device would resemble an inclinometer: however, since there is no mention or allusion to this in the treatise, we prefer to believe that the sight only had a vertical rotation and that it occurred in the traverse fork on the goniometric plate. A location functionally similar to the telescope, which makes the dioptr even more modern.

As for its transformation into a level, this occurred by replacing the sight with a wood rule containing a small copper tube whose ends extended outward forming a U. At the ends of the U were two transparent glass pipes. When an opaque liquid, such as red wine, was used, the two cursors could be made to coincide perfectly with the level of the liquid. In effect, this was two communicating vessels with one index.

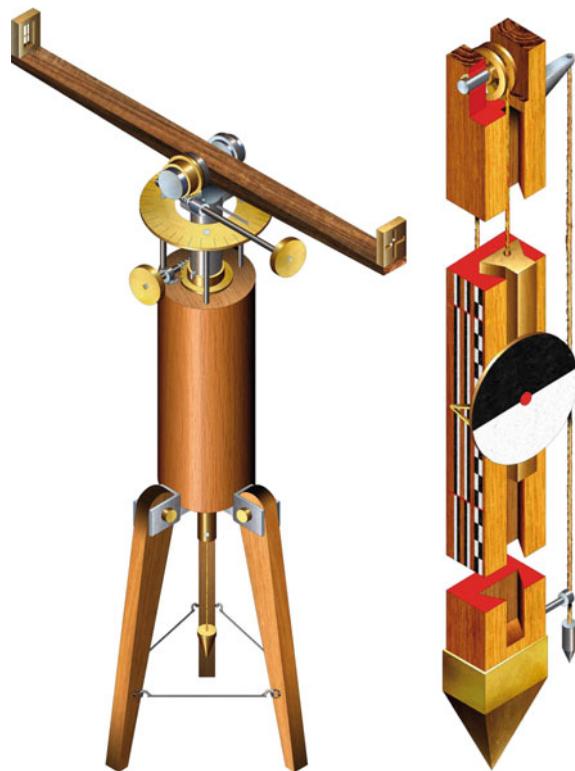
The cursors were actually two metal ties, each with a line of sight, that slid along the exterior of the glass tubes. Once the liquid was stabilised, these cursors were made to align with the liquid. The regulus containing the tube is described as being 12 fingers long, approximately 25 cm, a measure perfectly suited to its purpose.

The most interesting and least known accessory is the pair of levelling rods that completed the dioptr. However, since it was not possible to read the rod from a distance without a telescope, a solution was found to allow for direct reading. By looking through the sights of the level, a mobile pointer along the rod was brought to coincide with the direction. Since this had a wide disk that was half white and half black, collimation was not particularly difficult: in fact, once the assistant had blocked the disk after it had been aligned, the measurements could be read on the rod, as registered by the lateral pointer.

In Fig. 3.5 are shown reconstructions of Heron's dioptr and a roman era stadia, according to Heron's description.

In 1907, the relic of a Roman ship was found off the coast of Mahadie. Many decades later, when it finally became possible to bring up the cargo, among the numerous and valuable works of art were also several bronze flanges, two of which were semi-cogged. This was a symmetrical pair and was most likely intended to rotate the horizontal plane of a dioptr.

**Fig. 3.5** Virtual reconstructions of Heron's dioptra (left) and of a Stadia (right)



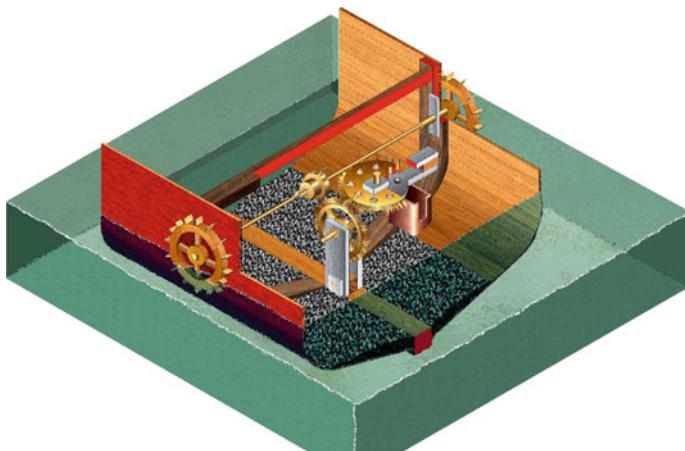
### 3.5 The Ancient Odometers

As for the devices for distance measurement that make use of mechanisms, during the Roman age odometers were invented and quite commonly used, both for land and sea use.

#### 3.5.1 The Odometer by Vitruvius

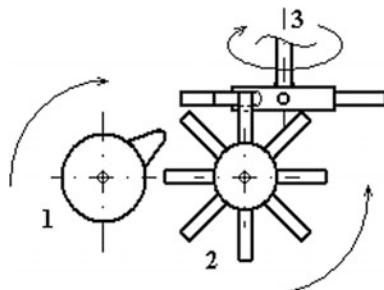
It is well-known that at the time of the Roman Empire it was not possible to determine the position of a ship by astronomical device. For this reason the only way to know the position was to determine the run covered by the ship. A first device for this task can be considered the naval odometer that was designed by Vitruvius.

A perspective reconstruction of it is shown in Fig. 3.6. A paddle wheel was installed at each of the side of the ship; the paddle wheel was moved by the movement of the ship. Both the paddle wheels were fitted on an axle that moved the mechanism of the odometer.



**Fig. 3.6** Perspective reconstruction of the naval odometer by Vitruvius

**Fig. 3.7** Scheme of the first 3 axes of the mechanism



Each revolution of the paddle wheels causes one teeth rotation of the first gear wheel; the latter by means of further gears (not represented) moves the pointers. A scheme of it is reported in Fig. 3.7; the axe 1 is that of the paddle wheels.

This devices, as far as we know, is the first log example. It has to be pointed out that, “log” in English indicates the piece of wood that was tied to a small rope and was thrown overboard. The rope had a number of knots, one every 1/10 of nautical mile. By means of an hourglass, the number of knots in the unit of time were counted, hence the speed was computed. This device, in the shape that has been just described, was “invented” in the 18th century, that is to say more than 18 centuries after the naval odometer by Vitruvius, and it is clearly much more unsophisticated. The term “log” is still used for mechanical or electrical devices used to measure speed and distances on the sea in more recent times.

Before the (very recent) use of the GPS, the coastal navigation, both sporting and professional, was made by log and compass till the present day. At the time of the Roman Empire, the navigation was mainly coastal as they were helped by a wide system of long range lighthouses.

### 3.5.2 *The Odometer by Heron*

The invention of this device is attributed to Heron of Alexandria. The biography of this very important ancient scientist and engineer is not very clear where dates are concerned. The century is established by a moon eclipse on March 13, 62 A.D. that he described; so, he was probably born in 10 B.C. and died in about 70 A.D. He studied the work of Ctesibius, Philon, Euclid and Archimedes; a lot of inventions are attributed to him, mainly in the field of the pneumatics, mechanics and automatics. In addition to the odometer, he was probably the inventor also of optical devices for distance measurement.

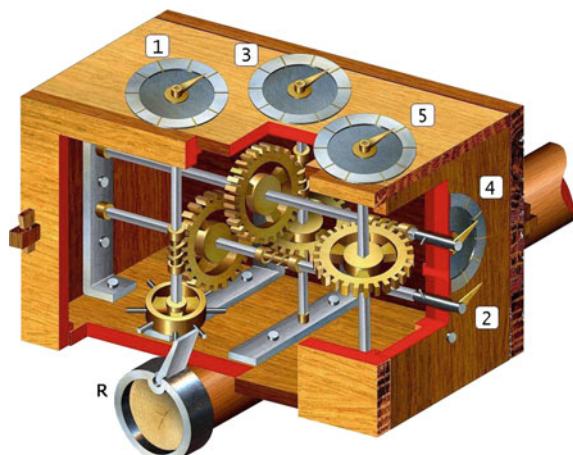
The odometer by Heron is, without any doubt, the predecessor of the modern mechanical mileometer and tripmeter that has been used in modern motor vehicles till less than 10 years ago. Although it was designed about 200 years ago, it works with the same principles of modern tripometers.

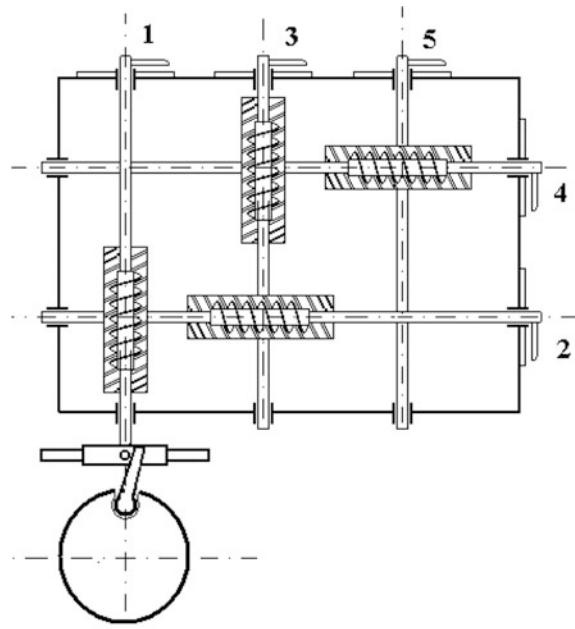
This device was of great importance during the Roman Empire since it was used to locate the mile stones; this permitted to plan the movements of the army units and military costs. In addition it is reported that an odometer was installed on the carriage of the emperors.

The description of the odometer by Heron is given by Vitruvius who was an officer of the Roman Army Engineers and an inventor himself. From the description of Vitruvius it is possible to propose the perspective reconstruction in Fig. 3.8.

The ring R is connected to the wheel and moves a pin of the input wheel through a small flap. On the axle of this first wheel is installed a pointer that indicates the steps named as “passus”. A dial (indicated as 1 in Fig. 3.8) was graduated 0–9. This first axle moved a second axle by means of worm gears with a gear ratio 10. On the second axle was assembled a second pointer, installed to indicate the ten steps. This axle (indicated as 2 in the Fig. 3.8) moved a third axle again with a worm gear and so on.

**Fig. 3.8** Perspective reconstruction of the odometer by Heron



**Fig. 3.9** Gears scheme

A cinematic scheme is shown in Fig. 3.9. With such a cinematic scheme, the odometer could have up to five pointers that indicated units, tens, hundreds, thousands and tens of thousands steps. Of course, the gear ratios will be all equal to 10. This means that probably the worms could have 2 principles and, consequently the wheels had 20 teeth. As for the pins on the input wheel and the wheel of the carriage, Vitruvius wrote that the standard wheel diameter of a roman carriage was 4 roman feet. Since a roman foot was 0.2964 m, the wheel circumference was 3,725 m.

Therefore, we can presume that, for a correct continuous transmission between carriage wheel and input wheel, the latter should have 8 pins; measurements can be computed as:

$$8 \text{ carriage wheel revolutions} = 10 \text{ roman steps} = 14.785 \text{ m} \quad (3.1)$$

Consequently, with 8 pins, the wheel diameter can be computed as:

$$14.785 / (8 \cdot \pi) = 0.588 \text{ m} \cong 2 \text{ roman feet} \quad (3.2)$$

that is one half of the standard wheel.

It must be observed that the small flap is not rigidly linked to the axle but it can rotate, slightly, with respect to it. This particular is not reported in some later designs by later technicians but it was very useful for a correct working.

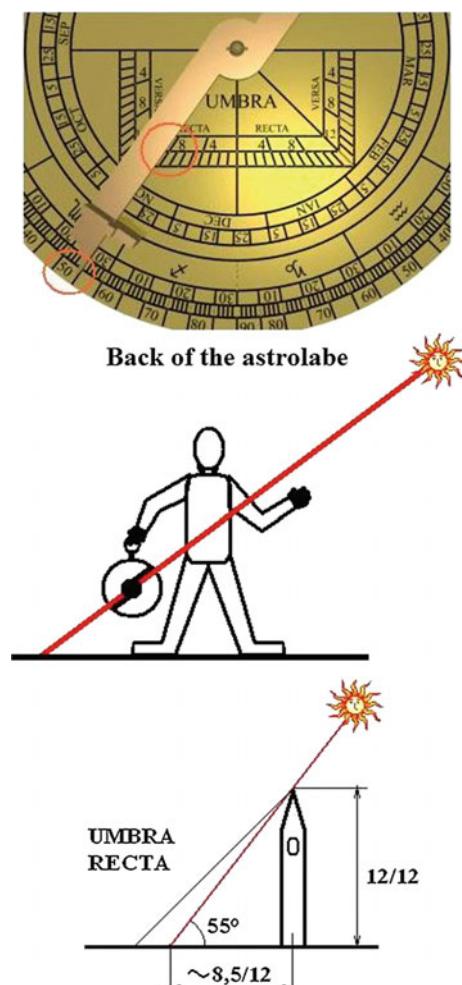
## Observations

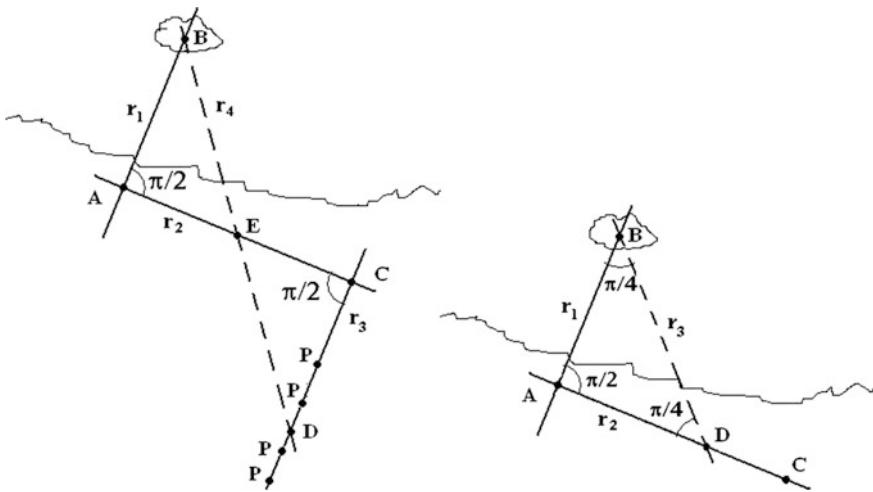
The devices presented in this chapter show that about 200 years ago the measuring of distances both for topographic and for civil engineering purposes were rather advanced.

### Measuring a Building Height by an Astrolabe

To measure the height of a building is necessary to keep the astrolabe vertically and moving the alidade up to look over the top of the building; On relevant scale of the instrument (the umbra) will read the height of the point observed with respect to the horizontal reference line. This height will be expressed in twelfths of the length of the shadow. Figure 3.10 shows the working principle.

**Fig. 3.10** Measuring a building height by an astrolabe





**Fig. 3.11** Measuring distances by the groma and by the surveyor cross

The example in Fig. 3.10 indicates that the alidade identifies quantity 8.5 on the umbra scale and  $55^\circ$  on the inclination scale. Thus the building is  $12/8.5$  times as tall as the length of its shadow in that given moment.

### Measuring the Distances by the Groma and by the Surveyor's Cross

Both the groma and the surveyor's cross can be used to measure distances (the latter being even more effective), even if the point whose distance from the observer is being measured is in an inaccessible position. The basic principle is illustrated in Fig. 3.11. Let us suppose, for example, that we wish to know the distance of a point B located on a reef at a certain distance from point A, the latter located on the coast, in which case it is not easy or even possible to extend a metric string between the two points.

One would place the groma at point A and sight point B, identifying direction  $r_1$ ; the groma detects direction  $r_2$ , perpendicular to  $r_1$  and sights point C along  $r_2$  placed in an accessible position. The groma is then moved to C (or a second groma is placed at C) and at this point we can find direction  $r_3$  perpendicular to  $r_2$  and thus parallel to  $r_1$ .

Along the AC segment we identify medium point E; finally we move along direction  $r_3$  until we reach point D so that points B and E are aligned when sighted. As we can see clearly from Fig. 3.11, distance CD (easily measured) is identical to distance AB, which is the distance we were searching for.

Since the surveyor's square allows us to also identify directions that form a  $45^\circ$  angle, the measurements described above can also be accomplished in a simpler manner. The method is clearly illustrated in Fig. 3.11.

# Chapter 4

## Measuring Time

**Abstract** In this chapter the ancient device to measure time such as sundials and water clock are presented. In particular, a virtual and a functional reconstruction of the water clock by Ctesibius is shown. The latter had a very interesting particularity: it could automatically adjust, in each of the days of the year, the length of the hour. In fact, except at the equinoxes, the length of the single hour for the Greeks and Romans was different from a day to the other and from the day to the night.

### Introduction

Speaking about time measurement we must, first of all, consider how the day length was divided in ancient times.

The Romans divided their day, or rather the interval between two consecutive sunrises and two consecutive sunsets, into 24 h, twelve for the day and twelve for the night, exactly as we do today. But contrary to our system, they believed that the day was the interval between dawn and sunset and, by obvious symmetry, night the period between sunset and dawn, events that varied in the course of the year. The day, in fact, reaches its briefest duration on the winter solstice, December 21 and the longest duration on the summer solstice, 21 June, while night is the exact opposite. After appropriate calculations, computing the hour according to current minutes, the Roman hour lasted a minimum of 45 min on December 21 to a maximum of 75 min on June 21 and vice versa for the night. Hence, the length of an hour varied in a range of approximately 50 %, or 30 min in the course of 6 months, coinciding with our duration only on 2 days of the year: on March 21, the spring equinox and on September 21, the autumn equinox.

To give an example, in Table 4.1 are reported the length of the daylight hours at winter solstice and in Table 4.2 are reported those at the summer solstice.

Because of the different duration of hours it was rather complex to build a clock, much more than our current mechanical chronometers. Some ancient technicians saw the solution in the flow of water from a tank: by varying the quantity, an empty tank could be made to coincide with the duration of the day. This is confirmed by the etymology of the word hourglass or *clepsydra* which does not refer to a sand based instrument but to one that uses water: the word comes from the Greek *clepto* = removal, and *idros* = water and suggests something that works by the removal of water. Such clocks probably existed around the 1st century B.C. as

**Table 4.1** Daylight hours at winter solstice

Hora	Latin name	English name	Modern time
I	Hora prima	First hour	07:33–08:17 a.m.
II	Hora secunda	Second hour	08:18–09:02 a.m.
III	Hora terzia	Third hour	09:03–09:46 a.m.
IV	Hora quarta	Fourth hour	09:47–10:31 a.m.
V	Hora quinta	Fifth hour	10:32–11:15 a.m.
VII	Hora sexta	Sixth hour	11:16–12:00 a.m.
VII	Hora septima	Seventh hour	12:01–12:44 p.m.
VIII	Hora octava	Eighth hour	12:45–1:29 p.m.
IX	Hora nona	Ninth hour	01:30–02:13 p.m.
X	Hora decima	Tenth hour	02:14–2:58 p.m.
XI	Hora undecima	Eleventh hour	02:59–03:42 p.m.
XII	Hora duodecima	Twelfth hour	03:43–04:27 p.m.

**Table 4.2** Daylight hours at summer solstice

Hora	Latin name	English name	Modern time
I	Hora prima	First hour	04:27–05:42 a.m.
II	Hora secunda	Second hour	05:43–06:58 a.m.
III	Hora terzia	Third hour	06:59–08:13 a.m.
IV	Hora quarta	Fourth hour	08:14–09:29 a.m.
V	Hora quinta	Fifth hour	09:30–10:44 a.m.
VII	Hora sexta	Sixth hour	10:45–12:00 a.m.
VII	Hora septima	Seventh hour	12:00–01:15 p.m.
VIII	Hora octava	Eighth hour	01:16–02:31 p.m.
IX	Hora nona	Ninth hour	02:32–03:46 p.m.
X	Hora decima	Tenth hour	03:47–05:02 p.m.
XI	Hora undecima	Eleventh hour	05:03–06:17 p.m.
XII	Hora duodecima	Twelfth hour	06:18–07:33 p.m.

during Augustus' time there was a competition among various competitors based on the precision and complexity of their devices. There were several types of clocks, with acoustics, the sound of tolling bells, whistles, etc.

The oldest devices to measure the time are represented by sundials and water clocks, hence we will present some examples of these ones.

## 4.1 The Sundial

The sundial was the first device that was used for thousands years to measure (or to visualize) the hour of the day and is based on the apparent motion of the sun. The device essentially consists in a thin rod or a sharp and straight edge, called gnomon

or style, fitted on a surface; on the latter some lines are traced and each of these lines indicates an hour. While the sun moves in the sky, the gnomon shadows moves from one line to the next, indicating the time.

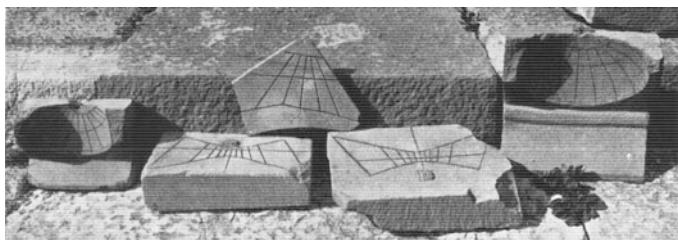
The oldest examples of sundials are represented by the obelisks (3500 B.C.) and solar clocks built by Egyptians and Babylonians. The Old Testament also describes sundials (Isaiah 38,8 and II Kings 20,11) similar to the Egyptian and Babylonian ones. The building of sundials in China date back to ancient times and one of them is still at the Forbidden City, Beijing.

The developing of sundials based on scientific knowledge is probably due to the Greek scientists who founded the scientific bases to build very precise solar clocks having dial surfaces were not only horizontal and also non planar.

The first Greek sundial builder might have been Anaximander from Miletus (about 560 B.C.). Plinius (*Naturalis Historia* II, 76) narrates that solar clocks were built by Anassimenes at Sparta, by Pherekydes of Siros (5th century B.C.) and also by Meton. In 4th century B.C. Democritos wrote a treatise on the construction of a sun clock that was made by a concave hemisphere in the centre of which the point of the style was located. Subsequently Berosus the Caldean, at the beginning of the 3rd century B.C. eliminated all the part that contained no marks. During the 3rd century B.C. sundial making become almost perfect; to that age are attributed some treatises on this topic which very probably were studied by Vitruvius and Ptolemaeus. At that time appeared the first conical sundials; Vitruvius attributes its invention to Dionysodorus of Milos. The dial is the inner surface of a right cone whose axis was parallel to the earth axis and the point of the style was on the cone axis; this in order to obtain that to equal spaces described by the shadow, correspond equal times.

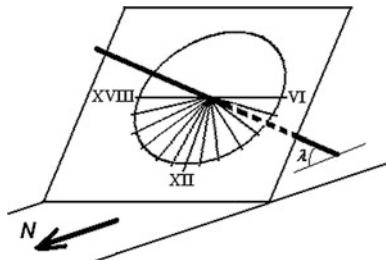
The Romans also built a very large sundial. Between the 10th and 6th century B.C. Augustus had a giant meridian built in Rome with the obelisk of Montecitorio as a gnomon, its shadow indicating the hours on the different bronze notches embedded in the pavement. This demonstrated the increasing interest in knowing the time as well as an evolution within society. In Fig. 4.1 are shown some sundials found at Pompeii.

The description of the working principle of the sundial implicates astronomical knowledge that are not the aim of this book, hence we will confine ourselves in describing just the fundamental types of sundials.



**Fig. 4.1** Sundials found at Pompeii

**Fig. 4.2** Scheme of an equatorial sundial



### 4.1.1 Fixed Sundials

These sundials are mounted on a fixed structure and can be roughly divided in three types as follows.

#### 4.1.1.1 Equatorial Sundials

The simplest type of sundial consists in a plane parallel to the equator of the earth and oriented toward the north and a gnomon that is parallel to the earth axis. A scheme of an equatorial sundial is reported in Fig. 4.2.

The dial is marked on both sides since the shadow will be on the north side of the dial in summer and on the south side in winter. Since the dial is parallel to the equator, this sundial is the simplest to build because the lines indicating the hours are equally spaced by  $15^\circ$ . A disadvantage consists in that near equinoxes, in spring and autumn, the sun rays are quite parallel to the dial and hence the shadow is not clearly observable.

#### 4.1.1.2 Horizontal Sundials

The working principle is very similar to the previous one but the dial is horizontal and the gnomon is parallel to the earth's axis, hence its inclination  $\alpha$  is given by:

$$\alpha = 90^\circ - \lambda \quad (4.1)$$

where  $\lambda$  is the latitude.

The lines indicating the hours are no longer equally spaced but each line is spaced from the line that indicates noon by an angle  $\gamma$  given by:

$$\gamma = \sin \lambda \cdot \tan(15^\circ \cdot t) \quad (4.2)$$

where  $t$  is the number of hours after or before noon.

The advantages of an horizontal sundial essentially consists in that it is easy to read the time because the sun lights the dial all the year long.

#### 4.1.1.3 Vertical Sundials

These sundials are generally placed on the walls of buildings. The gnomon is also aligned with the earth's axis and the lines indicating the time are spaced by an angle that is computed with an equation similar to Eq. (4.2):

$$\gamma = \cos \lambda \cdot \tan(15^\circ \cdot t) \quad (4.3)$$

Since the sun does not light a wall of a building in any period of the year, more than one sundial are placed on different walls.

#### 4.1.1.4 Non Planar Sundials

Non planar surfaces can be used to receive the shadow of the gnomon such as the inner surface of a cylinder, a cone or a sphere. In Fig. 4.3 is shown a meridian found at Herculaneum, Italy.

### 4.1.2 Portable Sundials

The portable sundial is a very ancient device; probably the Egyptian one showed in Fig. 4.4 is the oldest one.

The manufacturing of portable sundials was significantly developed during the Middle Ages. Portable sundials can be made in different shapes, in the following the diptych sundials and ring dials are presented.

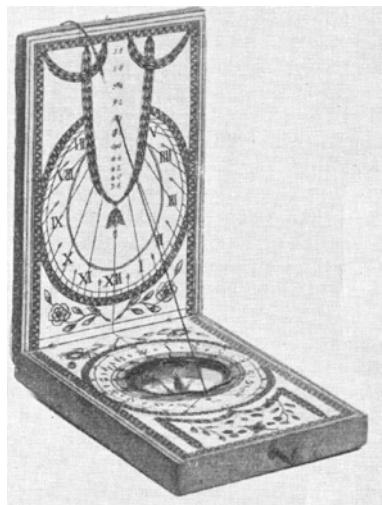
**Fig. 4.3** Roman sundial found at Herculaneum



**Fig. 4.4** Egyptian portable sundial



**Fig. 4.5** Diptych sundial



Diptych sundials are made by a couple of tablets joined by a hinge; a tin yarn is located between both the tablets' ends, hence the yarn is tightened when the tablets are open and functions as a gnomon. When the latter is tightened, the two tablets constitute two dials, one horizontal and the other quasi vertical. In Fig. 4.5 is shown a portable diptych sundial including a compass to correctly orientate it; such devices are already built and sold as curiosities.

Ring dials essentially consist in a ring held by a yarn. When the device was hung, a hole in the ring projected a bright point inside the ring where a scale indicated the hour. The device worked correctly at a given latitude but whether it was morning or afternoon had to be specified because a.m. and p.m. hours were not distinguishable. The hole was on a movable slide that was adjusted depending on the day of the year. In Fig. 4.6 is shown a ring sundial.

**Fig. 4.6** Ring sundial

## 4.2 Water Clocks

The services of solar clocks became increasingly useful and their ineffectiveness increasingly felt on days in which there was no sun. More important, the night-time needed to be measured in some manner for military camps and in cities for the changing of the guards and patrols. Since the hourglass only indicated the passage of a specific interval of time, like the modern day sports chronometer that can give the times but not the time, a method to measure time was required, but one that did not depend on sunlight.

It has to be remembered that the word clepsydra indicates a water clock; in fact, this word comes from ancient Greek *klepto* = I sieve and *udor* = water.

During the Roman Empire, within the space of a few decades, water clocks became a status symbol, an ostentation of wealth and distinction, without however leading to the frenetic pace of modern times. A fashion that paradoxically made it difficult to know the time was: "*horam non possum certam tibi dicere; facilius inter philosophos quam inter horologia convenit*" = I can't tell you what the time is with absolute certainty; it is easier to reach an agreement among philosophers than to find two clocks providing the same time. Roman time has always been approximate.

No wonder that even the genial Ctesibius, one of the most respected Hellenic scientists and curator of the Library of Alexandria became involved in constructing a water chronometer of extraordinary complexity, of which Vitruvius has left us his usual confused description.

### 4.2.1 Early Water Clocks

Water clocks, or clepsydras, were quite common two thousand years ago but generally they were very simple and not very accurate. Essentially they consisted in an upper water tank that filled a lower one through a regulated water flow; in the lower tank some marks indicated the hours. The oldest example of such a water clock dates 1417–1379 B.C. and was found in the Temple of Amen-Re at Karnak, Egypt. An oldest documentation of such a device was found in an inscription of the 16th century B.C. In an old Egyptian clepsydra the hours were read by the mark reached from the water level; the columns were twelve, one for each month.

In Babylon were built water clocks as old as the Egyptian ones but, although their existence is documented on clay tablets, none of them survived.

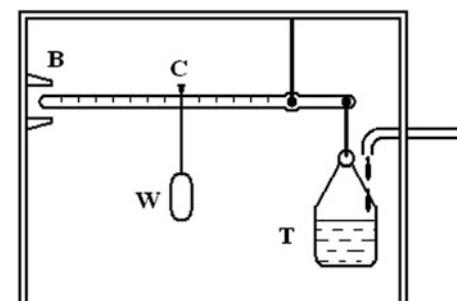
In India water clocks were built probably from the 2nd millennium B.C. An interesting example of an Indian water clock is at Nalanda, its working principle consists in a bowl having a little hole at its bottom that floats in a larger one containing water; the bowl sinks periodically and a mechanism linked to it beats a drum to mark the time. The working principle of this device is somehow similar to the one of the automaton “the elephant clock” by Al Jazari described in Chap. 16.

In China the oldest documents regarding water clocks are dated to the 6th century B.C. The working principle of many Chinese water clocks conceptually is similar to the one of the water clock made in other parts of the world as is based on the measuring of the water level in a tank that is filled by a constant water flow. The latter was obtained, in some devices, by a number of subsequent tanks. Another, more modern, type of water clock is conceptually different because the time is measured no longer by the water level but by its weight. In Fig. 4.7 a scheme of the working principle of this clock is reported.

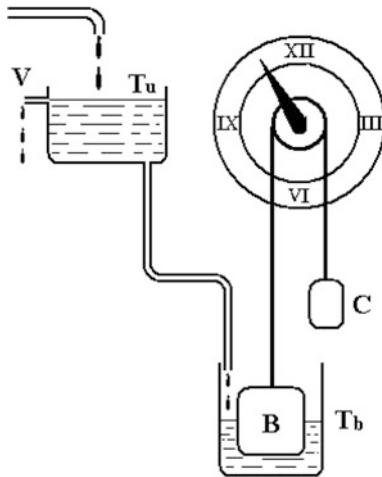
A tank T is filled by a constant water flow and its weight is measured by a stadera (see Chap. 2) moving the cursor C and the weight Q along the stadera’s arm. On a scale, marked on the latter, the time is visualized; the marks permitted to measure the time with different units of measure.

By the Romans most of water clocks used a float in a tank that was activated by the water flow; the float moved a pointer that indicated the time, as shown in Fig. 4.8. This type of water clocks was quite commonly used by the Roman

**Fig. 4.7** Working principle of a Chinese water clock



**Fig. 4.8** Working principle of a water clock



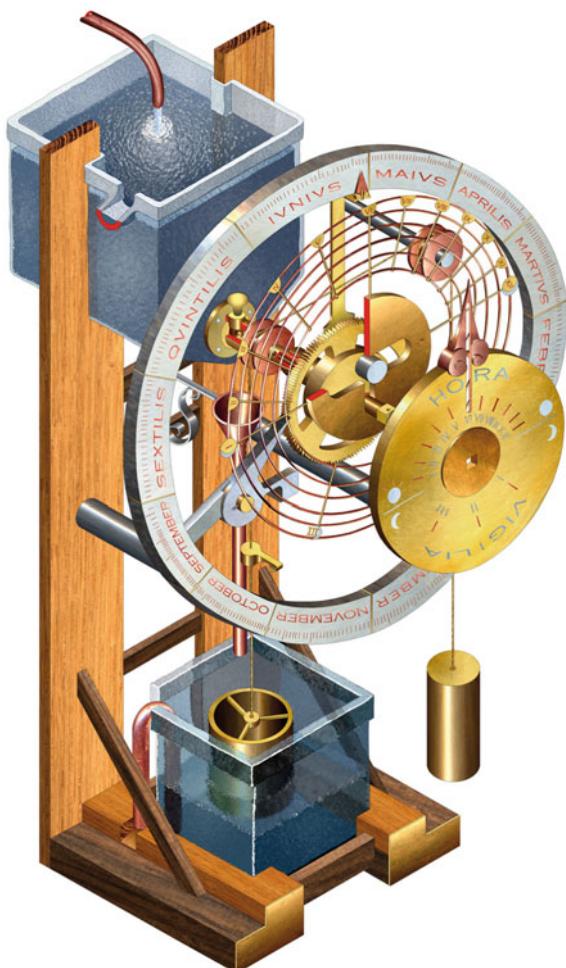
patriarchs. The working principle is very simple: a flow of water fills an upper tank  $T_u$  the level of which is constant since the surplus of water outflows through the vent  $V$ . From this tank, a constant flow of water fills the tank  $T_b$  at the bottom; in the latter is located a float  $B$ . A string is bound round a cylinder and one of its ends is tied to the float while the other end is tied to a counterweight. While the float goes up, the cylinder rotates and a pointer, linked to it, indicates the hour on a dial.

#### 4.2.2 *The Water Clock by Ctesibius*

As already described, in order to measure the time, there was another problem to solve. The length of a roman hour was not constant since it was defined as 1/12 of the time between sunrise and sunset during the day and 1/12 of the time between sunset and sunrise during the night. Thus, the time duration of one hour was different from day and night (except at the equinoxes) and from a given day to another one. The water clock that was designed by Ctesibius, solved this problem. A perspective reconstruction of it is shown in Fig. 4.9 on the basis of what was described by Vitruvius.

In the same way as the device clepsydra previously described, a bottom tank was filled by a constant water flow from a top tank that is continuously maintained full. A yarn was connected to the ball clock and to a counter weight and was wrapped in coil around the pointer axle. The bottom tank was drained daily and the cycle started again. The main parts of the mechanism are shown, in an orthogonal section, in Fig. 4.10.

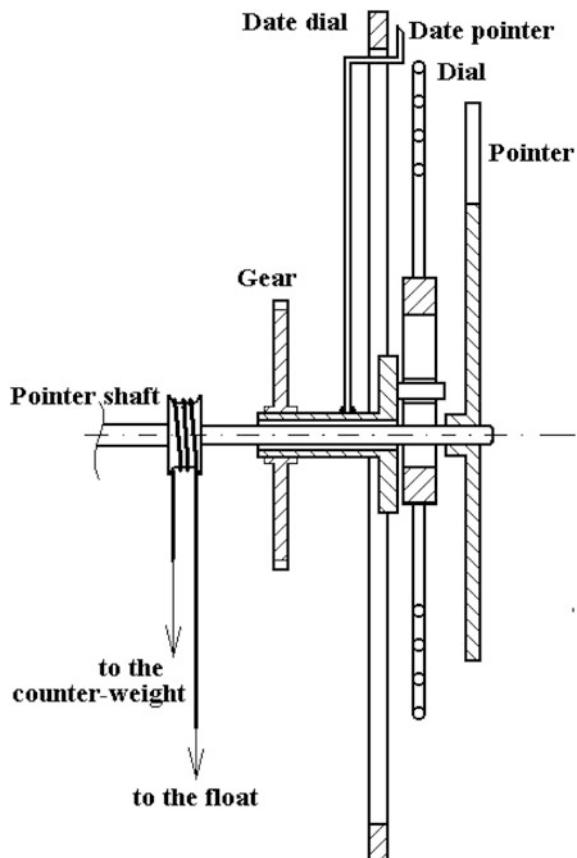
**Fig. 4.9** Virtual reconstruction of the water clock by Ctesibius



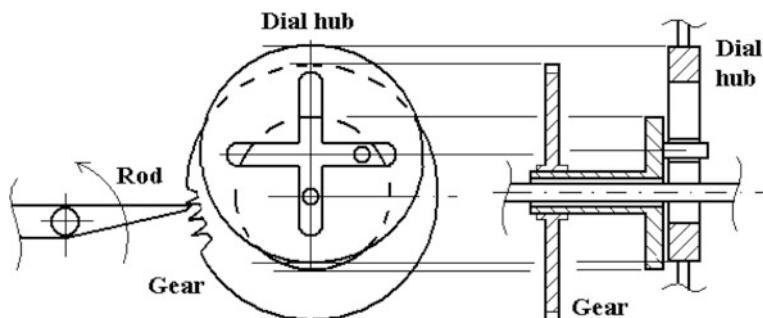
The problem of measuring hours of variable length was solved by Ctesibius by fitting the dial on a shaft that was off the centre of the pointer shaft and by moving the dial during the year. The mechanism is shown in Fig. 4.10 and in Fig. 4.11.

Any time the float passes through a certain position (once a day), it moves a rod that pushes one tooth of a gear. This last gear has 365 teeth, so it made a revolution in one year, and was fitted on a hollow shaft coaxial to the pointer shaft and connected to a rod, as shown in Fig. 4.11.

The dial was mounted on a hub having two orthogonal slots. Through the vertical slot passed the pointer shaft and in the horizontal one a crank was located and connected to the gear shaft. While the crank rotates, the dial could move just



**Fig. 4.10** Kinematic scheme of the clock by Ctesibius



**Fig. 4.11** Scheme of the mechanism for the dial motion

along the vertical direction. In this way, the dial centre moves with respect to the pointer axis from the higher position to the lower position to the higher again, once in a year. The 365 teeth gear moved also another pointer to indicate the day of the year.

### Observations

During the Middle Ages the art of clock manufacturing was continued by Muslim inventors; among them the most famous are Al-Jazari who made the elephant clock that is reported in Chap. 16 since it is mainly an automaton and Taqi al Din, that has will be widely mentioned in the Chap. 8 for his six cylinder water pump. Taqi al Din in his book “The Brightest Star for the Construction of Mechanical Clocks” describes four main types of time keeping devices known in the 16th century.

# Chapter 5

## Orientation

**Abstract** In this chapter the ancient device to find the orientation are presented. The oldest one was the sundial compass. Despite it was the oldest type of compass, it was still used during the II WW and on the Mars Exploration Rovers. Then the famous Chinese South pointing Charriot is shown and finally the first examples of the magnetic compass.

### Introduction

The ability to find one's bearings and thus the invention of suitable instruments for this purpose has certainly played a very important role in the history of progress. It is not possible to consider any type of exchange between societies that may be relatively distant one from the other without an instrument to assist in finding the right direction. This section discusses the first examples of the instruments invented to determine (and maintain) the direction of a voyage.

### 5.1 The Sundial Compass

In June 1931, Major Ralph Bagnold, British Army, carried out a patrol together with several friends using three Model T Ford light patrol lorries in the desert of Libya, searching for the legendary oasis of Zerzura. He traveled over 200 miles east of the Nile and in order to know which direction to follow over that wide-ranging plain of sand, having no points of reference as they could not use a magnetic compass since the needle would be deviated by the iron on the vehicles, they used a sort of compass that Bagnold had rediscovered and that worked by using the shade caused by the sun.

How such a Pelasgic or solar compass worked is simple: as an initial approximation it is a meridian with a vertical gnomon and a horizontal dial that when static marks the passage of time according to the varying direction of the shadow, while in mobile status it indicates north, making appropriate adjustments. To be more specific, in the northern hemisphere at exactly at 12 o'clock the shortest shadow of the day indicates the geographic north, thus by observing the progressive



**Fig. 5.1** Authors' reconstruction of the sundial of Qumran

contraction by the circles concentric to the gnomon, one can easily determine the minimum value and thus the north direction. This instrument, known since antiquity, consisted of a sort of bowl with a series of concentric circles engraved within, in the center of which was inserted a reed of the type used for writing, called “calamus”, that acted as a gnomon. By pouring red wine inside the bowl up to the level of one of the circles they were able to determine the horizontal direction, which was indispensable to confirm the reliability of the indication. In Fig. 5.1 an authors' reconstruction of a sundial based on the model found in Qumran is shown.

An implicit testimony of its use comes to us from Pliny the Elder, N.H. 167: “From Pelusium (a city in ancient Egypt about 30 km south east of what is now Port Said, ed. note) one can find the right direction only by using the solidly inserted calami, as the wind rapidly erases any trace”. The calami were not ancient black and yellow delineators used to mark roads when they are covered by snow, but were the reeds used in sundial compasses, one of which was inserted in the central hole of the specimen found in 1954 in a cavern in Qumran, Palestine. This was a bowl measuring 4.5 cm in diameter, with several concentric circles etched within and with approximate gradations. Even with such a crude instrument it was easy to determine noon and north and, by maintaining the indication, for the rest of the day as the successive notches progressively coincided with the shadow. The

advent of the magnetic compass replaced the solar one, especially since the majority of ships almost up to the past century were all made of wood.

With the outbreak of the Second World War Bagnold was once again called to active service, with the rank of colonel, and because of his experience he was permitted to form small units for long range desert patrols, and provided with jeeps equipped with automatic weapons, powerful radios and solar compasses installed on the dashboard. When the war ended, the senior officer was retired, as was his compass, by now obsolete thanks to the omnipresent electronic ones. In 1977 however as part of the preliminaries for the indirect exploration of Mars, NASA invited Prof. Bagnold, by now an instructor at the Imperial College of London and an authority on moving vehicles in arid and sandy deserts, to recommend effective orientation devices.

By a strange coincidence a Martian day has almost the same duration as an earth day and both planets have a similar angle of axis: consequently, latitudes and season being equal, one of our meridians would be moderately precise and ideal as a compass since the red planet had no appreciable magnetic field, was much more robust than a gyroscope and required no power. And so the solar compass, after 25 centuries of being used in desert sands, made its debut on the sands of Mars. Installed astern of the rovers to facilitate the work of the on board cameras, it provided crucial information without consuming even 1 kWh during the many years it was in operation, providing bearings as well as the solar hour: never as in this case can we justly say that there is nothing new under the sun!

## 5.2 The Chinese South-Pointing Chariot

Knowledge of China and its culture was brought to the West by the Jesuits, who had been establishing missions there since 1582. Until that time, whatever was known of the celestial empire came from the tales of Marco Polo and the testimony of merchants who traveled to that distant land to acquire silk. The Jesuits' missionary work began a few years later in India, Japan, China, the Americas and Africa, always with one specific guiding principle: mastery of the local language and respect for local traditions. In China these cornerstone were personified in the person of Father Matteo Ricci (1522–1610), mathematician, cartographer and explorer, reputed to be the true spirit of the Jesuit mission between 1582 and 1610, the year of his death in Beijing. He undertook a dual cultural promotion, disseminating Western knowledge and culture in China and Chinese knowledge and culture in the West, an example soon imitated by many of his colleagues who began a veritable osmotic process that was limited only by their own basic notions.

One example of such an interpretative relativism is found in the “south-pointing chariot” that the clerics knowledgeable of magnetism and the compass interpreted as an archaic magnetic device. An ancient magnetic compass that, in place of the needle, indicated direction by the outstretched arm of a statuette: an interpretative aberration that since then, and in spite of its obvious absurdity, dominates treatises on the history of technology, the compass and topography.

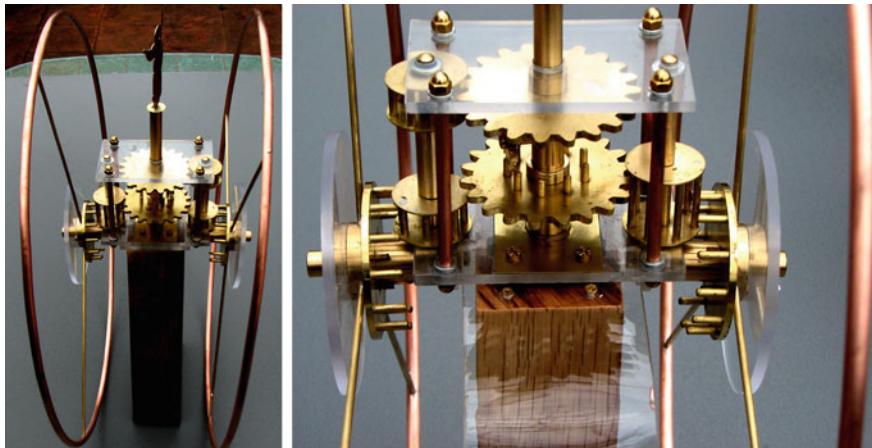
In simple terms the device was a small cart surmounted by a statuette whose outstretched arm indicated the correct direction. Each time the cart turned so did the statuette, but in the opposite direction, thus the arm always indicated the same cardinal point. The logical conclusion of the clerics who had seen this device in operation was that it was similar to a compass: the arm contained a magnetized rod that caused it to rotate by orienting itself according to the terrestrial magnetic field! The little cart became a magnetic chariot and its guiding principle a remote and heretofore unknown premise of the Amalfi compass.

There are numerous mentions of this singular chariot in Chinese historical texts, the most ancient of which is attributed to Huang-ti, the semi-legendary Yellow Emperor, who is thought to have lived around 2600 B.C. By logical consequence this was the same date assigned to the invention of the magnetic compass, rudimentary and embryonic as it may be. Other mentions of the chariot, by now magnetic by definition, are found through the centuries: we find it in writings concerning Cheng Wang (the second emperor of the Chou dynasty), around 1100 B.C. and later in the works of the philosopher Han Fei Tsi (who lived around the 3rd century B.C.) in which it was finally given the name Sse-nan.

Without continuing with the list, we will simply say that western scholars continued to define these chariots as “magnetic”, though there is nothing in Chinese sources to justify it. Magnetic chariot is also the name used by Father Tumoteo Bertelli (1826–1805) in 1893, in his *Studi intorno alla bussola nautica*, citing the name Sse-nan or Isinar (indicator of the South). Ultimately, however, and oddly so, the Chinese did not make the simple jump from rotating statuette to rotating needle, a refinement that is unexplainable as far as many western scholars are concerned, but obvious because magnetism had nothing to do with it! It is therefore inevitable to wonder: what did move the arm of the statuette to indicate south? The rotation of the arm, and this is proven by the many reconstructions of the device, was mechanically activated and was caused by an ancient differential gear, a train of interconnected gear wheels, forming a device similar to the one we see today between the driving wheels of vehicles, the mechanism that transfers the excessive revolutions of the interior wheel as it turns, describing a smaller trajectory, to the exterior wheel that requires them, as it has a larger trajectory.

In Fig. 5.2 a working reconstruction of the south-pointing chariot, by the authors, is shown.

In our case, the differential gear was activated by two opposing wheels located on the same axle of the cart, both of equal diameter and that rotated independently one from the other. Joined to these were two identical pinwheels, both connected to another two smaller ones, of equal size and horizontal. These rotated two symmetrical crown wheels, horizontal and neutral, on the same pin. Among the crown wheels were one or more planet wheels, also in neutral, above a support or brace attached to the same pin, with the statuette on the top. When the cart proceeded straight forward, the two crown wheels, turning at an equal angular speed in the opposite direction, rotated the crown wheels, which however only turned around their own axis, leaving the vertical hinge and related statuette in a fixed position. However, when the cart turned, they provided a different angular speed to the crown



**Fig. 5.2** Authors' working reconstruction of the south-pointing chariot

wheels, thus causing both the crown wheels and their support to rotate. This, together with the statuette, made an angle equal to the angle of the turn, but in the opposite sense, thus the extended arm did not change direction.

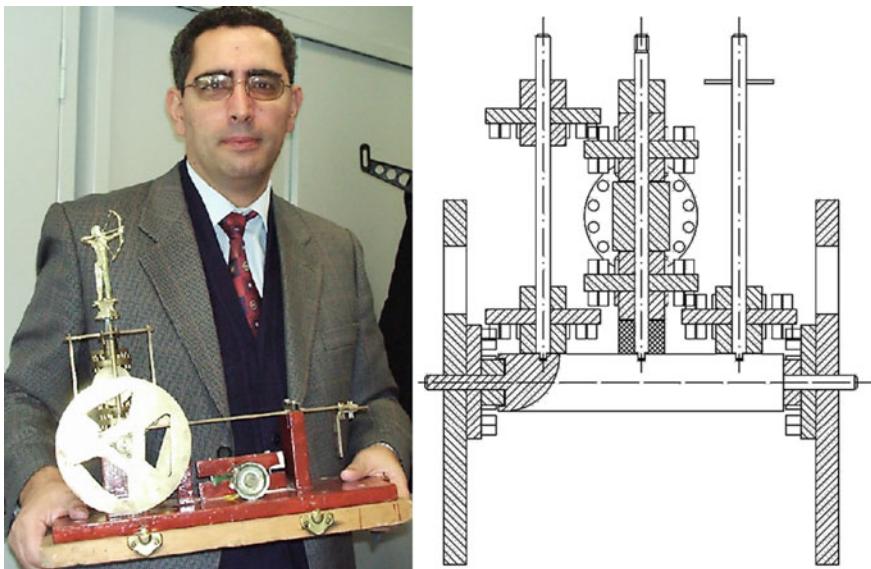
Such a device certainly was not very precise, and it functioned best only if there was no drag on the wheels and the road was level. In reality there was very little swerving and since in a day's March a cart could travel about 20 km, any deviation in the flat Gobi desert was negligible, and was compensated every morning at dawn and every noon when its minimum shadow indicated North.

In Fig. 5.3 a working reconstruction of the south-pointing chariot, and a technical drawing by Prof. Ing. Ettore Pennestri, is shown

### 5.3 The Windrose and the Magnetic Compass

The ancients navigated by cabotage, without losing sight of land, something that was fairly simple in the Mediterranean as it had a wide longitudinal basin and narrow latitude, but in order to avoid interminable journeys they also followed direct routes from North Africa to Sicily, Calabria or Sardinia, perhaps as early as the II millennium B.C. During those travels no land was in sight for one or two days, and the direction followed depended on astronomical observations by day and night and most probably a simple but effective instrument for orientation: a small rod inserted into a table. Placed on the water of a washbasin, that subdued the rolling of the ship making it horizontal, as the sun rose it highlighted the contraction of the shadow that, upon reaching the minimum level, indicated south and north.

The Romans were familiar with this instrument and did not change its Greek name *pinax*, literally "small square". This led to the table with an engraved eight



**Fig. 5.3** Working reconstruction and drawing of south pointing chariot, courtesy of Prof. Ing. Ettore Pennestri, University Tor Vergata, Rome, Italy

point star, one for each wind, like the Wind Tower of Athens that, according to sources, was painted on the deck of Roman war ships and had a rudimentary two-sight alidade, indicating north as well as local south.

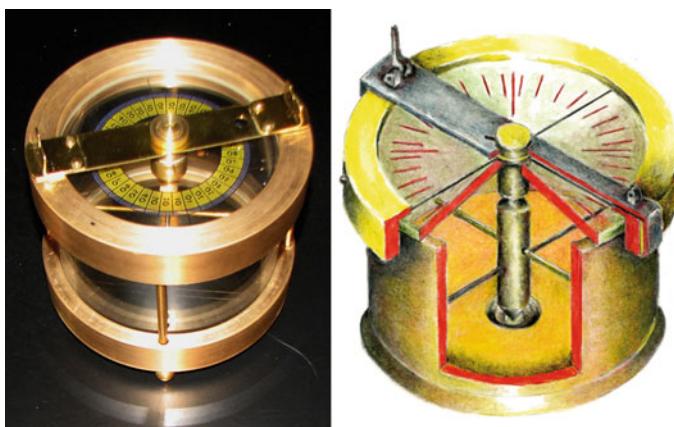
Like most inventions the compass too, as we know it, did not suddenly appear but was the result of an extensive evolution whose origins date to the Hellenic Era. The compass is an instrument that fulfills a basic nautical need: indicating a precise direction by using an invisible point of reference, thus one that was effective even with cloudy skies or in the thickest of fogs. The guiding principle that is basis for the compass par excellence, is the magnetic feature that tradition attributes to Flavio Gioia of Amalfi.

The first references to an actual magnetic compass are found in 1269 during the Angevin siege of Lucera, where the last of the Saracens faithful to the Swabians were trapped. On that occasion French engineer Petrus Peregrinus de Marincourt was convened, bringing a curious instrument, the buxidia or pixidis nautica, which he described as follows: “take a vessel of wood or brass or other material, circular in shape, moderate in size, shallow but of sufficient width, with a cover of some transparent substance, such as glass or crystal; it would be better still to have both the vessel and the cover transparent. At the center of this vessel fasten a thin axis of brass or silver, having its extremities in the cover above and the vessel below; In the middle of this axis let there be two apertures at right angles to each other, through one of which passes an iron stylus or needle, through the other a silver or brass needle crossing the iron one at right angles.”

This is a rudimentary dry magnetic compass that followed the wet one he had previously described in these words: «It is well known to all who have made the experiments that when an elongated piece of iron has touched a lodestone and is then fastened to a straw, one end will turn toward the star which has been called the Sailor's star because it is near the pole; but the truth is that it does not point to the star but to the pole». Thus around the middle of the 13th century, there was a magnetic compass with a rotating needle in a casing, but that was not effective for navigation because of the motion of the sea. And this is where the Republic of Amalfi comes in, with Flavio Gioia. But, as demonstrated by various scholars of certain competence, that name is the result of an error that confused a reference to the invention of the compass by the humanist Flavio for the supposed inventor Flavio (Gioia). In Fig. 5.4 a reconstruction of the compass and an image of same, both by the authors are shown.

A certain Giovanni Gioia from Ravello or Positano, however seems to have actually played a role in the matter, perfecting the *pixidis nautica* before 1300 and perhaps even before 1269. Since his family was thought to have come from Puglia, it may be that he improved the instrument described by Petrus Peregrinis, in Amalfi. In effect, he placed a paper disc with the effigy of an eight-point windrose on the magnetic needle, a windrose not coincidentally similar to the Amalfi cross and later the Maltese cross. The principal eight winds of the Mediterranean, listed in a clockwise direction, are given in Table 5.1.

It may be interesting to point out that some of the names of the winds derive from the direction they take in respect of the Ionian Sea, that is from the center of the Mediterranean Sea. Thus, considering that area of the Mediterranean, the Libeccio comes from Libya, the Scirocco from Syria, the Grecale from Greece and the Tramontane from the mountains regions of the north.



**Fig. 5.4** Reconstruction of the compass and an image of same, both by the authors

**Table 5.1** Main winds and directions

North	$0^\circ$	Tramontana
North–East	$45^\circ$	Grecale
East	$90^\circ$	Levante
South–East	$135^\circ$	Scirocco
South	$180^\circ$	Ostro o Austro
South–West	$225^\circ$	Libeccio
West	$270^\circ$	Ponente
North–West	$315^\circ$	Maestro o Maestrale



**Fig. 5.5** Reconstruction of a suspended compass with chain (*right*) and image of exploded view of the compass, both by the authors

Figure 5.5 shows a reconstruction of the compass with “thurible” suspension, that is suspended with a chain that acts as a rudimentary cardanic support and an exploded view of the compass, both by the authors.



**Fig. 5.6** Windrose of the compass reconstructed by the authors

It is certain that only a windrose compass could have aided in tracing nautical maps, whose first example dates to 1296, and that some consider to be a copy of an original from 1250, the *compasso de navigare*, while mentions of such maps date them to the first half of that century. As for the windrose, it may be considered a diagram upon which are the directions of the origins of the eight winds characteristic of the Mediterranean, each indicating a primary or secondary cardinal point. Figure 5.6 shows a detail of the compass reconstructed by the authors in which the windrose is clearly visible.

# Chapter 6

## Ancient Computation Devices

**Abstract** In this chapter some ancient computational devices are presented. Among the latter, particularly interesting are the Greek devices to compute the cubic roots. Some reconstructions of the famous Mechanism of Antikitera is also presented. Finally, a technique to compute the multiplication using the Greek and Roman notation for the numbers is shown.

### Introduction

In the previous chapters the most important devices for environment measuring have been reported. A measure has no sense if no computation devices are available. For this reason in the present chapter the main ancient computation devices are reported.

What we call today “computing machines” were invented and developed after the 16th century but, as is exposed in the following paragraphs, older devices are, without any doubt, the precursors in the computation. Some of them show a surprising skill and modernity of their ancient inventors.

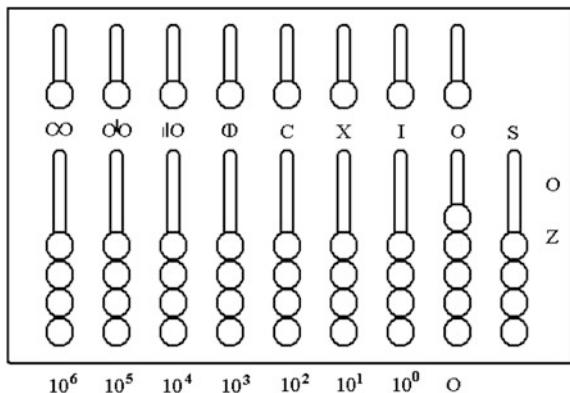
### 6.1 The Abacus

The abacus is the oldest computation device and is found at almost any population in every part of the planet. Incidentally, the authors have observed that it was still used in the sixties of the last century in the shops in Russia. The word abacus comes from the ancient greek  $\alpha\beta\alpha\xi$  (=tablet), possibly derived from the Hebraic  $abaq$  (=sand) as thousands of years ago tablets spread with sand were used to write.

The pre-Columbian civilizations (Incas talking knots) and many others, all over the world, used and still use yarns and knots to count. These devices can not be considered as abaci or computing tools but, more properly, as data stores.

The oldest surviving example of an arithmetic device is the salamis tablet, used by the Babylonians circa 300 B.C., discovered in 1846 on the island of Salamis and at the present at the National Museum of Epigraphy, Athens. It is a marble slab approximatively 1490 mm in length, 750 mm in width and 45 mm thick, with 5 groups of markings.

**Fig. 6.1** Layout of a Roman hand abacus



The oldest example of a “hand computer” is the Roman hand abacus, a specimen of which is at the Museo Nazionale Romano. It is made of a bronze plate approximatively  $115 \times 90$  mm with nine long slots and eight short slots. A layout of it is shown in Fig. 6.1.

In each of the slots are located some buttons that can slide in the slot itself. All the long slots (in the lower part of the Figure) have four buttons except for the second from right that has five buttons. The short slots (in the upper part of the Figure) have only one button that indicates the number five. Each of the buttons in the first seven slots starting from the left has a numeric meaning reported below in the Figure; the eighth slot indicates the ounces and the ninth slot indicates a fraction of ounces: half (S semis), a quarter ( $\square$  silicus) and  $1/12$  (Z sextula).

Other Roman abaci were made by boards with grooves in which some little stones were placed; in Latin the term “calculus” means little stone from the word calculus, calculations etc. derive.

The Chinese abacus (swanpan) is similar and quite as old as the roman one. It is composed by twenty bamboo sticks (ten in the upper part and ten in the lower) and the buttons are generally made of ivory. Each of the upper sticks have two buttons and each of the lower two.

The Japanese abacus is similar to the Chinese one but has just one button in the upper sticks.

The abacus permits to compute additions and subtractions easily, with a little training also multiplications and even divisions.

During the Middle Ages many mathematicians investigated on the possibilities given from the abacus; among them we can mention Gerberto d'Aurillac (950–1003 A.D., who became Pope Silvestro II) and the “*Liber abaci*” by Leonardo Pisano (1180–1250 ca), better known as “Fibonacci” because he was the son of Bonacci.

## 6.2 The Mesolabio

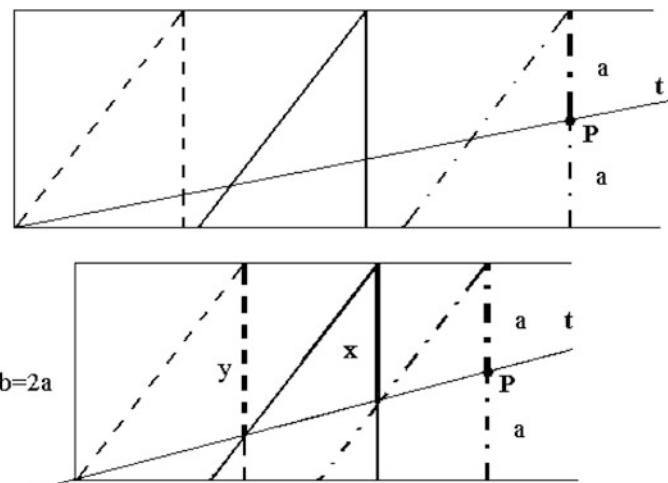
This device is also known as the problem of doubling the cube or the problem of Delos. The word “mesolabio” comes from the ancient Greek μεσος = middle and λαμβανω = to take. In fact, the mesolabio makes it possible to compute two mean proportional segments between two given segments.

Some ancient Greek mathematicians proposed a solution of this problem; in the following paragraphs those solutions that were used to build devices are presented.

### 6.2.1 The Mesolabio of Eratosthenes

As the story goes, at the isle of Delos a pestilence broke out. The oracle said that the god Apollo ordered a marble altar that had to be the double of the existing one. The inhabitants of Delos suddenly made an altar whose dimensions were doubled, obtaining in this way an altar the volume of which was eight times that of the previous one. Hence the pestilence was not over. The problem was solved by Eratosthenes who invented the Mesolabius.

This device is shown in Fig. 6.2. It is made up of three identical tablets, having the shape of a parallelogram, that can run along two parallel guiding rulers; on each of the tablet is drawn a right triangle. A twine  $t$  was tightened between an edge of the first tablet and a point  $P$  of the external side of the third tablet, as shown in the Figure. The tablets were moved till the hypotenuse of the second triangle intersects



**Fig. 6.2** The mesolabio from Heratosthenes

the cathetus of the first triangle in the point where the string intersects the same cathetus; the same was made moving the third triangle. Now it is:

$$\frac{a}{x} = \frac{x}{y} = \frac{y}{b} \quad (6.1)$$

from the previous equations, three couples of equations can be written; let us consider the followings:

$$\begin{cases} x^2 = a \cdot y \\ x \cdot y = a \cdot b \Rightarrow y = \frac{ab}{x} \end{cases} \quad (6.2)$$

If point P is set in the middle of the cathetus of the third triangle, it is:

$$b = 2a \quad (6.3)$$

hence, from the second of Eqs. (6.2) comes:

$$y = \frac{2}{x} a^2 \quad (6.4)$$

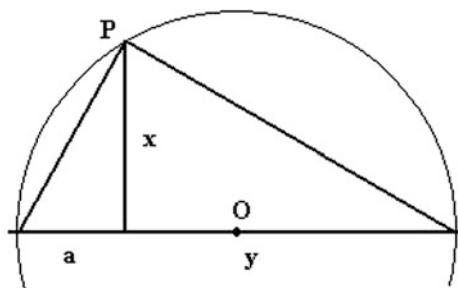
and, by substituting in the first of Eqs. (6.2):

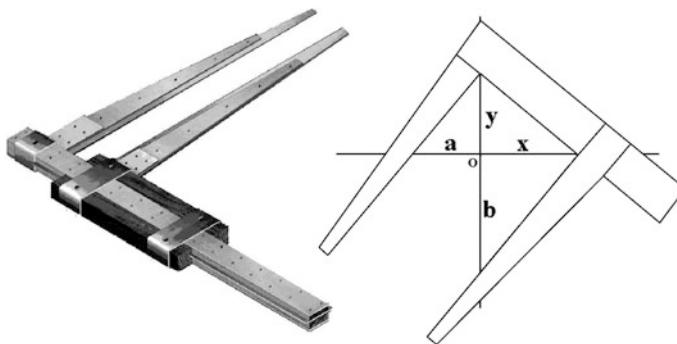
$$x^3 = 2 \cdot a^3 \quad (6.5)$$

### 6.2.2 *The Solution by Hippocrates and the Mesolabio by Dürer*

The solution by Hippocrates is based on Euclid's theorem that is: if in a right-angled triangle a perpendicular is drawn from the right angle to the base, then the triangles adjoining the perpendicular are similar both to the whole and to one another. In Fig. 6.3 is shown a right angled triangle the hypotenuse of which is the diameter of a circumference; if point P moves along the circumference it always is:

**Fig. 6.3** Visualization of Euclid's theorem





**Fig. 6.4** The mesolabio by Dürer

$$\frac{a}{x} = \frac{x}{y} \quad (6.6)$$

In Fig. 6.4 is shown a reconstruction of the mesolabio built by Albrecht Dürer (*Underweysung der Messung*, Nurnberg 1525). The left of the Figure shows the working principle: a couple of orthogonal lines was drawn, the device was fitted as shown and the lengths of the segments were measured. By moving the sliding rule it was possible to change the segments' length, while the relations among them did not change. Further details on the working principle are given in the observations.

This device, like the one by Eratosthenes, makes it possible to compute two mean proportionals between two given segments, but it is based on the solution by Hippocrates of Chios, a disciple of Pythagoras.

The mesolabio was used in the Reanissance also to divide in two equal parts any musical interval.

Both devices were described by Vitruvius (Vitruvio Pollio—"De Architectura, IX liber). The treatise by Vitruvius was also translated by Daniele Barbaro (Venezia 1513–1570) in his "*Dieci libri dell'architettura*", 1556; the page where both devices are described is reported in Fig. 6.5.

### 6.3 The Mechanism of Antikitera

This mechanism is considered as the progenitor of modern computers and has been deeply studied by a number of scientists in the last decades.

Some people assume that this is an out of place artifact but it is not: the Mechanism of Antikitera is a very brilliant work of its era; together with other devices presented in this book, it shows, once again, that 20 centuries ago the knowledge was much more advanced than one can commonly suppose.

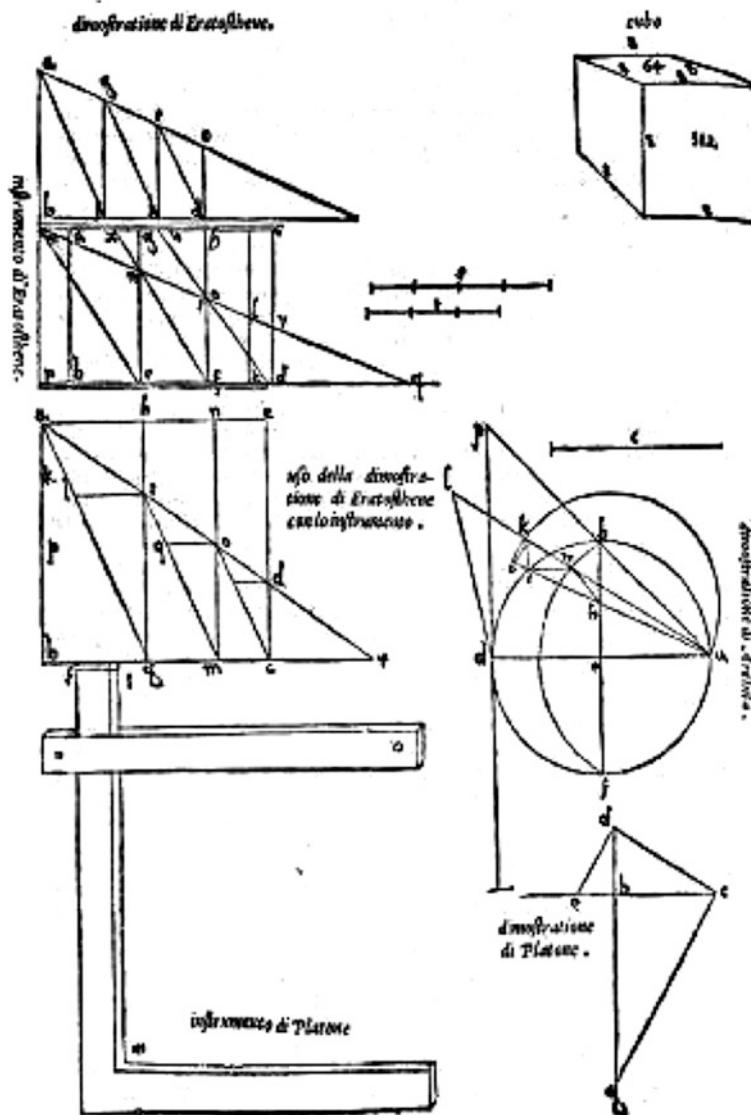


Fig. 6.5 Mesolabia, from D. Barbaro's translation of Vitruvius' treatise

### 6.3.1 The History of the Finding

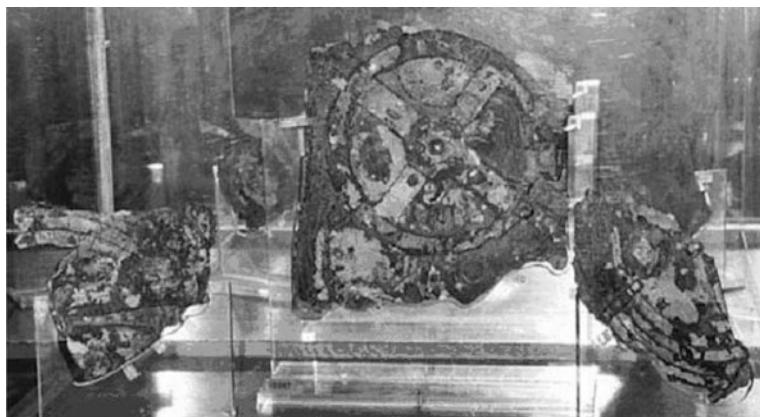
First of all it is useful to remember where, when and how the mechanism was found. These circumstances are reported in the first paper from Professor Derek de Solla Price (1922–1983), Professor of History of Science at Yale who was the first who had deeply studied the mechanism.

A few days before Easter 1990 a group of sponge-fishers from Rhodes coming back from the Tunisian coasts, stopped at the little isle of Antikytera that is in the channel between Kythera and Crete that links the Mediterranean sea with the Aegean. This channel has been sailed for thousands of years by vessels and is also ill famed because of many shipwrecks. The spongefisher's cutter dropped anchor near a little bay called Port Potamo (lat.  $35^{\circ}52'30''N$ , long.  $23^{\circ}10'35''E$ ) where Elias Stadiatis, 42 m deep, found a large ship lay wrecked on the sea bed. In the ship, among amphora and other finds, he found something that seemed like a piece of bronze partially covered by calcareous incrustations.

It is estimated that the ship sunk between 80 and 60 B.C. and was a Roman or Greek cargo for Rome that was carrying more than 100 statues similar to the ones the Romans brought to Italy after they had conquered Greece.

Later the find was brought to the Athens' Museum where it was not deeply studied before 1928, when the Greek admiral Jean Theophanidis mentioned the find in some articles. Theophanidis describes some visible gears in the mechanism and proposed a reconstruction with stereographic projection suggesting that the device was an astrolabe. In Fig. 6.6 is reported a picture of the find at the Athens' National Archaeological Museum.

In 1951 professor Derek De Solla Price, with the cooperation of the director of the Athens' National Archaeological Museum, Christos Karouzos, started a deep investigation on the mechanism. During his studies De Solla Price was also helped by several other scientists for the radiographic and chemical analyses. In the following years other researchers among which Allan George Bromley, Michael Wright and the ones who participate to Antikytera Mechanism Research Project that has recently been constituted continued the investigations on the mechanism discovering new possibilities in the interpreting and reconstruction of the mechanism. Among the scientists that presently investigate on the mechanism Giovanni Pastore must be mentioned; he wrote an entire chapter of his book on the slide rulers to the Antikytera mechanism.



**Fig. 6.6** The find (Athens' National Archaeological Museum)

### 6.3.2 Description of the Mechanism

According to the reconstruction by De Solla Price, the mechanism was constituted by a number of gears that were contained in a wooden box the dimensions of which were about  $30 \times 15 \times 7.5$  cm. Outside the box was located a crank handle that was used to give the motion. In Fig. 6.7, on the left, a working model of the mechanism made by John Gleavè, based on the studies by De Solla Price is reported; on the right of the same Figure, is reported a possible pictorial reconstruction of the device with the wooden box, hypothesized by the authors.

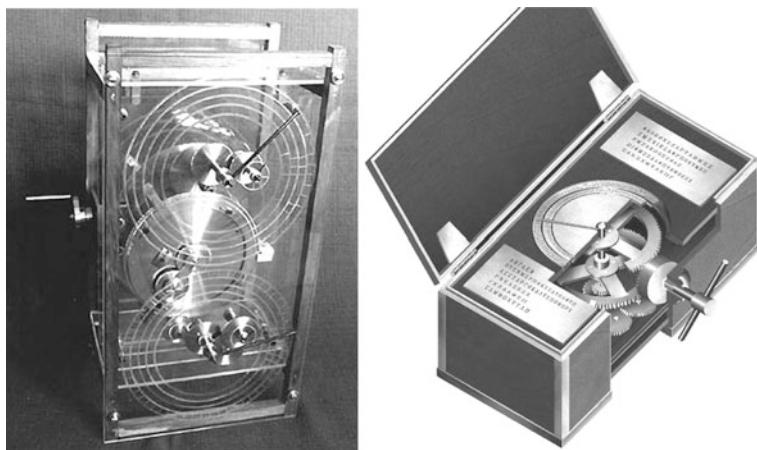
The wooden box was the frame and had three circular dials: one on the front panel and two on the rear panel. The shape of the Greek letters suggest that it was constructed around 150–100 B.C. In Fig. 6.8 the reconstructions of the three dials are reported.

The only dial that is clearly understandable is the one located on the front panel. The reconstruction of it is based on a fragment as big as about one fourth of the entire circle; on it there is a circular scale about  $45^\circ$  wide. This dial contains two annuli as shown in Fig. 6.9. On the external the months are reported while on the inner the constellations of the zodiac.

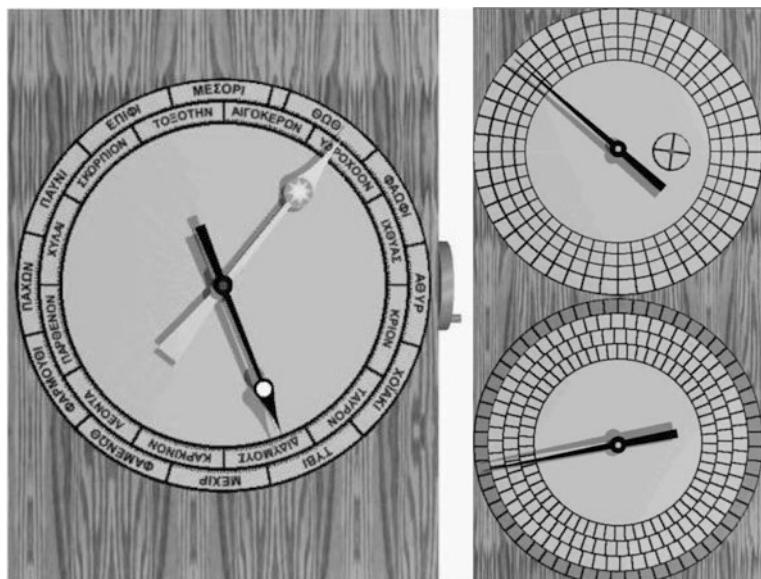
The marks are not precisely spaced: the mean error is about  $1/3^\circ$ . The front dial clearly shows the motions of the sun and of the moon respect to the constellations of the zodiac; it also shows the rise and the set of stars and important constellations.

The other two dials on the back are more complex but less intelligible as they are very corroded. These dials possibly showed the moon and the other planets that were known at that age. One of these dials on the back shows the Synodic month that is the length of time (29, 53 days) of the moon orbit around the earth, observed from the earth. The other dial is not intelligible.

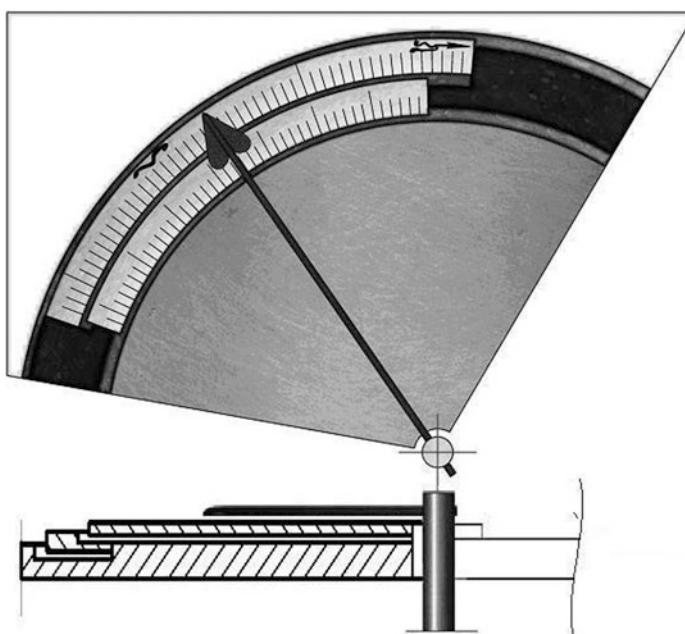
In Fig. 6.10 is shown the scheme of the gear trains by De Solla Price.



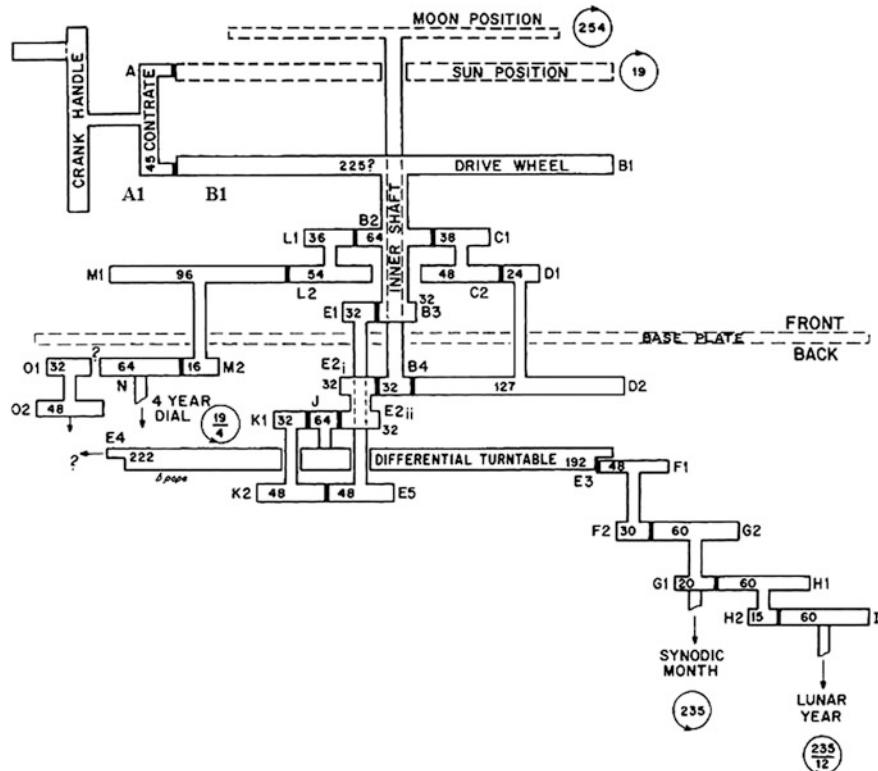
**Fig. 6.7** Reconstructions of the mechanism of Antikytera



**Fig. 6.8** Reconstruction of the dials



**Fig. 6.9** Front dial, detail



**Fig. 6.10** Scheme of the gear trains by De Solla Price

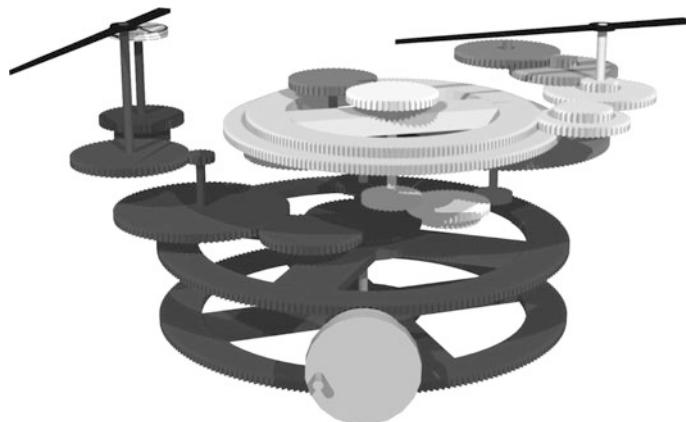
The motion is given by the crank handle on which shaft is fitted a first wheel A1 having 45 teeth. This wheel gears with the wheel B1 that has 225 teeth; the latter gives the motion to all the other gears and shafts. As  $225/45 = 5$ , it takes five crank turns for one turn of wheel B1; consequently to one turn of the crank should have corresponded 73 days.

De Solla Price has recognized 27 wheels; the main part of the gear train is constituted by about 20 wheels that represent an epicyclic gear train. One of the main functions is to make the fixed ratio 254/19 that represents the ratio of sidereal motion of the moon respect to the sun. The differential gear aim was also to show the lunations that were obtained by subtracting the motion of the sun to the sidereal motion of moon.

Another purpose of the mechanism was to show the Metonic cycle (235 synodic months  $\approx 19$  years) and the lunar year (12 synodic months).

In Fig. 6.11 is reported a frame from the animations of the mechanism by Dr. M. Roumeliotis, University of Macedonia.

After De Solla Price, many other scientists have studied the mechanism; among them we can mention Allan George Bromley (University of Sydney) and Frank



**Fig. 6.11** A frame of an animation of the mechanism

Percival, a clockmaker who collaborated with him, Michael Wright (London Science Museum) and Tony Freeth. These scientists used new radiographic techniques.

Wright made new proposals to interpret the working of the mechanism and its components. Among these interpretations, he suggested that the mechanism was a planetary, as already thought by De Solla Price, and also that it showed the motion of those planets (Mercury, Venus, Mars, Jupiter and Saturn) that were known in that age, in addition to the motion of the sun and the moon.

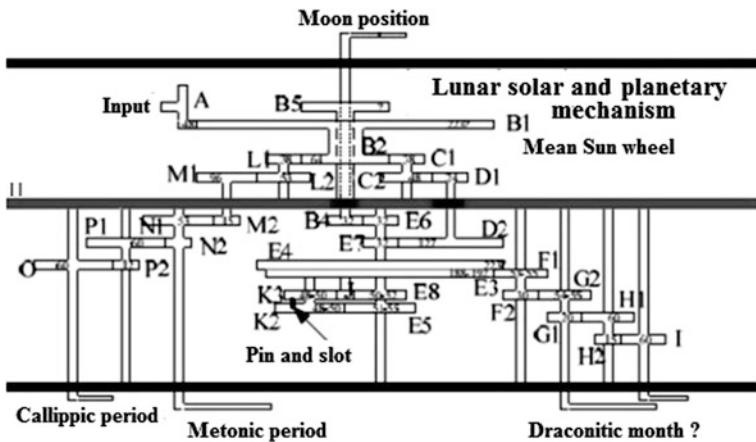
Wright also proposed that the motions of the moon and the sun were represented according to the theory of Hipparchus and the motion of the five planets as described by the simple theory of Apollonius' theorem.

The number of recognized gears rise to 31. In addition, Wright proposes also that the scale of the dials on the rear panel had 5 turns disposed on a coil with 47 marks per turn. In this way the angular indexing of each dial scale had 235 marks that represent the 235 synodic months of the Metonic cycle. One of the dials could have counted the Draconian months and could have been used to predict the eclipses. In Fig. 6.12 a scheme of the reconstruction proposed by Wright is reported.

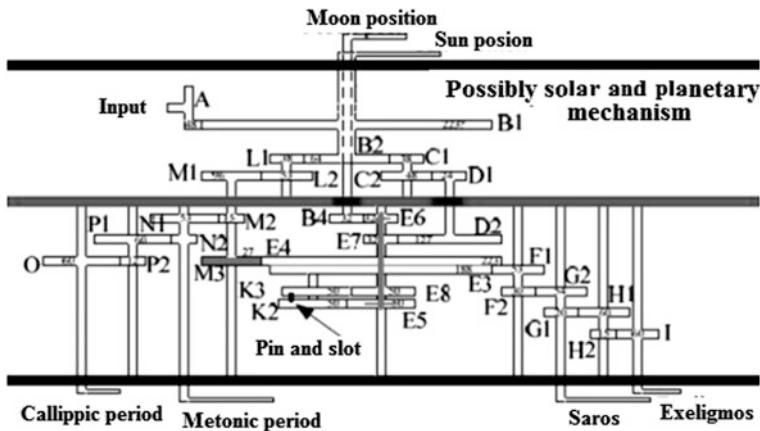
Presently the mechanism is being studied by the team of scientists of the “Antikytera Mechanism Research Project” that is composed by universities, museums, and private companies research centers, and has the financial support of the Greek National Bank.

The last research results confirm that the mechanism really was an astronomical computer or a planetarium that was used to predict the position of the celestial bodies; in addition, it is presumed that the gear wheels were 37 but only 30 have survived. It has been also supposed that on the back side of the box two more pointers that showed two more important astronomical cycles: the Callippic cycle and the Hipparchus cycle.

Dr. Tony Freeth and Dr. Mike Edmunds They observed that each of the rear quadrants was not composed of several separate rings, but by a single spiral. Their



**Fig. 6.12** Scheme of the gear trains proposed by Wright (Courtesy of Prof. Ettore Pennestri)



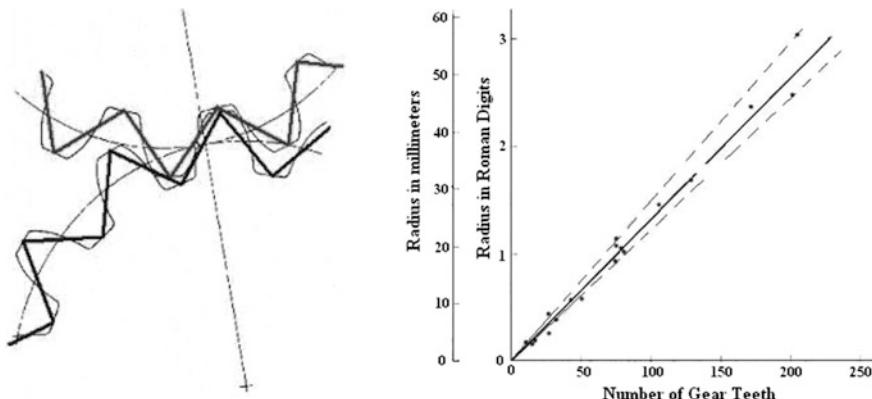
**Fig. 6.13** Scheme of the gear trains proposed by Freeth (Courtesy of Prof. Ettore Pennestri)

explanation is that the spiral in the lower rear quadrant showed a draconitic period of 4 months divided to 218 and a half days.

In Fig. 6.13 a scheme of the reconstruction proposed by Freeth is reported.

### 6.3.3 Technological Aspects

The main technological aspects regard the alloy used to make the gears and the other components of the mechanism and the shape of the gear teeth.



**Fig. 6.14** Teeth profile compared with modern involute (left) and diametral pitch of the wheels (right)

Cyril S. Smith (professor emeritus M.I.T) was asked by De Solla Price to make a spectrographic analysis of two samples from the find: one was an average sample of the miscellaneous debris, the other one was selected compact particles from the core of a sheet. The analysis results are reported in the De Solla Price reports. Professor Smith concludes that the material was a good quality bronze containing about 5 % tin, very small quantities of lead, arsenic and sodium and traces of other metals some of which probably adsorbed by salt water; no zinc was found. In conclusion, the alloy and the impurities were perfectly compatible with the technology of two thousand years ago.

The gear teeth are very simple and inaccurate. In Fig. 6.14 on the left are shown the teeth of the mechanism gears with a thick line and, for comparison, the teeth having an involute profile of the modern gears, with a thin line. The tooth profile is represented by a simple triangle; the working was possible just because the backlashes were very wide. On the right of Fig. 6.16 the number of gear teeth versus the wheel radius that was estimated by De Solla Price for some of the gears is reported.

Figure 6.14 shows that also the diametral pitch is quite inaccurate:

The solid line represents a diametral pitch equal to 0.50 mm, the dashed ones represent 0.45 and 0.53 mm respectively.

In conclusion, from a technological point of view, the Mechanism of Antikytera certainly represents one of the most brilliant pieces of the Hellenistic age but it is perfectly compatible with the technology of those centuries.

### 6.3.4 Planetariums in Ancient Literature

In ancient literature some examples of similar devices (planetaria) can be found.

Marcus Tullius Cicero in “De Republica” I, 14, writes about a planetarium that simulated the movements of sun, moon and the planets that were recognized in that

age. In the description, this device had been brought to Rome after the conquest of Syracuse and had been built by Archimedes who had improved a device by Thales of Miletus. Very interesting is the passage:

hoc autem sphaerae genus, in quo solis et lunae motus inessent et earum quinque stellarum quae errantes et quasi vagae nominarentur, in illa sphaera solida non potuisse finiri, atque in eo admirandum esse inventum Archimedi, quod excoigitasset quem ad modum in dissimillimis motibus inaequabiles et varios cursus servaret una conversio. hanc sphaeram Gallus cum moveret, fiebat ut soli luna totidem conversionibus in aere illo quot diebus in ipso caelo succederet, ex quo et in [caelo] sphaera solis fieret eadem illa defectio, et incideret luna tum in eam metam quae esset umbra terrae, cum sol e regione...

But a rotation of the sun, the moon and the five stars that are called roaming and quasi wanderer, Gallus explained to us, could never be reproduced in that solid globe hence in this (aspect) the invention by Archimedes is awesome: he founded the way to reproduce, with a single rotation, stars' motions that can not be equalized and their various runs. When Gallus moved this globe, the moon and the sun following each other every turn was observed in the same way it happens in the sky every day, hence in the [sky] the sun globe shows the same eclipse, and then the moon occupies that position that is the shadow of the Earth, when the sun is in line...

Unfortunately the following sheets of this paragraph of “De Republica” have been lost.

From Cicero's description we can deduce that:

- Similar devices were in Rome about 50 years after the shipwreck at Antikitera, and had been built in Syracuse (Sicily) before the Roman conquest of the town in 212 B.C.
- The one described by Cicero was made up by many wheels because: “stars’ motions that can not be equalized were reproduced with a single rotation”, hence a big number of kinematic chains should have been used.
- The invention and the development of such devices was attributed to Greek scientists.

Some other references to planetariums can be found but none is as wide as the one by Cicero.

## Observations

The devices presented in this chapter can suggest some observations.

As for the roman abacus, everybody knows that the Greek and the Roman notation consisted in using letters as Figures and that the value of each letter did not depend on the position. Using a decimal numeration, whereas, the figures' value depend on the position they have in the number. The Roman abacus demonstrates that, for computing purposes, the Romans used decimal numeration. Moreover, the ninth slot of the abacus shows that also fractions were used during computations.

It must be also observed that, by using Greek or Roman notations it was very difficult to obtain the product of two numbers. Suppose, for example, to compute:  $15 \times 31 = 465$ ; in Roman notation it becomes:  $XV \times XXXI = CCCCXLV$ .

The computing was carried out, using the abacus, by means of the procedure described in the followings.

A table having two columns is arranged. One of the number (no matter which one) is written at a top of the first column and then divided by 2; the integer (that is to say the remainder is neglected) is written under the previous number in the same column and then divided by two again and again until the value 1 is reached. Then the second number is written at the top of the second column and multiplied by 2 as many times as the first number was divided; these results were put in order in a second column.

Now consider the numbers of the second column: each of them must be summed, if the corresponding number on the first column is an odd number, otherwise is not considered.

In Table 6.1 an example for the multiplication  $33 \times 15 = 495$  is reported; in brackets the corresponding numbers in Arabic notation are written.

Now: in the second column the numbers 15 and 480 correspond to the odd numbers of the first column, hence must be added to obtain the result:  $480 + 15 = 495$ . Obviously the result does not change if 15 is chosen as the first number, the example is shown in Table 6.2. In this case to all the numbers in the second column correspond an odd number in the first column; hence they all must be added:  $33 + 66 + 132 + 264 = 495$ .

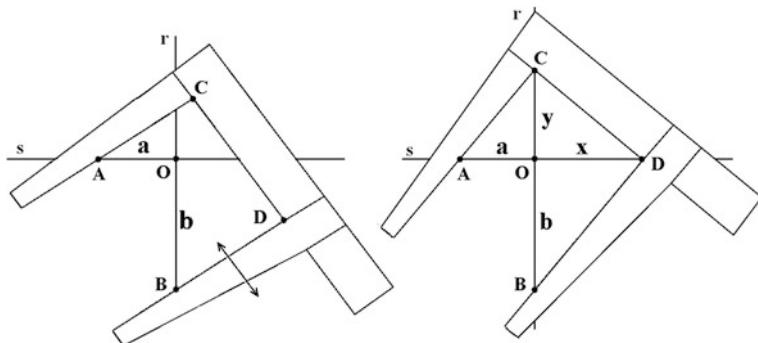
As for the mesolabio, it must be observed that the importance of this device is due to the modularity that in that age was adopted in the field of buildings. For instance, it is known that for temples the unit of measure was the base diameter of the column; to this dimension all the other dimensions were referred. The same was done also for mechanical devices: in these cases, each single part was dimensioned in scale to the corresponding part of a device that has been considered as the one that had given the best performances. In other terms, many ancient engineers generally thought that, once a very satisfactory prototype had been tuned up, to make another one, bigger or smaller, the same good performances would have obtained only if the dimensional ratios had been respected. Obviously this was a

**Table 6.1** Example of multiplication with Roman numbers

XXXIII (33)	XV (15)
XVI (16)	XXX (30)
VIII (8)	LX (60)
IV (4)	CXX (120)
II (2)	CCXL (240)
I (1)	CCCCLXXX (480)

**Table 6.2** Example of multiplication with Roman numbers

XV (15)	XXXIII (33)
VII (7)	LXVI (66)
III (3)	CXXXII (132)
I (1)	CCLXIV (264)



**Fig. 6.15** The working principle of the mesolabio by Hippocrates

mistake: for instance if a ball having doubled weight, at a same given distance, has to be thrown by a ballista, this does not mean that a ballista having all its dimensions doubled is required.

Really this aspect was known by some other ancient engineers: for instance, for 5 centuries, the dimensions of the main components of the ballistae (one of the most advanced device of those centuries) did not change significantly.

The possibility to compute the cubic root of a given number by using the mesolabio by Hippocrates (or by Dürer) is shown in the Fig. 6.15.

Suppose that the cubic root of a number  $R$  has to be computed. The first step consists in drawing two orthogonal straight lines  $r$  and  $s$ . Then, in a given scale, on the line  $s$  is fixed a point  $A$  at will. On the line  $r$  a point  $B$  is fixed so that is:

$$\overline{OB} = b = R/a^2 \quad (6.7)$$

Now the sliding ruler of the mesolabio is slid and the mesolabio is rotated until its points  $C$  and  $D$  fall on the lines  $r$  and  $s$  respectively. Now, according to the Euclid's theorem shown in Fig. 6.4, it is:

$$\frac{a}{y} = \frac{y}{x} = \frac{x}{b} \quad (6.8)$$

From the first two ratios it is possible to obtain:

$$x = \frac{y^2}{a} \quad (6.9)$$

And from the first ratio and the last it is possible to obtain:

$$y = \frac{a \cdot b}{x} \quad (6.10)$$

Now, by substituting (6.9) in (6.10), it comes:

$$y = \frac{a^2 \cdot b}{y^2} \Rightarrow y = \sqrt[3]{a^2 \cdot b} \quad (6.11)$$

And, by substituting (6.7) in (6.11), the cubic root of R is obtained:

$$y = \sqrt[3]{R} \quad (6.12)$$

Moreover, if in the given scale the point A was fixed so that is:

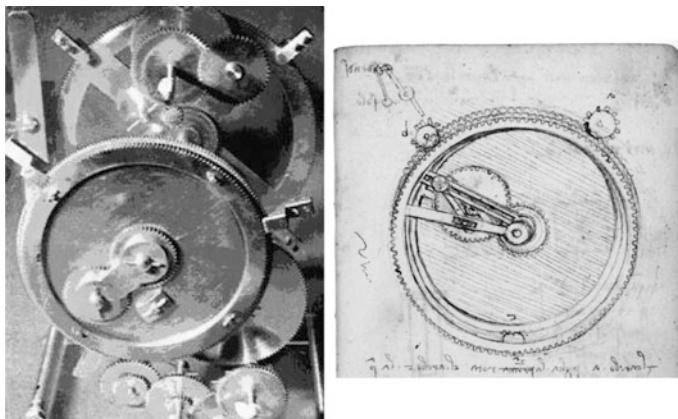
$$a = 1 \quad (6.13)$$

From Eq. (6.11) it comes directly:

$$y = \sqrt[3]{b} \quad (6.14)$$

As for the presence of epicyclic gear trains in the mechanism of Antikytera, the authors think that probably De Solla Price was right. In fact epicyclic gear trains can be very usefully used to show and compute planets' and satellites' orbits as was shown by G. Pastore in his book and in some conferences. In addition, in Fig. 6.16, on the left, is reported the reconstruction of the mechanism made by John Gleavè based on the studies by De Solla Price; on the right a drawing of an epicyclic gear train by Leonardo da Vinci.

Since Leonardo da Vinci also draws mechanisms older than him, probably epicyclic gear trains were known also in a very ancient age.



**Fig. 6.16** Epicyclic gear trains

Finally, it is possible that the mechanism of Antikytera has been used also for sailing applications: the knowledge of the moon position is useful to predict the (spring and neap) tides. This was important for ships that went in and out of the ports by oar propulsion if they were military and just by a square sail if they were merchant vessels. In the Mediterranean sea, tides are not very strong but the Roman ships sailed even to the British isles, crossing the English Channel.

# Chapter 7

## The Natural Energy Used in Antiquity

**Abstract** In this chapter the early sources of mechanical energy are presented. The sources of energy that were considered are: muscular energy (from man, and animals) by acting on capstans, thread wheel, wind motors, water wheel. For all those motors, rough formulas to evaluate their power and energy are also reported.

### Introduction

The first energy to be used was muscular energy, the work provided by humans and domesticated animals. For this reason it is interesting to provide some indicative data on the work and energy that an average man and principal work animals can provide. The work and power provided by a man or by an animal depend on many different factors, such as the conditions in which the force impressed by man or animal is exercised and also by whether we consider loads that are transported or lifted, etc. Furthermore, since these are beings who tire as a result of the work they perform there are significant differences between what can be obtained over brief periods and the average work that can be obtained in the course of a work day.

To give an idea of the energy and power that a man or a domestic animal can provide we will consider a man turning a lever and a draught animal pulling a cart or similar mobile system.

### 7.1 Energy from Man

We commonly assume that a man of average body weight ( $\sim 70$  kg) working a lever can exercise the following force:

80–100 N continuously  
250–300 N for short periods.

With a crank that moves with a peripheral speed of 0.75–0.9 m/s.

Given the above data consider a man working a lever having a range of 0.4 m, rotating at a speed of 20 revolutions per min, equal to:  $20 \cdot 2\pi/60 \cong 2.1$  rad/s.

It will thus have a peripheral speed of:  $2.1 \cdot 0.4 \cong 0.84$  m/s.

Since we can assume that the average force applied (continuous work) is 90 N, the momentum applied is:  $90 \cdot 0.4 = 36 \text{ Nm}$ .

The continuous power supplied is:  $36 \cdot 2.1 \cong 76 \text{ W}$  which thus represents the average power provided by a man working continuously for rather long periods.

In the same way we can easily determine that the maximum power that a man can provide for brief periods is around 230 W.

The average amount of work that a man can provide for each hour of the work day is therefore:

$76 \text{ Wh} \cong 273,600 \text{ J}$  for long periods;

$230 \text{ Wh} \cong 828,000 \text{ J}$  for short periods.

If the same lever is being worked by two men together, we assume the total average effort to be 1.7 times the average effort of each man, this because of the practical impossibility of synchronizing the actions of both men.

## 7.2 Energy from Animals

In the case of horses, mules and donkeys one assumes that they can exercise a traction, expressed in Newton, equal to their mass expressed in kilos, working in a continuous manner and at a speed of 0.8–1.0 m/s.

Thus, a horse having a mass of 400 kg, will exert a traction force of 400 N. If it is assumed that the horse exerts such a traction proceeding at a speed of 0.9 m/s, the (continuous) power provided will be equal to  $400 \times 0.9 = 360 \text{ W}$ , that is about  $\frac{1}{2} \text{ CV}$ .

The average continuous power supplied for every hour of the work day will therefore be  $360 \text{ Wh} \cong 1.3 \times 106 \text{ J}$ .

Naturally horses of particular selected races, reared specifically for pulling and hauling can reach masses and traction power that are even triple compared to the above indicated average values.

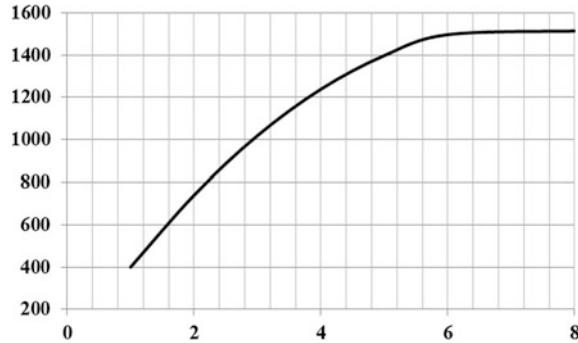
For oxen, on the other hand, we assume an average traction force of 600–800 N, with the animal proceeding at a speed of 0.6–0.85 m/s. The average continuous power is then  $700 \times 0.725 = 507.5 \text{ W}$ .

Thus the average work that it can provide for each hour of the work day is  $507.5 \text{ Wh} \cong 1.8 \times 106 \text{ J}$ .

### 7.2.1 Two or More Animals Together

When several animals are yoked together, the traction power does not increase in a manner proportionate to the number of animals. This is because it is not possible for all the animals to exercise their traction together.

**Fig. 7.1** Traction exerted by a number of horses



To consider this, Bockelberg proposed the following formula that is reported in the texts on Agricultural Mechanics:

$$F_{\text{tot}} = 1.075 \times (1 - 0.07 \times n) \times F \times n$$

where  $F_{\text{tot}}$  is the total force exerted by  $n$  animals, each of which exerts a force  $F$ .

The Fig. 7.1 shows  $F_{\text{tot}}$  function of the number of animals, assuming that each of them exerts a force  $F = 400$  N

The Figure shows that according to the formula by Bockelberg, there would be no practical utility in yoking more than 6–8 horses.

### 7.3 The Capstan

In Fig. 7.1 is shown the working principle of a capstan.

If a force  $F_1$  is exerted (from a man) on the bar B, it gives rise to a moment  $M$  on the axis of the capstan. This moment is balanced from the one given by the force  $F_2$  that acts on the rope; this last force originates from the friction between capstan and rope, hence a little force is necessary to tighten the “unloaded” end of the rope; the latter will be neglected for the sake of simplicity (Fig. 7.2).

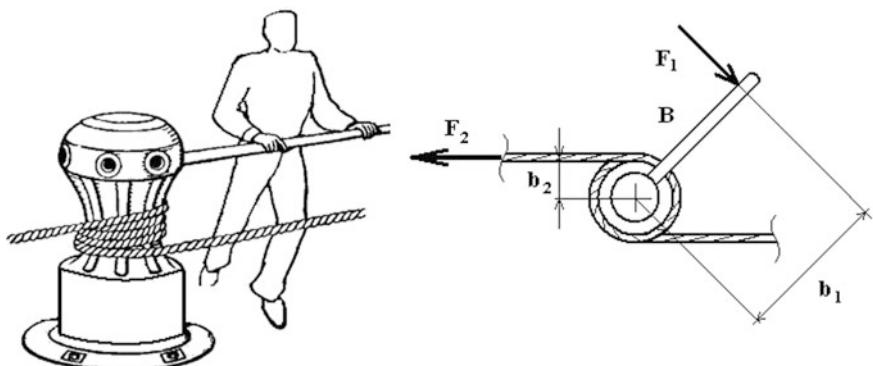
If only the first two forces are considered, the equilibrium of their moments, that are given (see introduction to part II) by the product of the force and the distance:

$$M = F_1 \cdot b_1 = F_2 \cdot b_2 \quad (7.1)$$

From Eq. 5.1 the force on the rope is:

$$F_2 = F_1 \cdot \frac{b_1}{b_2} \quad (7.2)$$

This means that, a force exerted on the capstan bar is increased as much as the longer the bar is with respect to the capstan radius.



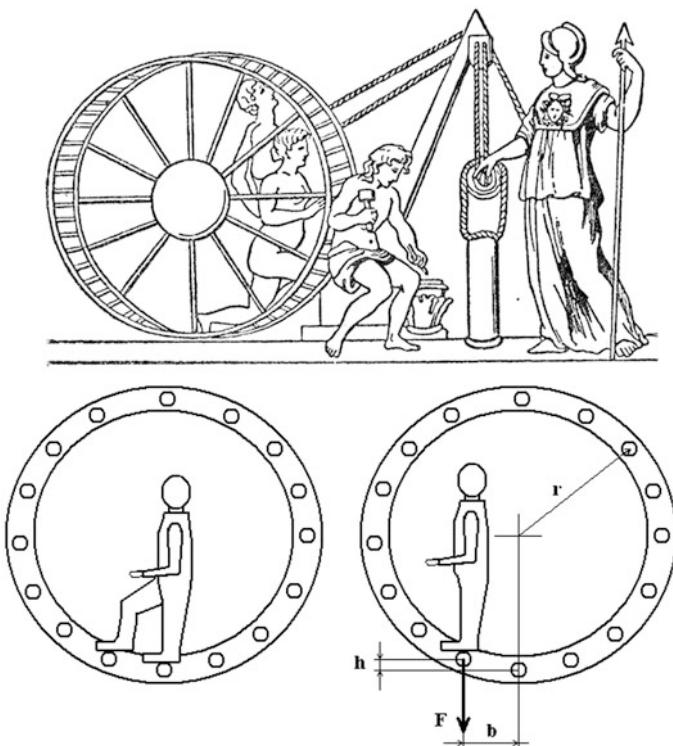
**Fig. 7.2** Working principle of a capstan

For example, suppose that a man exerts on a bar 1 m long a force of 200 N ( $\approx 20 \text{ kg}_F$ ) and that the capstan radius is 25 cm, this means that on the rope (if the tightening force is neglected, as aforesaid) will act a force of 800 N. Now, on a medium sized capstan can act (say) up to five men; this means a considerable traction. An application of capstans to the propulsion of vehicles will be shown in Fig. 11.18.

## 7.4 The Treadwheel

For higher traction efforts like in cranes, the force of the men was applied by using a quite different device: the treadwheel. The treadwheel is very similar to the one that is often fitted in the cages of squirrels and other rodents. In Fig. 7.3 is reported a drawing from a bas-relief found at Capua (Italy) showing a Greek crane (Hellenistic age) used by the Romans also and the working principle of the “squirrel cage motor”. The torque is given by the moment of the weight of the men that climb on the rotating steps; a capstan is linked to the shaft of squirrel cage, having a horizontal axis, on which a rope is wound. In this case no tightening force on the unloaded end of the rope is required since all the rope itself is bound onto the capstan. The equilibrium of the moments is the same that has been previously considered; hence the force  $F$  given by the men’s weight will be magnified by a factor  $b/b_2$  were  $b_2$  is the radius of the capstan.

Treadwheel powered cranes were built till the Renaissance and later, having diameters up to some meters; obviously, the larger is the radius of the squirrel cage, the higher is the force exerted on the rope.



**Fig. 7.3** Treadwheel crane and its working principle

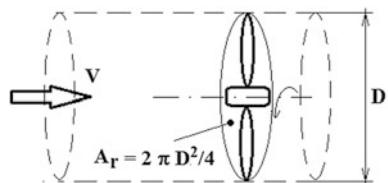
## 7.5 Rough Evaluation of the Power from a Wind Motor

Generally speaking a wind motor consists of a rotor with blades that rotates around and axis when struck by a current of air (wind) moving at a specific speed  $V$ . In Fig. 7.4 a scheme of a wind motor having horizontal axis is shown.

The kinetic energy  $E_c$  of a moving air mass is:

$$E_c = 1/2 m V^2$$

**Fig. 7.4** Scheme of an horizontal axis wind motor



where

$m$  is the mass (kg)

$V$  is the wind speed (m/s)

The power available is therefore:

$$P = 1/2 \rho A_r V^3$$

where

$\rho$  is the air density ( $\sim 1.25 \text{ kg/m}^3$ ).

$A_r$  is the rotor surface perpendicular to the current ( $\text{m}^2$ )

Naturally, it is impossible to get that power by the rotor of a wind motor because, if that happens, this would correspond to a total air kinetic energy transfer to the rotor. This could happen only if the air, after having reached the rotor with its speed, had zero speed immediately after the rotor section.

Albert Betz (1885–1968) showed that the maximum theoretical rate that you can get wind energy is equal to 59.3 %. Therefore, the maximum power theoretically obtainable is:

$$P = 0.296 \rho A_r V^3$$

that represents the theoretical maximum power that a “perfect” wind motor could develop.

Since the motors, especially the old ones, are far from being “perfect”, the power will be obtained from the previous report multiplied by a coefficient of efficiency  $\eta$ .

$$P = 1/2 \rho A_r V^3 \eta$$

For ancient mills the following indicative values of  $\eta$  can be assumed:

Vertical axis mill:  $\eta = 0.1$

Cretan mill:  $\eta = 0.25$

Traditional mill:  $\eta = 0.25\text{--}0.3$

So, for example, if you consider a Cretan mill having a 6 m diameter rotor, it will develop roughly the following powers depending on the wind speed.

Wind speed (m/s)	Power (W)
1 (light air)	4.5
3 (light breeze)	120
5 (gentle breeze)	552
7 (moderate breeze)	1515

## 7.6 Rough Evaluation of the Power from a Waterwheel

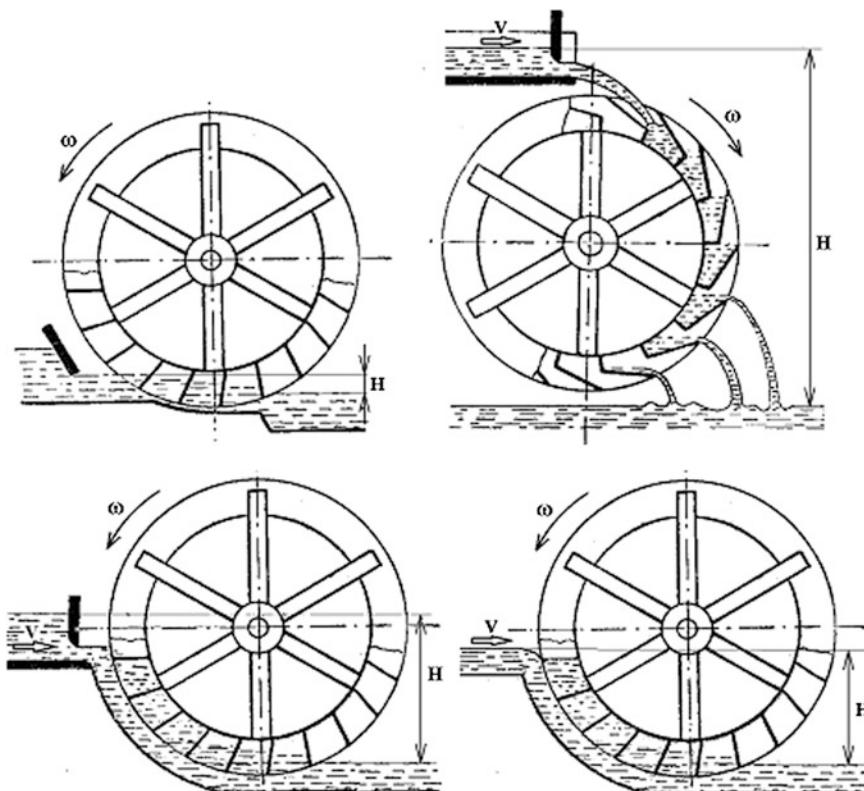
The horizontal axis waterwheels used in antiquity are essentially of three types:

- Undershot waterwheel
- Overshot waterwheel
- For next Breast waterwheel

From Figure clearly shows the principle of operation. The water wheels with horizontal axis in antiquity used are essentially of three types:

- Undershot waterwheel
- For above Overshot waterwheel
- For next Breast waterwheel

Figure 7.5 clearly shows the working principle.



**Fig. 7.5** Schemes of waterwheels

### ***7.6.1 Undershot Waterwheel***

This is the oldest type of waterwheel. In this type of hydraulic motor what is converted into mechanical work is essentially the kinetic energy of the water. The oldest versions have straight blades and only much later a waterwheel was built by French engineer Jean-Victor Poncelet (1788–1867) with curved blades; this solution improved the efficiency.

This wheel has the advantage of being able to work with low hydraulic head and does not require complicated and expensive hydraulic works. Thereby, it can be used in any stream having sufficient flow and speed.

Besides the advantages mentioned above, this waterwheel presents, however, the considerable disadvantage of having a very low efficiency.

### ***7.6.2 Overshot Waterwheel***

This type of waterwheel can be considered as the evolution of the previous type. In it what is converted into mechanical work is essentially the potential energy of the water. Since the force which produces the mechanical work is essentially the weight of the water, in these wheels the blades (of the preceding wheels) are replaced by buckets.

Compared with the former has the advantage of having higher efficiency.

The disadvantages compared to the previous type consist in the fact of requiring a greater hydraulic head and also hydraulic works are necessary to make the appropriate channeling that feeds water to the wheel.

### ***7.6.3 Breast Waterwheel***

This type of waterwheel can be considered as an intermediate type between the two previous ones and is used when the hydraulic head is not sufficient to operate an overshot wheel.

There are two types of breast waterwheel depending on whether they are fed by:

- Orifice using gradients of between 1 and 3 m and dispose even significant flow  $Q(Q = 0.2\text{--}3 \text{ m}^3/\text{s})$ .
- Spillway suitable for use extremely small differences in height ( $H = 0.3\text{--}2.5 \text{ m}$ ) with large flow rates ( $Q = 1\text{--}4 \text{ m}^3/\text{s}$ ).

### 7.6.4 *Power from a Waterwheel*

The power generated by a water wheel depends on a large number of factors. However in order to roughly determine the power that these machines were able to develop, we can proceed as follows:

The work L developed is:

$$L = m \cdot g \cdot H \cdot \eta$$

where  $m$  is the mass of water that descends from an altitude  $H$ ,  $g$  is the acceleration of gravity and  $\eta$  the overall efficiency of the plant.

The power is therefore:

$$P = L/t = Q \cdot \rho \cdot g \cdot H \cdot \eta$$

where  $Q$  indicates the volume flow rate and  $\rho$  the density of the liquid.

The efficiency of the plant varies in dependence of many factors including the load on the machine. Values of the efficiency, as guidelines, can be taken as follows:

Undershot water wheel: from 15 to 25 % or less

Low breast shot water wheel: from 30 to 35 %

Middle breast shot water wheel: from 35 to 45 %

High breast shot water wheel: from 45 to 65 %

Overshot water wheel: from 55 to 70 %

# Chapter 8

## Wind Motors

**Abstract** This chapter shows some the early examples of wind motors, starting from the II millennium B.C. Both devices having vertical axis and horizontal axis rotors are shown. Then a survey on the evolution of the sails is shown.

### Introduction

The first non muscular source of energy used by man was wind energy; examples of wind motors, in fact, are very old. Wind motors can be considered all the devices that give energy by using the kinetic energy released by the movement of an aeriform mass.

Since it does not have a specific volume or a precise mass, air occupies all available space, varying its intensity in accordance with the space. Considering that warm air is lighter than cold air, the expansion of air is also a consequence of its temperature. Hellenic scientists were perfectly aware of this, although they may not have known that air was not an actual gas, or *spirit* as they called it, but an unstable mixture of numerous gases. Consequently, they considered it as the third element, without any additional distinctions and specifications apart from acquired certainties: it was indispensable to life, capable of rising when warm, of compressing significantly and of violent expansion, causing fast and whirling currents, actual aerial rivers capable of producing powerful thrusts. This latter characteristic they knew had a variable force, from a soft breeze to a devastating storm, and could facilitate or obstruct the movement of ships, according to whether it pushed in the direction of their progress or in the opposite direction.

The rudimentary Tibetan prayer wheel moved by the wind may very well have been the precursor of the primary motor. These prayer wheels were soon succeeded by the Afghan mill which perfected the idea and provided a modest amount of work. Their advent must be placed immediately following the perception of the dynamic force of the wind, which is easy to verify in those regions. Nevertheless, an extremely long time was required to pass from a mere sensation of pulling to actual use and the construction of a device that could capture this force, its achievement coinciding with the disappearance of prehistory.

Sanskrit has the adjective *tur-as* and the verb *tur-ami*, respectively signifying *fast* and *to speed up*. The dynamic meaning of the root *tur* is implicit, taken from the Latin first and then from Italian, acquiring the more forceful meaning of fast and

whirling motion, of rotary motion, as for cyclones and whirlpools: *turbine, tornado, torment, perturbation* and, by figurative analogy, *perturbation or disturbance* are all synonymous with a sudden and radical inversion of the state of being. The same root is found also in *turban*, with reference to the winding around the head of a strip of cloth.

The *turbine*, the physical reality of the etymological root, was first defined simply as *paddle wheel* or, in respect of its primary use, mill. Regarding this last accepted meaning, specifically indicating the motor of a machine used for grinding, they soon had to specify whether by wind or by water, the two natural currents. It is only in very recent times that these have been replaced by liquid or gaseous fluids, the extreme derivation of the original separation and thus requiring a clearer definition.

In the following paragraphs some examples of ancient wind motors are presented both on the heart and on the sea.

## 8.1 The Wind Mills

Wind mills can be considered as the ancient ancestors of modern aeolic generators the use of which had a considerable increase in the last decades because of the great rise of the cost of fossil fuels.

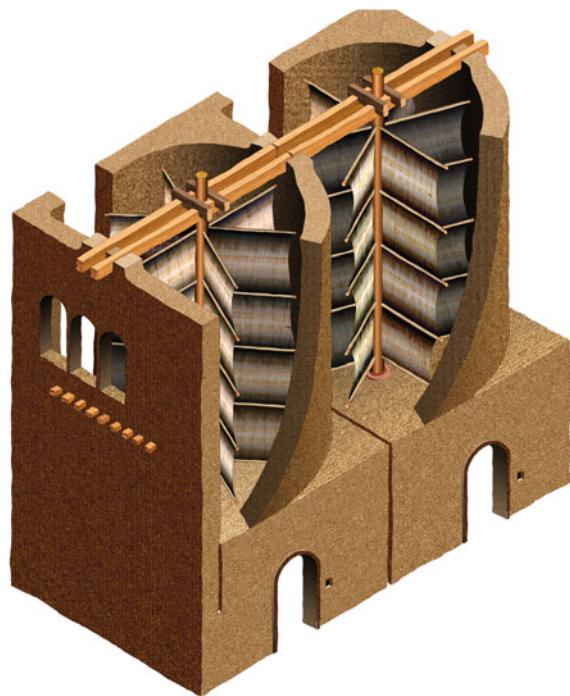
The archaic vertical axis wheel and vertical paddle wheel were complex machines capable of intercepting the kinetic energy of the wind and later of water. A shaft activated by numerous levers, the result of equating currents to a material thrust produced by invisible and tireless hands, capable of providing a propitious help. A device long exploited simply to ignite fire, dry clothes, sort grains or dry food.

### 8.1.1 The Afghan Mill

In approximately 1000 years that same guiding principle that was used by our ancestors to build primitive sails would be used on land, in the Afghan or Persian windmill. This primitive device underwent a long series of improvements, finally becoming a mill, a very rudimentary one, but certainly effective. That fundamental technological step forward must have taken place around the dawn of the II millennium B.C. in Mesopotamia, as seems to be suggested by some allusions in the Code of the great Hammurabi. In Fig. 8.1 is reported a pictorial reconstruction of an Afghan mill and in Fig. 8.2 orthogonal views of the same mill are reported.

Upon his famous stele of black basalt there is mention of wind wheels used to irrigate the fields. However it is laborious to attempt to understand the technical connotation of those very remote machines, but they probably did not greatly differ

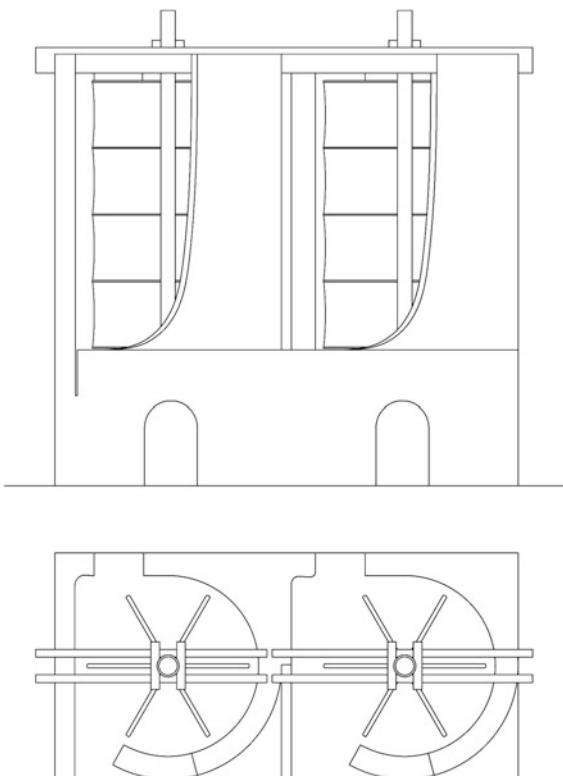
**Fig. 8.1** Virtual reconstruction of an Afghan mill



from the primitive vertical axis windmills of Afghanistan, Mesopotamia and Persia. Though their origin is lost to us, we are familiar with them because many continue to be used today to grind wheat, in the same locations. As stated, the archetype of the vertical axis typology consisted of a shaft, whose lower extremity was set in a horizontal stone and in whose opposite extremity were installed numerous laths in a ray formation, acting as a paddle. This primitive rotor was located in a building on the top of which were two beams acting as stock for the upper end of the shaft, permitting rotation. A very ancient source describes these mills thusly: "... they have eight wings and are behind two pillars between which the wind must push a wedge. The wings are placed on a vertical pole whose lower end moves a grind-stone that rotates above an underlying one".

The two pillars in reality formed an opening slightly smaller than the radius of the rotor, through which penetrated the wind, constant for the greater part of the year. Thanks to this conveyor, only one paddle at a time was pushed by the current, the only condition required to rotate the shaft. Mills that were more exposed to the wind also had a strong shutter with mobile listels attached, to act as an adjustment shut-off-valve. On the opposite side, the wind exited through a flared opening, formed in such a way as to prevent the formation of harmful turbulence. Obviously neither then nor later did the ingenious builders of the sophisticated vent understand the reason, limiting themselves simply to exploiting the advantages of rotation.

**Fig. 8.2** Orthogonal views of the Afghan mill



From a functional aspect the diagram for these mills indicates that they were very similar to the manual ones in which the grain was ground by two stone discs, the lower one fixed and the upper one rotating. A more recent source states that: “in Afghanistan all the windmills ... are moved by the north wind and thus are directed toward the north. This wind is very constant in that country and is even more so and stronger in the summer. The windmills have rows of shutters that are closed or open to withhold or introduce wind. If the wind is too strong the flour burns and becomes black and the grindstone can overheat and be damaged”.

The fixed direction aeolic mill described did not use any kinetic action nor a serrated reduction gear, a peculiarity that in spite of the unsatisfactory performance, explains its longevity, perhaps the longest in the history of technology.

We know of a second type of vertical axis windmill that is a direct derivation of the wind activated prayer wheel typical of central Asia. Its debut supposedly dates to the I millennium B.C. Because of the inverted location of the rotor, placed under the grindstone, not only was it more logical than the other but it required no support for the shaft and was able to grind using greater pressure.

We do not know when the old Afghan mill reached the Europe of antiquity but we do know that it still existed in the modern era as it can be seen in a drawing dated 1595 by Fausto Veranzio (1551–1617); this last scientist will be more widely cited in Sect. 7.4 for his water wheel. Its true novelty, and perhaps its greatest contribution, consists in fixed paddles of the same height as the rotating paddles. Placed at a precise angle, they conveyed the flow of air to the rotation unit at a constant incidence, independent of the direction of the wind.

The idea, which found no use in subsequent centuries, reappeared in the *Francis* turbine, where a crown of fixed paddles directs numerous, highly forceful jets of water onto the blades of the rotor, improving performance.

### 8.1.2 *The Cretan Mill*

The great stimulus that navigation enjoyed from the Middle Ages onward thanks to the sail, encouraged the expansion of longer range commerce. The sail also proved that the motive power of the wind could be exploited from oblique directions: a crucial potential for windmills as they could operate even in the coldest of seasons with the ice blocking its paddle wheels, but not when there was a transversal wind! To encourage a wider use of sails, however, they had to overcome the rigid orientation of the Afghan mill, perhaps the oldest primary engine, because the intensity and direction of Mediterranean winds change very rapidly as opposed to continental winds. Nevertheless, until today, no indisputable confirmation, no written or iconic source, and no archaeological findings relating to the Cretan mill has ever come to light to confirm its existence in the classical era.

However, we do have the singular testimony of Heron, a personage of such unquestionable competence that his statements become a determining factor. In “speaking of a pneumatic part activated by a wheel with a paddle, he described the wheel as somewhat similar to an “amenurion” ( $\alpha\pi\mu\omega\rho\tau\circ\text{v}$ ) which he evidently considered an object well known to the reader. The word consists of a first term that means ‘wind’, but the context makes it clear that he is speaking of an object capable of creating a rotary motion using the wind. The word  $\alpha\pi\mu\omega\rho\tau\circ\text{v}$ , is also a toponym of two promontories in Cilicia. One may conjecture that in this case they were wind mills (unless the word is being used to indicate a windy hill, that only by coincidence coincides with Hero’s term)”.

Since all the promontories in Greece, and other countries, are always windy, the reference to the wind is logical only if it relates to a distinctive feature, such, for example, as a mill. A mill that for obvious reasons, not the least being a geographic one, is not the Afghan type, useless because of its rigid orientation, but Cretan, with an oblique axis, manoeuvring ropes and triangular sails. This is obviously not a confirmation but it is a significant clue: however, mastery of the mechanical skill required for such a rotor appears applicable to the nautical skills of the first marine

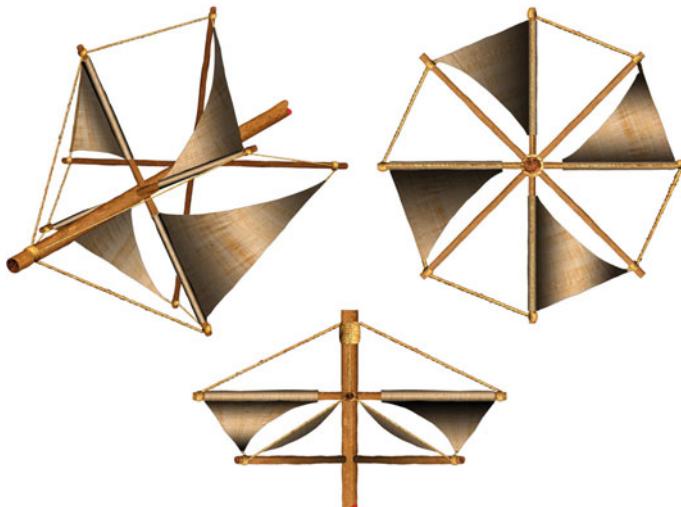
supremacy of the Mediterranean, genitrix of the mythical Minoan civilisation. The use of diverse sails around an axis was an ingenious invention, plausible in a culture characterised by the Figure of the resourceful Daedalus.

Structurally, the Cretan eolic rotor had four to twelve triangular wings of canvas, the same used for the sails of a ship. Fixed to a crude wood frame, they were suspended at a  $10^\circ$  angle in respect of the level of the rotor, so that they were oblique to the wind. By regulating the exposed surface, exactly as occurred on ships, the speed of rotation could be increased or decreased. This detail, that in many aspects resembles the manoeuvre that transformed the square sail into a triangular sail, is additional proof of the probable existence of the Cretan mill in the classical era.

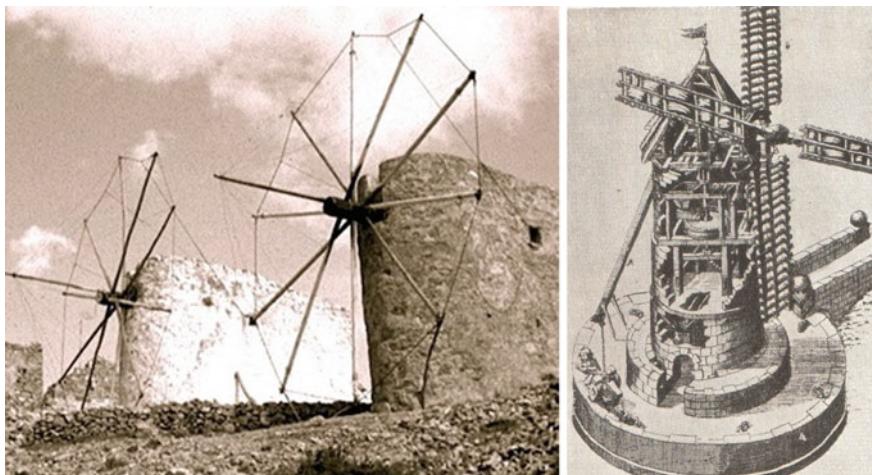
Since the power supplied by the Cretan mill varied according to the number rather than the size of its sails, obviously they chose to have many small ones rather than a few large ones, even though this was more laborious. When they opted for rotors with only four or at the most six wings, they did so to facilitate manoeuvres, relegating rotors with a greater number of sails to more difficult tasks or to less windy locations.

In Fig. 8.3 is reported a reconstruction of the rotor of the Cretan mill.

Cretan mills were used along the Mediterranean coasts till the last century and can be considered the ancestor of all the horizontal axis wind mills like the famous and typical Dutch ones. In Fig. 8.4 are reported a Cretan mill in Greece and a German one.



**Fig. 8.3** Virtual reconstruction of the rotor of the Cretan mill



**Fig. 8.4** Cretan windmill in Crete, courtesy of Dr. Antonio Ulzega, and a German windmill

## 8.2 Wings on the Sea: The Sails

Perhaps it was by observing the motion of the whirling leaves that our ancestors first understood the dynamic potential of the wind, even before that of water. Almost certainly one of the first applications was the rudimentary mat used to push the pirogues on the tranquil lagoons, accomplished in accordance with complex calculations around the IV millennium B.C. if not before.

There is no way of knowing when the sail first made its debut on the sea, partly because we cannot determine what is meant exactly by the word sail. Various clues indicate that they were probably introduced at least 6000 years ago and had mere archetypical characteristics and functions. Sails that most closely approach the modern day meaning were probably invented by the Egyptians for navigation on the Nile and its delta. Perhaps, and this theory is shared by many scholars, it was the branch of a palm tree erected on the prow of a ship to capture the wind. Viewed from this perspective, it does not appear to be very important since the ability to move a float by increasing the thrust of the wind is not sailing. For a less rudimentary use of the sail, we must wait for the branch to become a braided cloth, forming a continuous surface to oppose to the wind, a solution dating to 3500 B.C.

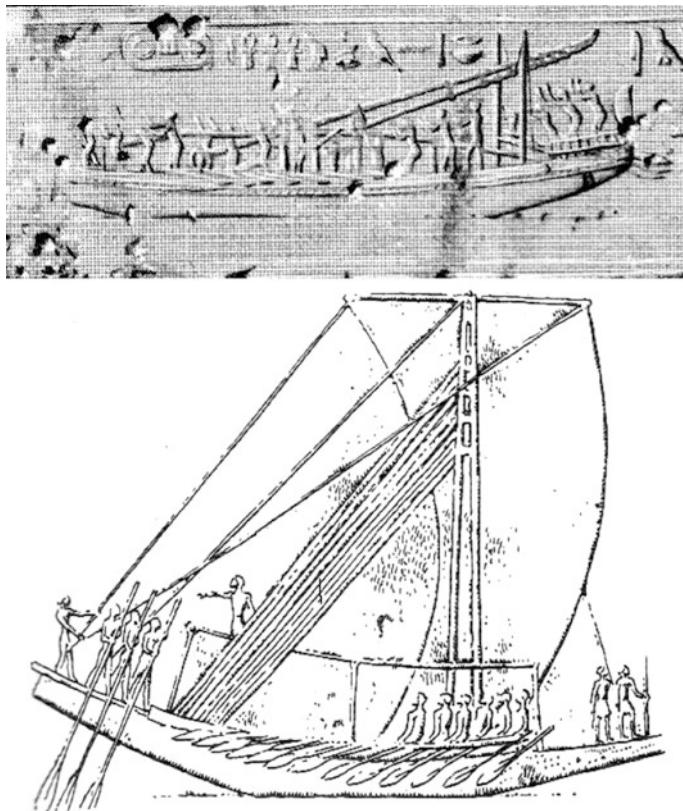
But to attribute the name sailboat to this floating device we must wait until it provides evidence not only of moving by means of the wind, but also of having the ability to move along a specific route, or to navigate. It was therefore indispensable for the hull to have a specific shape, tapered like a fish and the sail to resemble a wing, with a wide surface. Two essential criteria that appear to be antithetical, the first to reduce resistance to water, the second to increase resistance to air!

For the ancients, a sail was square, or quadrilateral, simple to conceive, easy to build and quick to manoeuvre: the joining of many pieces of cloth, woven on a

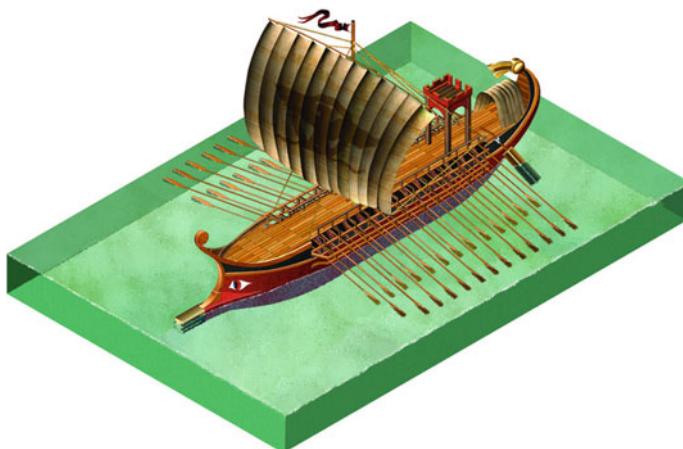
loom, fixed to a yard or a pole. It is believed that the Egyptians started to sail on the Mediterranean sea just before 3000 B.C.; an abundant series of ancient illustrations testify to this and date it to around 2900 B.C. Some hieroglyphics certify that around 2670 B.C. the pharaoh Snefru sent 40 vessels to Bibllos (near the modern Beirut) to bring cedar tree trunks to Egypt that had to be used to built boat hulls.

In Fig. 8.5 are reported a bas-relief and a painting showing an Egyptian ship dating about 5000 years ago. How it can be observed, the mast is made of two poles and has many backstays, just one forestay and no shrouds. This permitted to put down the mast easily and to move on by oars.

For the millenniums that followed, there was a single and very obvious evolution: the placement of the rectangle of fabric, first with the longer side placed vertically and later horizontally. The explanation is simple: it better exploited the resistance of the pole at equal thrust, increasing the surface of the sail without having to increase the height of the pole, a crucial detail. And so sails were always rectangular but of significant width, hung to cords that facilitated manoeuvres.



**Fig. 8.5** Egyptian ships



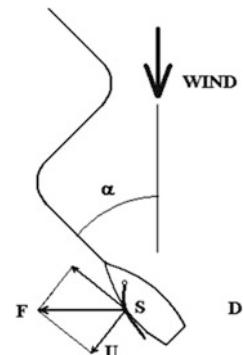
**Fig. 8.6** Virtual reconstruction of a Roman liburna

The unsatisfactory performance of these sails and the inconstancy of the winds in the Mediterranean, led military units to select double propulsion: eolic in transfer cruises; rowing in combat and, obviously, when there was no wind. The square sail dominated the entire Mediterranean from pre-dynasty Egypt to the Roman Empire; in Fig. 8.6 a reconstruction of a Roman liburna galley is reported. From the Figure it is also possible to note the couple of rudders, each one is installed on a side of the ship. Lateral rudders were used on European ships till the Middle Ages with very few exceptions.

The developing of the square sail went on till the second half of the 19th century when the advances in naval architecture permitted to design and build the fabulous clippers that represent a masterpiece of the sail ship construction. The clippers were very fast, more than the steam ships of that age: it is believed that some of them have maintained mean speeds of 15 knots for many days. They had been designed to carry tea mainly from China to Europe and, for them, to reach the port before the others, meant higher profits. Unfortunately for these superb vessels, the channel of Suez, that they could not cross, and the low price (at those times) of coal and oil gave a great advantage to the steam ships. In addition, the latter required a small crew while clippers needed many experienced sailors. Some of these magnificent vessels ended their career transporting goods from South America to Europe; in Italy some of them survived till the twenties of the past century.

The square sail may be considered as an excellent propulsor when sailing before the wind and this is the reason why it was mainly used for oceanic sailing where the wind has a more constant direction; on the contrary it was of little use when the wind blew from the sides or if it was a headwind.

In order to understand the evolution of the sails, it is necessary to roughly expose the following concept. A vessel has the possibility to reach any point with any wind direction if its sail gives propulsion to it even if the angle between the wind

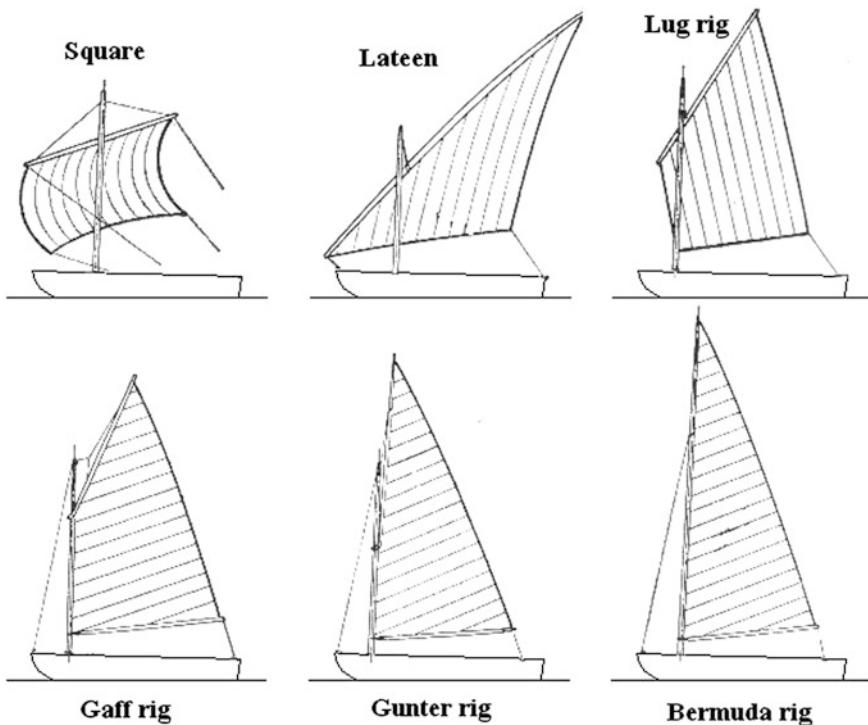
**Fig. 8.7** Tacking

direction and the ship's longitudinal axis is lower than  $90^\circ$ . In this case the vessel will run over a zigzag route going up the wind as schematized in Fig. 8.7; this way of sailing is called tacking.

This can be obtained with particular sail shapes and thin and deep hulls. The elementary theory of sailing is very simple: let us consider a ship that is running over a route forming an angle  $\alpha$  with the direction of the wind. If the sail is correctly oriented, when the wind blows on its curved profile the air flow is deflected and, consequently, a force  $F$  (lift) orthogonal to the wind direction takes place. Let us consider the two components of  $F$ : the first one  $U$  in the direction of the ship longitudinal axes and the second one  $D$  orthogonal to  $U$ . The component  $U$  is the propulsive force while  $D$  tends to tilt the ship and to move it obliquely; hence a thin and deep hull is necessary to offer resistance to this component. Naturally the wind gives to the sail not only a lift but also a resistance that depends on the sail efficiency. In order to obtain a lift it is necessary to adopt sails having an opportune shape. As far as this aspect is concerned, the clippers could sail with an angle  $\alpha$  not lower than, say,  $75\text{--}80^\circ$ , adopting particular lines (bow lines) to stretch the forward edge of the sail (luff); the ancient vessels with square sail, till the 16th century, could not sail with angles lower than  $135\text{--}160^\circ$ , just the Scandinavian drakkars could reach about  $90^\circ$ . This made it difficult to use square sails in a narrow sea like the Mediterranean where the direction of the wind is changeable. Ships filled with wheat directed towards Rome from Egyptian ports may have been favoured by the wind when heading towards Egypt and obstructed on their return voyage, thus new methods for placing the sail were conceived daily to limit these preclusions.

### 8.2.1 Evolution of the Sail Rig

The first sail that permitted to sail with lower angles than  $90^\circ$  is the lateen sail. In Fig. 8.8 is schematically showed the evolution of the sails that permitted to sail closer to the wind.



**Fig. 8.8** Evolution of the sail

The definition of lateen sail does not indicate the population that invented it or adopted it first, but is the result of a mutation of the Italian “*vela trina*”, that is, triangular sail. Though its initial appearance is currently placed in the 9th century of our era, there are some embryonic mentions of a lug rig as far back as the Roman era, especially with reference to small boats. A Greek bas relief of the 2nd century A.D. gives a very precise illustration, as do a few other rare images from the period immediately following. Regarding its possible origin, it is theorized that the sail went through various phases, all provoked by the modification of the square sail necessitated by the action of the wind. As early as 330 B.C., Aristotle wrote in his *Meccanica*.

Why do navigators, after sailing with a favourable wind, when they desire to continue their course even if the wind was not favourable, bring down that part of the sail towards the rudder [referring to the double side oar rudder], and embracing the wind, leave unfurled the part of the sail near the bow? It is because the helmsman cannot produce an effect against the wind when it is strong, but can do so when it is not and it is for this reason that they take it down [the rear of the sail].

In practice, they first inclined the pole obliquely, then they removed any excess from the original profile of the sail, vertical and horizontal, reducing it to a

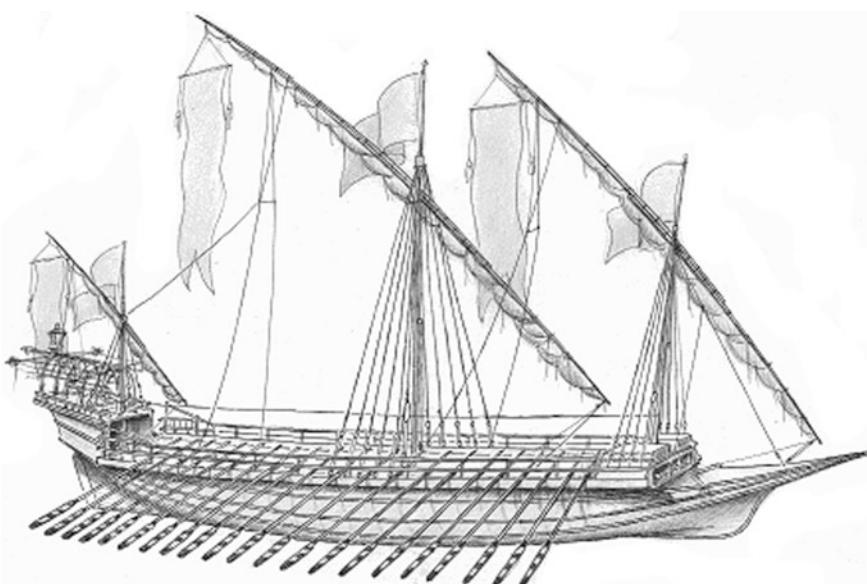
rectangular triangle with the hypotenuse fixed to the pole. Subsequent passage to the lateen sail was rapid. It is curious to note that both the advent of the lateen sail and the Cretan eolic mill, consisting of a rotor with multiple lateen sail, date to the 8th century of our era. Its simultaneity confirmed by various allusions and indications, many scholars tend to predate its appearance to the Hellenic age.

Probably the most famous ships moved by lateen sails were the Mediterranean galleys that, during the battle were powered only by oars. In Fig. 8.9 is showed a Venetian galley of the 16th century; this kind of warship was the most commonly used both by European and Arabs during the Renaissance because it had good maneuverability and oar propulsion that was very useful in the Mediterranean.

Lateen sail was used by fishermen in the Mediterranean Sea till a few decades ago and is still used by Arabs in the Red Sea. Nowadays the lateen sail has a revival in competition for old fashioned lateen rigged boats.

Lug rig appeared later and is still used on the Atlantic coasts of Europe and in the Adriatic Sea till today.

Gaff rig sail was the first important improvement to sail with low angles to the wind since this rig is the first one that has no sail surface beyond the mast; this rig was used also for prestigious racing yachts till the first decades of the 20th century. Gunter rig can be seen as an improvement of gaff rig towards the Bermuda (or Marconi) rig that is considered the most efficient one in order to sail close to the wind.



**Fig. 8.9** Venetian galley of the 16th century (courtesy by Dr. A. Cherini)

### 8.2.2 *The Chinese Junk*

In the Far East, during the middle ages, while the European vessel still had square sails and lateral rudders, in China a much more modern vessel than the European ones was used: the Chinese junk. This ship had many interesting and innovative aspects both in the hull and in the sail rig. The oldest description of a Chinese junk was given by Marco Polo (Venice 1254–1324) in his “*Il Milione*”, in 1298.

“We start to describe the freighters made in pine wood. They have just one deck, and under it the space is divided in sixty little cabins—more or less, depending on the hull dimensions—each of them has furniture like a little accommodation for the merchant. There is just one rudder. The masts are [generally] four with four sails and some ships have two extra sails that can be folded or unfolded when it is necessary. In addition to the cabins, the hulls of some ships, the largest ones, are divided in thirteen compartments by means of thick boards linked together. The aim is to defend the ship in case of a leak caused by collision with a rock, for instance, or by a strike of a mad whale, event that is not rare”.

From the description of Marco Polo, the hull had some important innovations: it was divided in compartments and this gave a considerable increase to safety and seaworthiness; in addition there was an unique central rudder that is more efficient than the couples of paddle-rudder used in Europe during the middle age.

Moreover, the Chinese junk had a particular type of sail that was much more efficient than the ones used in Europe. The Chinese sail rig essentially consists in masts without any forestay, backstay and shroud; the sail was made by a mat with many battens disposed horizontally and as wide as the sail. Almost each of the batten is connected to a line that is used to orient the sail and helps to give to it an efficient profile. The Chinese junk rig has many good qualities: it is easy to handle, to reduce its surface when necessary and to maintain, its centre of effort is relatively low, hence a less deep hull and less ballast is required. For these reasons, over the past few years, some sailing yachts have been designed with this rig type, made with modern materials (Fig. 8.10).

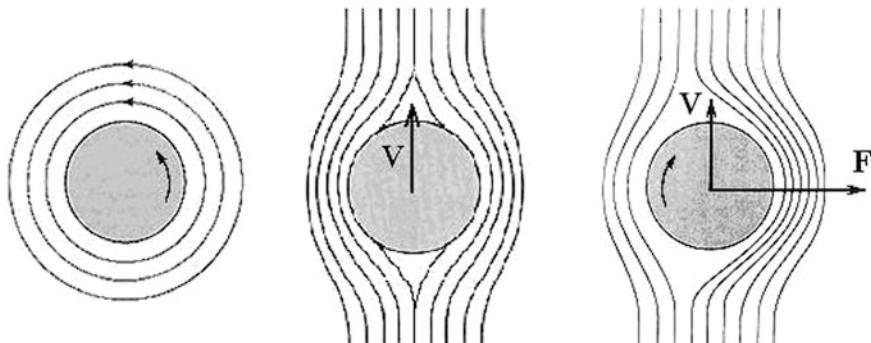
### 8.2.3 *The Flettner Rotor*

An interesting evolution of the sails is represented by the Flettner rotor; really it does not represent an ancient invention and probably is not a precursor but it can represent the last evolution of wind motors and for this reason it seemed interesting to give a short description of it. The working principle is based on the Magnus effect, discovered by Heinrich Gustav Magnus (1802–1870) and schematically presented in Fig. 8.11.

In the Fig. 8.11 is shown a cylinder in a fluid. On the left, the cylinder rotates around its axes without translating; in this case the speed of any of the points

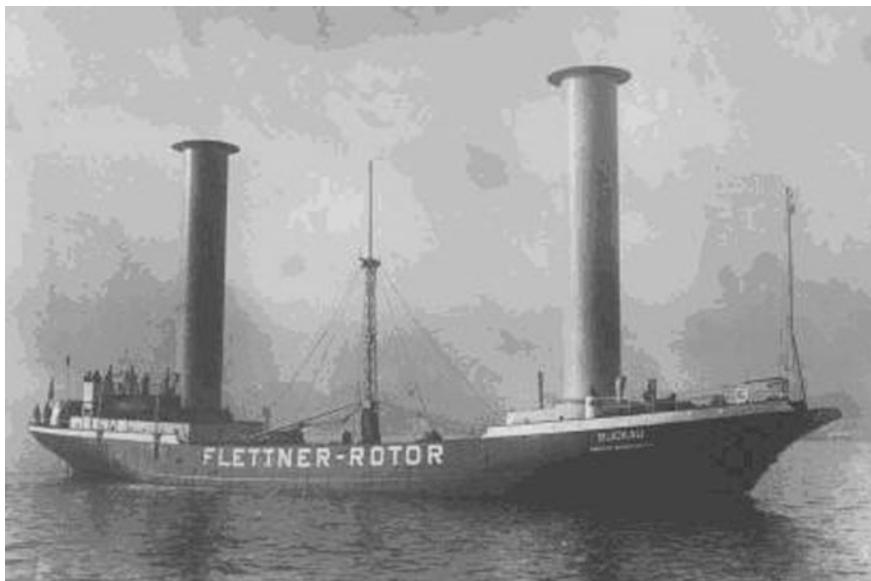


**Fig. 8.10** Chinese junk (courtesy by Dr. A. Cherini)



**Fig. 8.11** Scheme of the Magnus effect

belonging to the cylinder surfaces have the same intensity, hence the same happens for the fluid particles that are dragged by the cylinder surface. In the middle is shown a cylinder that translates into a fluid without rotating; in this case, in the direction of the motion, the speed of any of the fluid particles on a side of the cylinder has the same intensity of a particle on the other side and no fluid force acts in the orthogonal direction to the motion. On the right, the cylinder rotates and translates; in this case, respect to the direction of motion, the fluid particles velocity



**Fig. 8.12** The rotor ship Buckau

on the right cylinder's side is higher than the velocity of the fluid particles on the left side, hence the pressure on the right side is lower and a force  $F$ , orthogonal to the direction of the velocity, takes place.

In 1924 Anton Flettner (1885–1961) applied the Magnus effect to the propulsion of the ship “Buckau”, shown in Fig. 8.12. The ship was 51 m long at the waterline and had its two masts replaced by two rotors 15.7 m high and 2.8 m in diameter; the rotors were moved by two 11 kW electric motors, at a maximum speed of 125 rpm, powered by diesel generators. The tests showed an excellent behavior of the rig: the ship could tack with values of the  $\alpha$  angle as low as 20–30° while the original sail rig permitted to tack with angles not narrower than 45° to the wind; moreover, the rig permitted to sail safely with strong winds and required a smaller crew. These good results encouraged the building of a larger vessel, the Barbara, having three rotors.

The idea of the Fletter's rotors has been recently reconsidered because of the increase of the cost of fossil fuels.

Very recently air motors based on the Magnus effect have been proposed for wind generators.

### Observations

The aeolian energy presents the following interesting aspects:

1. Aeolian motors are the first examples of a non animal motor having a rotating shaft.

2. The developing of the sails permitted the navigation on the sea and hence the diffusion of ideas, devices and knowledge.
3. Nowadays wind motors have a second childhood: the modern wind motors are used in some applications in the field of renewable energy.

# Chapter 9

## Hydraulic Motors

**Abstract** In this chapter examples of the hydraulic motors are presented. Several authors' reconstructions of the early water wheel powered mills are shown, both having horizontal axis and vertical axis. Most of the devices above belong to the Greek-Roman but examples of mills built during the Renaissance are also shown.

### Introduction

According to the Greek concept of "motor" one of the first liquid state motors was unquestionably the float that was transported by the current of rivers or the tides of the sea. These spontaneous machines were later copied, transforming them into blades and turbines. It soon became clear that the latter two were also reversible, that is, capable of rotating when immersed in moving water and movable when rotated in still waters. The first wheeled ship designed with great skill and without any mechanical errors dates to the 4th century A.D.: a war ship.

Water which requires a moderate energy to be raised, can in turn provide a moderate amount of power when it falls upon a paddle wheel or when it pulls it. Both are confirmed by literary evidence from sources and clear descriptions in treatises as well as important relics, the most famous of which is unquestionably the wheel of Venafro.

There were also systems with multiple wheels, located at different heights, that could exploit the same flow of water dividing it into several drops, since the force of one significant gradient exceeded the mechanical resistance of the wheels.

### 9.1 Water Wheels with Vertical Axis

The close similarity between the vertical axis windmill with rotor superimposed on the millstone and the water mill of archaic conception but similar configuration, better known as the Scandinavian or Greek mill, has induced many scholars to consider it as its derivation. Since there is no certainty regarding the location in which the first hydraulic wheel began to turn, no confirmation supports this priority, and even less so the above mentioned similarity, which could actually demonstrate

the opposite. In fact other scholars are of this latter belief, considering the vertical axis hydraulic rotor to be an adaptation of the aeolian rotor to the small and eddying courses of water typical of Scandinavia and Greece. Whatever may be the origin of this wheel it is certain that whenever and wherever it emerged, it proved to be of modest power but ideal for torrential systems.

### **9.1.1 The Greek Mill**

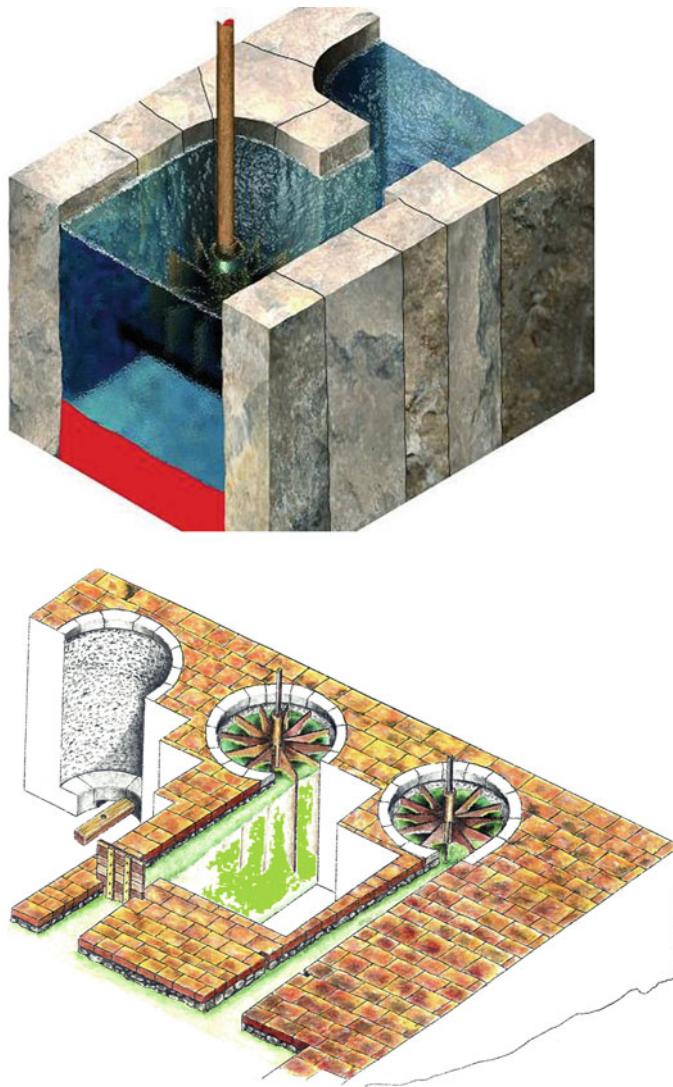
In Fig. 9.1 is represented a virtual reconstruction of a vertical axis mill whose rotor has vertical blades and the mill grinders.

In very general terms it consisted of a shaft equipped with squat blades around the bottom, inserted like the spokes of a wheel. These were eight or twelve very solid and thick planks, not longer than half a meter and of even smaller width. A hole in the rock acted as a bushing for the base of the shaft, whose opposite extremity was embedded in the millstone, which rested on another identical but fixed millstone.

In Fig. 9.2 is reported a virtual reconstruction of the rotor installed in its housing.

**Fig. 9.1** Virtual reconstruction of a vertical axis mill





**Fig. 9.2** Virtual reconstruction of the vertical axis rotor in its housing

This vertically immersed rudimentary rotor opposed a strong resistance to the current: however, since its right and left blade were identical, it could only turn when one of these was shielded. In effect, the course of the current had to narrow at the mid point of the wheel diameter, a blockage obtained by partly obstructing the feed bottom, using an early form of sluice-gate. Plausible to imagine it consisting of a splash gate made of stone or planks, firmly scarfed to the adjacent shore. This type

of wheel was very widespread because of its great simplicity of construction and installation suitable to even the smallest streams.

### 9.1.2 *Vertical Axis Rotor with Oblique Blades*

Perhaps it was the difficulty of modifying the stream bed in a lasting manner to adapt it to a straight paddle rotor that suggested introducing the blade or paddle into the hub at a slight angle to the longitudinal axis, or the idea may have been copied from the oblique empennage of arrows or from a broken conch. The fact remains that by installing the blades in an inclined direction the resulting rotor vaguely resembled the modern multiblade axial fan, and even more so a helical gear. Strangely enough this method also resembles a particular type of Islamic male funerary stele that theoretically represents a sort of stylized turban. In reality, the rigid symmetry of the funeral stone is very different from a turban and rather evokes the oblique paddlewheel invented in that particular area of the near east, several millenniums before. The common etymology of turban and turbine is also interesting.

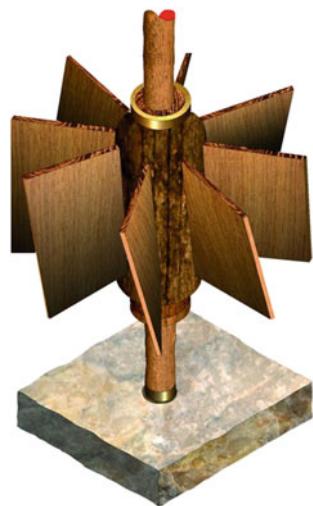
Having ascertained the connotation of that singular rotor, its advantages are obvious, then as now. No imperative need for shielding or for narrowing the stream, as any sudden or even faster movement of the water could rotate it. With such a rotor, any small stream with a strong inclination and limited capacity could be profitably transformed into a source of power by immersing the oblique paddle rotor at a slight inclination. In this manner, the current struck all the blades with the same intensity, causing them to rotate at their given inclination, an improvement over the perpendicular blade rotor of the same diameter and with equal current thrust.

This may have been the reason it was so widely used even though it was more complex. Not incidentally, this, rather than the archaic hydraulic wheel, is considered the true predecessor of the turbine—the precursor of a device still used today, called the Kaplan, very similar to a marine propeller and excellent for small differences in height.

Structurally, both the parallel blade rotor and the oblique blade rotor could increase power only by a very moderate amount as the blades that provided the dynamic thrust were made of a fragile material and could not be longer than 1 m or risk being shattered by the current. Since it was not possible to build larger rotors and larger systems, this particular type of primary motor was rigidly limited to very modest and marginal uses.

Only a different criteria could have allowed them to overcome the obstacle, encouraging the construction of wheels with larger torques, even to the detriment of an already scarce overall performance. Such rotors appeared a few centuries later, supplying a potential that had been so far unimaginable. This may have been the result of the casual observation that when a suspended straight paddle wheel with a horizontal axis came into contact with the current, it turned freely and developed an

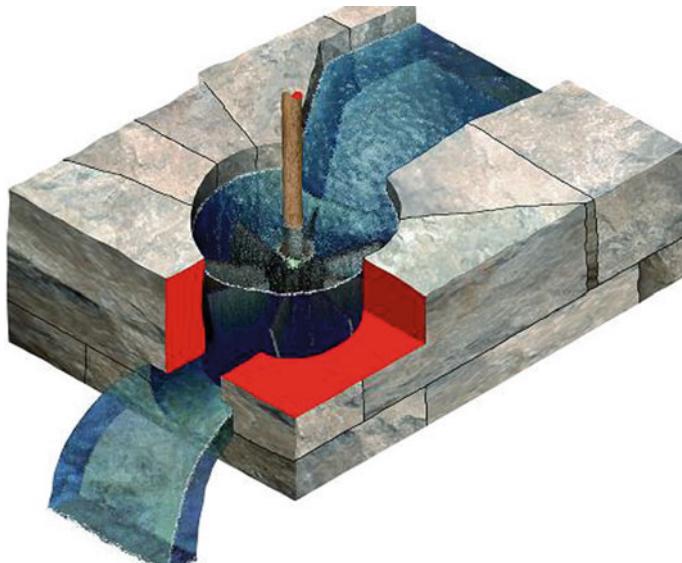
**Fig. 9.3** Virtual reconstruction of a vertical axis rotor with oblique blades



incredible power when the water fell on the blade, rotating not only by the speed of the water but also by its weight, a dynamic action emphasised by the surface and length of the blades.

In Fig. 9.3 is reported the virtual reconstruction of a vertical axis rotor with oblique blades and in Fig. 9.4 the same rotor in its housing.

If we were to even schematically quantify the performance of the three rotors, we would have 75 % for the rotor powered from the top, 60 % for the one pushed



**Fig. 9.4** Virtual reconstruction of the rotor in its housing

along the sides and 25 % for the one pulled from the bottom. Without considering that while there was no way to enlarge the last two blades, no such difficulty existed with the horizontal axis blade as it could be widened and lengthened by simple reinforcements.

## 9.2 Water Wheels with Horizontal Axis

An increase of efficiency was obtained by feeding the wheel with a water stream that flowed under the wheel. The simplest type was essentially made up by a hub installed on a horizontal axis with a number of blades like the ones represented in Fig. 6.3.

The horizontal axis innovation led to additional changes. It soon became clear that a vertical rotor applied to a horizontal shaft could provide a motive power as great as the down stroke of the water. Suitable channelling with a shut-off-valve to regulate quantity could also vary the speed of rotation. In order to lengthen the blades, they were secured laterally between two metal rims, an idea that may have been taken from the water-wheels, which also provided another idea: the box shape of the blades. The slight modification, a wooden panel about 30 cm by 20 cm high that, following initial impact, could keep the water on the blade for a longer period of time, better exploited the force of the weight and improved performance.

From a dynamic perspective a horizontal shaft was not only more comfortable to support but also simpler to lubricate, including its rudimentary bushings. It was also easy to equip it with a serrated reduction gear to slow the number of rotations, as experience had shown that an excessive rotation speed could burn the wheat. Which, by making even the slow flow of large rivers compatible, led to concentrating canalizations, rotors, reduction gears and millstones into a single system, built behind the shore and the cultivated areas. Although the use of the water mill, and even its invention is placed in the Middle Ages, in reality it was the water mill of the classical era that ensured all its benefits and that had significant repercussions. In the first century, in fact, Antipatrus of Thessaloniki wrote: "Stop grinding ye women who work in the mill; sleep until late, even if the rooster announces the dawn. For Demetra has ordered the Nymphs to do the work formerly performed by your hands, and they, jumping from the top of the wheel, turn its axis which, with its rotating rays, turns the heavy concave blades of the mill". Albeit with some minor errors, Antipatrus fully understood the utility of this machine and its most salient feature: a wheel powered from the top by drop force.

### 9.2.1 Undershot Water Wheels—*The Wheel of Venafro*

Some archaeological expeditions have unearthed and identified fragments of water wheels; among these the most important is a wheel built by the veterans of the

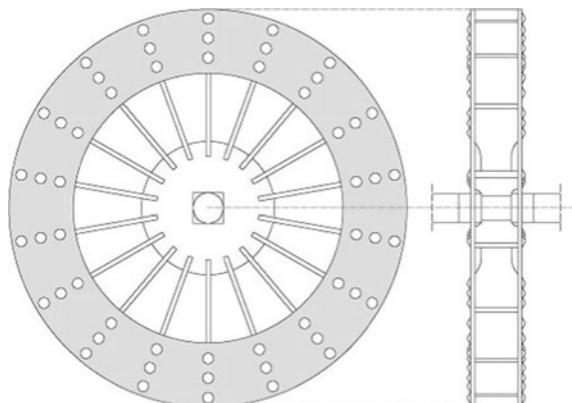
colony of Venafro in the Molise region, Italy, for the local mill. In many aspects it coincides with the description of the mill provided by Vitruvius. The exceptional nature of this remnant, until now the only one of its type, justifies a brief digression on its discovery in 1914, in the course of repair works to the river bottom of the Laurenziana mill, a short distance from the Tuliverno springs near S. Maria dell'Oliveto. At a depth of approximately 3 m two large stones of a volcanic nature were found, one whole stone measuring 83 cm in diameter and 26 cm thick, with a central hole, and another broken in half. So far nothing exceptional: near these stones however was an extraordinary imprint embedded in a limestone formation, measuring 40 cm long, 12 wide and about fifteen cm deep. We read that: "at the bottom of the Tuliverno stream, in 1914, a mass of solidified mud was found, with holes and characteristic streaks". This find is indicated as "Ruota di Venafro" (=Wheel of Venafro).

Through Prof. Aurigemma they were transferred to the National Museum of Naples, it was identified as an ancient waterwheel, made of wood, that had once sunk into the mire and in dissolving, left a full imprint. "Using ingenious means, without altering the imprint formed in such a strange and original manner, Ing. Jacono was able to make a cast and reconstruct the wheel completely, up to and including the number of bolts ...".

In the Figs. 9.5, 9.6 and 9.7 some drawings of the "Ruota di Venafro" are reported; respectively: an orthogonal drawing, a virtual reconstruction and some details of the axis and of the system to embed the blades.

As a source of power that rotor, powered by the drop method, could provide approximately 0.5 kW: nothing if compared to the more than 100,000 hp of our current hydraulic turbines, but definitely a great deal if we consider that this corresponded to the unceasing work of half a dozen slaves! And since labour, whether by free people or by slave, was beginning to have a strong impact on the cost of products, this type of wheel multiplied, at times even in a cascade manner, in order to fully exploit the kinetic energy of water. In Barbegal, for example, in the south of France, a grandiose grinding complex existed as early as the 2nd century A.D. with

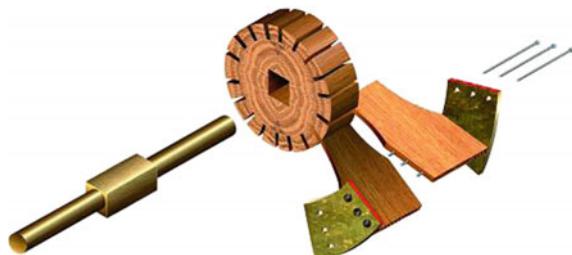
**Fig. 9.5** Orthogonal drawing of the "Ruota di Venafro"



**Fig. 9.6** Virtual reconstruction of the “Ruota di Venafro”



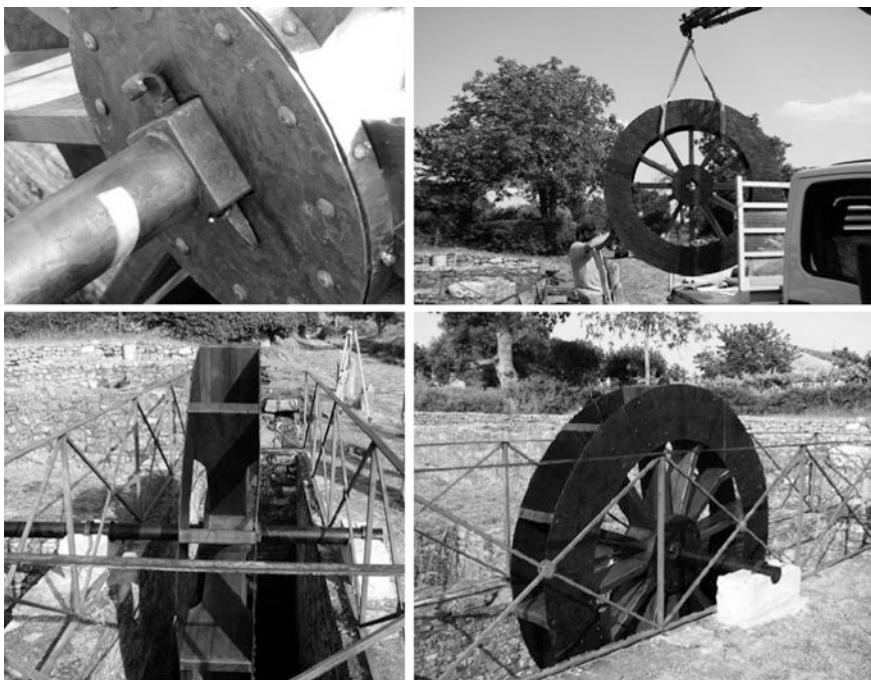
**Fig. 9.7** Details of shaft, hub and blades assembly of the rotor



16 hydraulic mills, connected in pairs and in series, powered by the drop force available from a pre-existing aqueduct. Its grinding potential was estimated to be approximately 4 tons of grain per day, an amount sufficient to meet the needs of at least 10,000 persons. Some scholars believe the system was built by a local engineer, Candido Benigno, considered the most capable builder of hydraulic machines and water conduits.

Similar systems, also using multiple wheels, were used in mines to evacuate the water. We know for example of the wheels of Tharsis, in Spain, located on various levels and probably not much different from those of Venafro.

Recently the authors have taken part in an interesting program of experimental archaeology that consisted in the reconstruction of a working model of the Ruota di Venafro; it has been built and installed, practically, in its original place. In Fig. 9.8 are reported some pictures of the rotor as it is installed on a channeling of the river



**Fig. 9.8** The reconstruction and installation of the Ruota di Venafro

Tammaro in the archaeological site of ancient Saepinum near the town of Sepino, Campobasso.

The wheel was reconstructed by using oak wood for the blades and the core of the hub, while the shaft and the rims of the hub and the blades are made by hand forged steel.

In the picture above on the left it is possible to observe a detail of the coupling between hub and shaft.

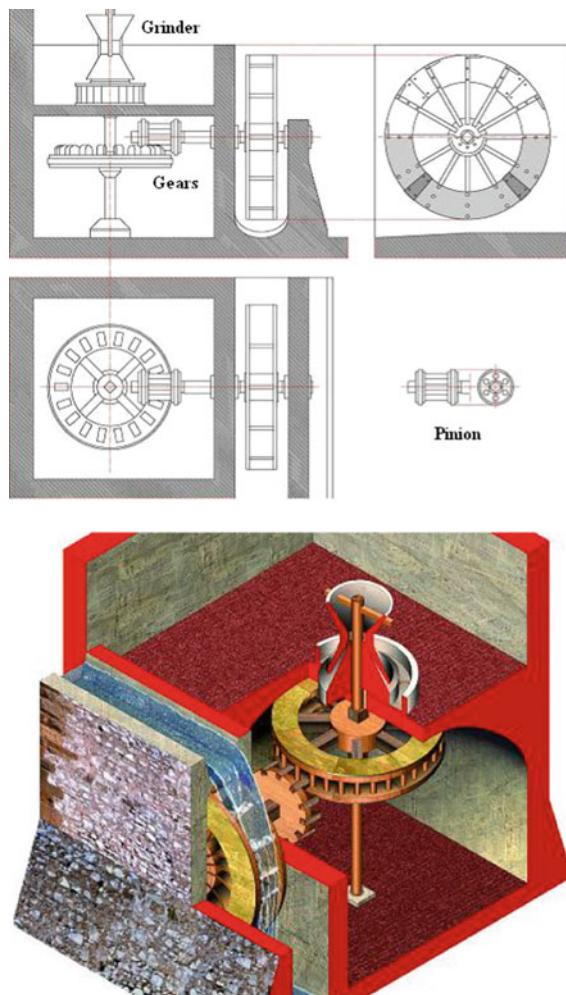
### 9.2.2 Overshot Water Wheels

A further increase in efficiency was obtained by feeding the water wheel from above. In Fig. 9.9 an orthogonal drawing of a mill powered by a horizontal axis water wheel and a virtual reconstruction are reported.

A very interesting water turbine application is the saw powered by a waterwheel represented in the bas relief reported in Fig. 9.10.

The bas relief was found on a cover of a sarcophagus at Hierapolis of Frigia (Turkey) and the picture (Archivio MAIER—Missione Archeologica Italiana a Hierapolis di Frigia) is reported with the kind permission of Prof. F. D'Andria,

**Fig. 9.9** Orthogonal drawing and a virtual reconstruction of a mill powered by an horizontal axis water wheel



director of the Italian Archaeological Mission at Hierapolis. It was dated by Professor Tullia Ritti (University of Naples "Federico II") to the 3rd Century A.D.

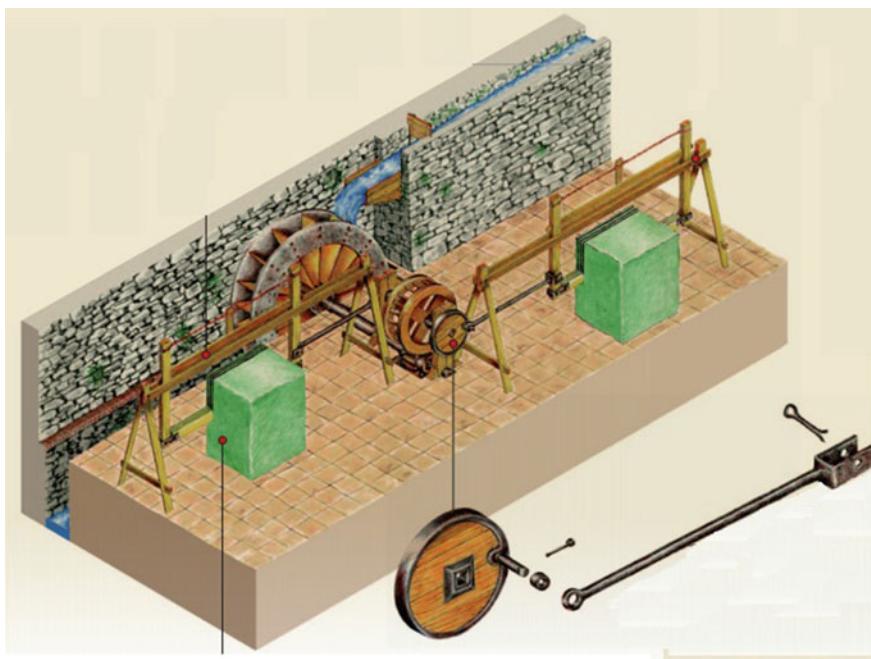
A first reconstruction was made by P. Klaus Grewe and Paul Kessner. In this device it is possible to observe one of the first realizations of a crank and slider mechanism. The device essentially consists in a double saws to cut marble powered by a water wheel. The saws are moved by the wheel shaft throw a gear train and a crank and shaft mechanism. The latter, before this discover, was commonly considered as a very later invention.

In Fig. 9.11 is reported an author's virtual reconstruction of the device.

It can be interesting to remember that for almost two millenniums the water wheel remained the primary hydraulic motor, rapidly adapting to a variety of applications, from saws for marble to lathes used for the columns, from the bellows of forges to the



**Fig. 9.10** Bas-relief representing the Hierapolis saw



**Fig. 9.11** Authors' virtual reconstruction of the Hierapolis saw

pump used to raise water. In the 4th century Decimus Magnus Ausonius (Burdigala, today Bordeaux, 310–395 ca.) wrote in his *Mosella*, vv. 362–364:

Praecipi torquens cerealia saxa rotatu  
Stridentesque trahens per levia marmora serras  
Audit perpetuo ripa ex utraque tumultus

The other that rotates at sustained speed the corn grindstone  
 And run the rasping saws through the smooth marble  
 Their noise is heard from both the river banks.

His reference to the grindstones of the mills is explicit as it is to the unceasing harshness of the saws for marble, rotated by waterwheels along the Moselle river. Unfortunately, since they were made mostly of wood and iron, generally, little has escaped destruction.

### 9.3 The Floating Mill

From a strictly formal aspect there is actually no difference between a floating mill and a wheeled ship, although the kinematic movement differs as the former is immobile and the latter navigates. This was perhaps the starting point for the wheeled ship that dates to the last centuries of the empire.

It may have been the need to contain costs that led to the realization of a singular hydraulic mill during those same years, along the Tiber River in Rome: the floating mill. Its advantage depended on the transportation requirements of the period: numerous carts filled with wheat compelled to travel for kilometres to reach the mill, led to an increased cost of flour such as to vanify the benefits of the machine. But a mill that could move, descending or ascending the current, or that could easily be reached by boat, would, if nothing else, have reduced distance and cost to the minimum, obviously deferring processing times.

It is certainly significant that in the many drawings of medieval engineers, we often find a boat with a paddle wheel used to haul a rope in order to ascend the current. There are also numerous images of floating mills of various shapes and types.

The essential feature of a floating mill was a hull with a paddle wheel: the former fixed to the shore by ropes or chains, the latter always partially immerged and made to rotate by the current. However, due to the asymmetry of hydrodynamic resistance, such a mill tends to rotate until it neutralises the thrust, requiring multiple anchorages. To avoid this anomalous stress, they soon opted for two adjacent joined hulls, with a wheel installed between the two: a sort of catamaran, with a single deck for the millstones. An idea of this particular system is provided by the dredger designed by Francesco di Giorgio Martini (Siena, 1439-1501) and repeated by Leonardo da Vinci. In Fig. 9.12 are reported both the dredgers: on the left the one by di Giorgio (T.A., f. 64 v, T.120) and on the right the one by da Vinci (Ms. E, f.75 v).

It is interesting to observe that, while in the device by di Giorgio Martini the wheel is moved by a capstan through some step-down gears, the one (later) by da Vinci is hand operated by a crank; this is obviously non sense.

As pointed out, the performance of a wheel dragged from the bottom is much inferior to that of a wheel powered from the top. This deficiency, however, was compensated by the fact of not having to support the weight of the wheel plus the



**Fig. 9.12** Draggers by di Giorgio Martini and by da Vinci

weight of the water on the axis, and so it was possible to build much larger ones. This not only compensated for the deficiency but provided much greater power.

To compare the two, a wheel 3 m in diameter and 1.5 m wide—a size compatible with the space between the two hulls, installed in the same manner as river boats—was twice as powerful as a wheel powered by drop force, of the same diameter but only 0.3 m wide.

As expected, floating mills quickly became very popular and have remained in operation to the present time. It was very similar to the famous “Mulino del Po”, the novel by Riccardo Bacchelli.

## 9.4 Water Wheels in the Middle Ages and the Renaissance

Also in this field during the Middle Ages the studies on Greek and Roman water wheels were carried out by Arab engineers. A famous example of Arab water wheels are the hydraulic motors of the noria at Hama that are reported in the Chap. 12. The oldest description of a Hama’s water wheel is due to Nasir Khusraw (1004–1088), a Persian poet, philosopher and traveler in 1147.

Very well-known are also the devices powered by water wheels designed by Al-Jazari; since these water motors were coupled to a water pump or automata, these devices and their inventor will be presented in Chaps. 12 and 21.

In Europe, water wheels, derived from the Roman ones, were built during the Middle Ages and Renaissance and were used until few centuries ago; their widest development was reached in the 18th century before the diffusion of the steam engine. An interesting example of overshot water wheel designed in the Renaissance is shown in Fig. 9.13.

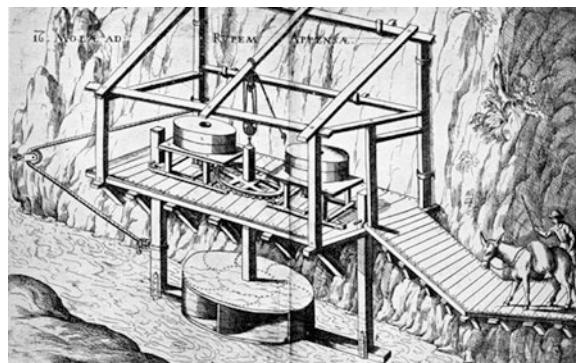
The device is an overshot water wheel whose axis is extended and some cams are fitted onto it. The cams move some hammers to crumble the mineral taken from the mine.

It was designed by Georg Bauer (1494–1555) in his treatise “De Re Metallica” (=About the metals) in 12 books on metals and mining, published in

**Fig. 9.13** Water wheel from “De Re Metallica” by Georgius Agricola



**Fig. 9.14** Water wheel powered mill by Fausto Veranzio



1556 but finished almost 6 years before. The author was a German scientist better known as Georgius Agricola that is a Latin translation of his name. He designed some other devices powered by water wheels like cranes, mine elevators and water pumps.

Another interesting example of a water wheel designed during the Renaissance is the one by Fausto Veranzio, reported in Fig. 9.14.

Veranzio (Sebenico 1551–Venice 1617) had many field of interest: he was glottologist, historiographer, politician, literary man and engineer specialist in fortifications. He was appointed commander of the fortress of Vezptim and studied military techniques and machines. His Masterpiece is “Machinae novae” (New machines), published in Venice in 1595 ca., in which most of his inventions are

presented. The book had many editions and translations and his inventions were frequently cited and used; among these the parachute and suspension bridge are very interesting. The water wheel powered mill reported in Fig. 9.14 is particular because it is suspended to a rocky wall.

### Observations

The horizontal axis wheel, powered from the top or the bottom, was paradoxically a technological step backward compared with the more archaic oblique paddle wheel. But since it was the only machine of unquestionably simple construction that could provide a significant level of power, it continued to exist, arriving almost unchanged to the present day: one example is the Pelton turbine. The paddle wheel reached its peak in the Middle Ages, when it was used in all productive contexts.

Paddle wheels or box wheels, activated the pumps that drained the mines, they pulled the large water wheels to raise water, they activated the hoists for wells, moved the saws that cut the large blocks of stone, rhythmically lifted the hammers on the anvils. Yet other wheels moved great bellows to light crucibles: we have knowledge of such systems, called hydraulic bellows, existing around the 15th century, from the notes of many Italian engineers. And it was by virtue of their massive immission of compressed air, that furnaces led to an obvious improvement in metal products and to what is not incidentally defined as the age of iron.

# Chapter 10

## Refrigeration and Heating

**Abstract** This chapter shows some techniques used during the Roman era in order to obtain a sort of refrigeration or of heating in the houses. Techniques to obtain ice during the same era are also reported. Finally, an example of the use of solar energy for heating is reported.

### 10.1 Air Cooling with Wind Towers

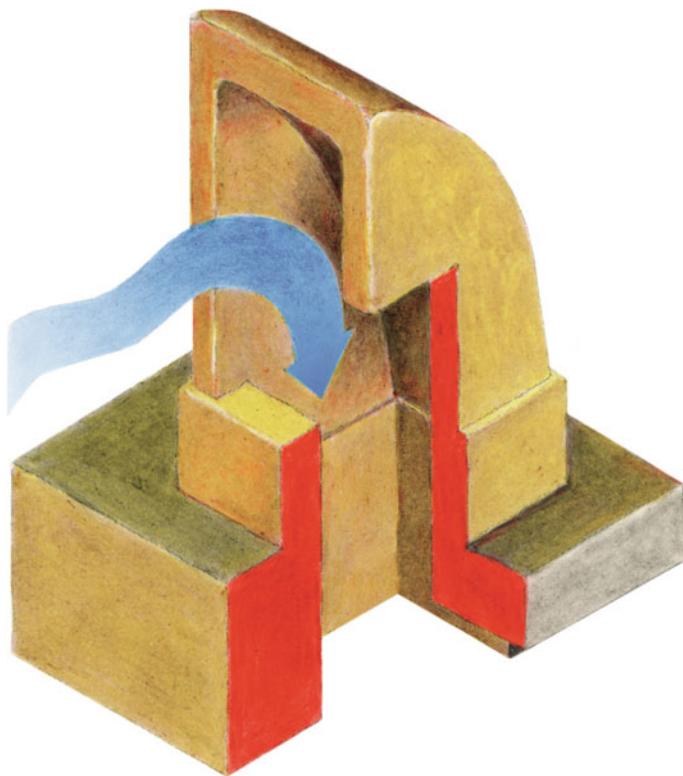
A fresco in the tomb of Nebamun, a senior official who lived during the reign of Egyptian pharaoh Amenhotep III (1387–1348 B.C.) describes his properties, including a house surmounted by two rather strange opposing rectangular triangles: see Charles K. Wilkinson: facsimile of a scene representing an estate (Tomb of Nebamun, circa 1375 B.C.) in Heilbrunn Timeline History of Art. New York: Metropolitan Museum of Art, 2000-. <http://www.metmuseum.org/toah/works-of-art/30.4.57>.

These are two ventilation outlets, present in Egypt since ancient times and known as *malqaf*, one directed downwind and the other windward.

These wedge shaped bodies were actually wind catching devices, one of the two systems providing passive ventilation, not requiring any energy, while the other extracted the warm air from inside the building by convection. Both were well known in antiquity. The former acted as gigantic nostrils through which the wind penetrated the house, while the latter consisted of tall towers in which, the joint action of the wind and the heat of the sun created a sort of draught, similar to what occurs in fireplaces, forcing the warm-humid air out of the house while introducing dry fresh air from the exterior.

In Fig. 10.1 a pictorial reconstruction of a ventilation outlet, by authors, is shown.

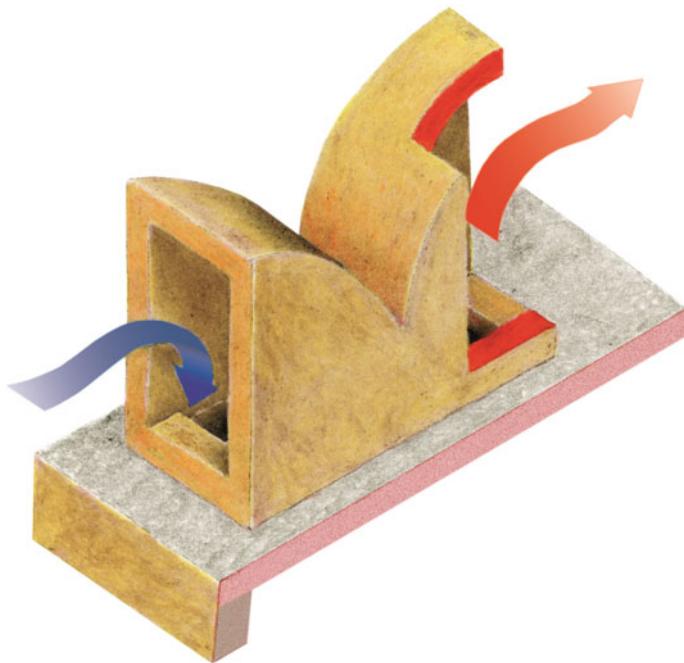
In the final analysis both systems functioned by means of the greater pressure exercised by cold air compared to warm air. The cold air that was introduced into an environment lacking any ventilation would force the warm air upward, expelling it. The higher the outlet the faster was the air thrust out, thus explaining the improved performance of the double *malqaf* installed on the house of Nebamun. This triggered an air flow fed by the different solar heat.



**Fig. 10.1** Ventilation outlet. Pictorial reconstruction by authors

This is the same process that occurs in fireplaces and may be the reason that from the very beginning Roman homes had their impluvium in the atrium—from *ater*, black because of the soot (actually carbon particulates)—in order to allow the smoke to exit, ensuring healthful ventilation, rather than for the accumulation of water.

In other words, these wind catchers were based on a very simple principle as they were, in effect, aerators, similar to the ones installed on tile rooftops or the air vents found on the decks of ships to aerate the spaces underneath, obviously of appropriate size. Since their orientation was stable they were ideal wherever the wind was constant, which was the case in the Near East. In Egypt, for example, the *khamsin*, a hot and oppressive dusty wind from the south or south-east can blow for up to 50 days. Catching it by using an inclined aerator and directing to the interior of the house, while keeping one side open, produced ventilation that provided a certain level of breathability and well-being. Practical experiments have confirmed that if a second conveyor is installed on the roof, performance increases and reaches its highest level when the two outlets face opposite directions, as in Nebamun's house, tripling the rate of air renewal and thus providing stronger ventilation.



**Fig. 10.2** Double entry aeration vent. Pictorial reconstruction by authors

In Fig. 10.2 a pictorial reconstruction by the authors of what above described is shown.

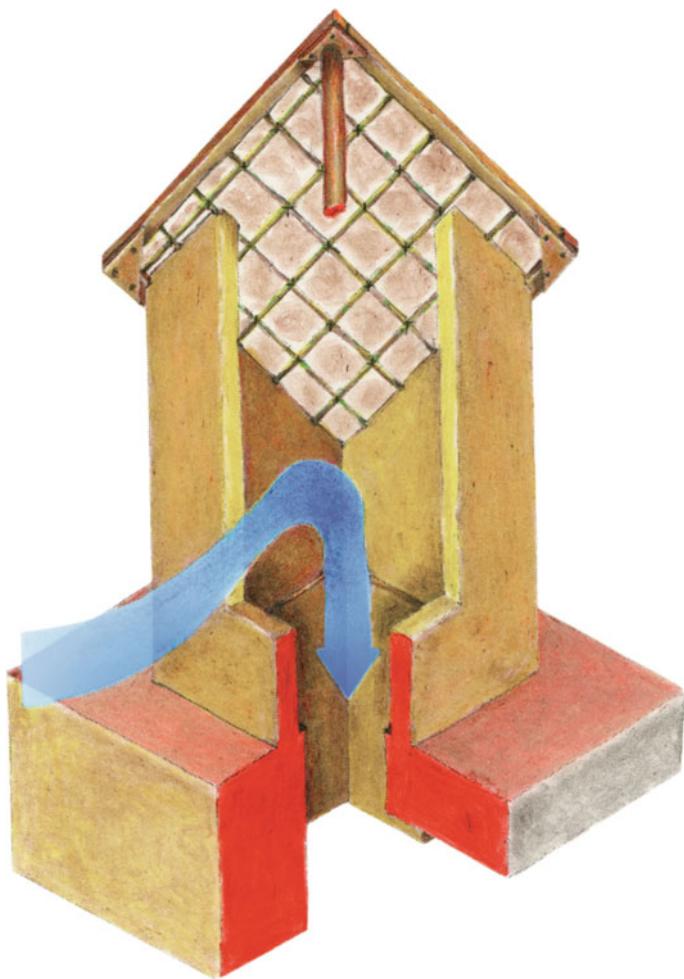
It must also be said that a two opposing malqaf system is optimal to catch cyclical winds coming from opposite directions, such as breezes from the sea and from the mountains.

On the roofs of many of the houses in the Near and Middle East, such as in Hyderabad, Pakistan, a city battered by monsoons, the malqaf was transformed into a square conduit measuring approximately 1 m per side, surmounted by an inclined plank of wood or adjustable pane, connected underneath with the interior of the house.

These systems were also used in more recent times in cities of the Middle East. In the book by B. Rudofsky “Architecture Without Architects: A Short Introduction to Non-pedigreed Architecture”, for example, we find several images of the Pakistani city of Hyderabad where such “conditioning” systems are easily recognizable and clearly still in use in the 1960s.

In Fig. 10.3 a pictorial reconstruction of the above system, by the authors.

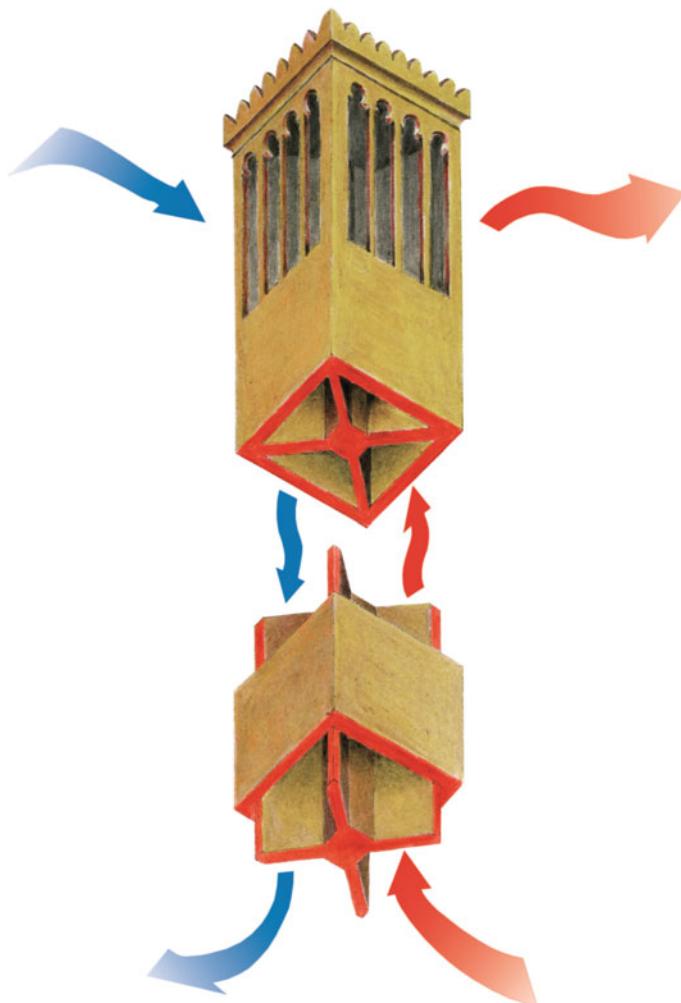
The wind captured in this manner did not decrease temperature, but, like a modern axial fan, it ventilated the premises, renewing the air and reducing humidity, greatly improving breathability. In order to really lower temperature they sometimes placed rags or blocks of carbon soaked in water in the downward internal conduit or introduced a light drip issuing from a tank placed on the terrace.



**Fig. 10.3** Pictorial reconstruction of square ventilation conduit, by the authors

In all cases, as the water evaporated it removed heat from the air, lowering the temperature and refrigerating the area. The *malqafs* were built, and in some regions still are, with a single opening or with two opposing ones but with separate conduits, later evolving into towers with four or eight outlets installed on the rooftops. At that point the ventilation system evolved from simply catching the air to extracting the air: at higher levels, in fact, the wind is cooler and faster and since it carries less suspended particles of dust and sand, it provides more effective ventilation.

Between  $15^{\circ}$  and  $30^{\circ}$  latitude are Iran—ancient Persia—Afghanistan, Saudi Arabia and Yemen, with average daily temperatures of between  $40^{\circ}$  and  $50^{\circ}$  and a very strong temperature fluctuation between day and night. Since it was not



**Fig. 10.4** Pictorial reconstruction of wind tower, by the authors

possible to use windows as they would allow additional heat to enter, they began to use tower ventilation systems. The majority had a square base, rose to a height of between 8 and 15 m, and in Persian were called *badghir*—literally, «wind catchers»—, known to us as ventilation towers.

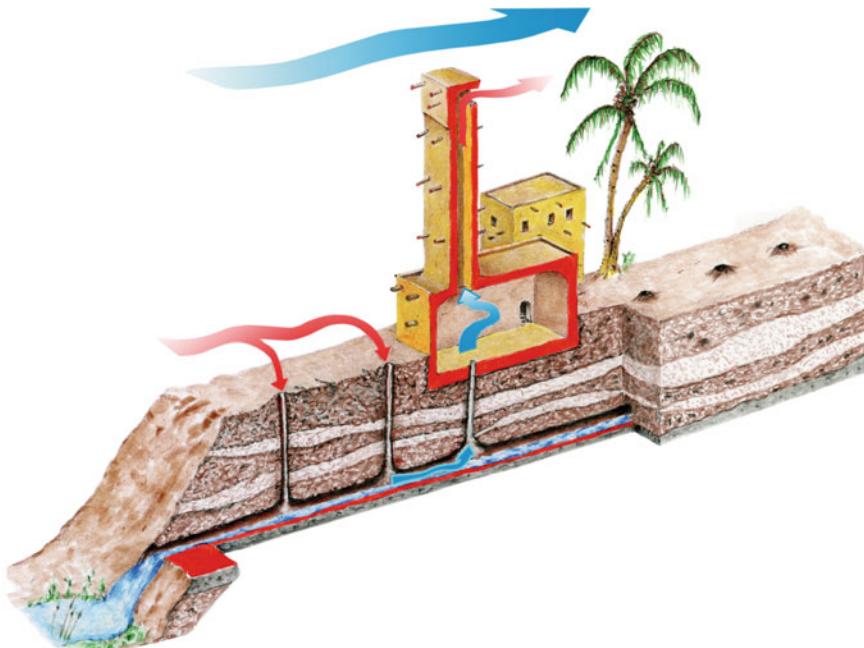
In Fig. 10.4 a pictorial reconstruction of a ventilation tower, by the authors is reported.

As it can be observed, the upper part of each side had numerous narrow vertical slits, forming a sort of intake grid in front of the rear conveyor box, as wide as the tower. The main body was divided by an X shaped vertical diaphragm into as many conduits, all expelling into the underlying premises. In effect, the top of a tower was

divided into four adjacent *malqafs*, oriented toward the four winds in such a manner that the dominant wind would penetrate the opposing grid, enter its conduit and flow into the house. Since the surface of the vent measures an average of roughly  $1.5 \text{ m}^2$  and the conduit barely  $2 \text{ m}^2$ , as the air descended it underwent a slight pressure that did not increase the temperature but did increase speed. Thus once it reached the room below the hot air at low pressure, instantaneously expanded, cooling, and expelling the air from the other conduits of the tower, facilitating its ascent. No matter which direction it was facing, during the day a square tower always had two sides in the shade, thus even if there was no wind the air inside the four conduits reached very different temperatures: torrid in the sides facing the sun and cool in the others. This also caused a difference in pressure that in turn generated strong convective currents, creating a forced ventilation of the house and making it  $7^\circ\text{--}8^\circ$  cooler day or night.

The temperature decreased even further when, as with the soaked rags of the *malqaf*, the wind towers caught the fresh air circulating in the *qanat* (long tunnels with numerous vertical wells), very common in Persia and Arabia, that collected the phreatic waters and brought it to the exterior, given the almost complete absence of evaporation.

In Chap. 11 an authors' virtual reconstruction of a *qanat* is reported. In Fig. 10.5 a pictorial reconstruction of the wind towers of a *qanat*, by the authors is shown.



**Fig. 10.5** Pictorial reconstruction of the wind towers of a *qanat*, by the authors

As the tower was constructed over one of the many wells of a *qanat*, the pressure caused the cold air that had penetrated from the other wells (an average of one every 30 meters of tunnel, indispensable when excavating in order to remove the debris and later to provide ventilation of the aqueduct) and that circulated over the surface of the water, to be drawn upward. The temperature of the air in the *qanat*, in fact, was significantly lower than the exterior, both because it was a few dozen meters in depth but also because it was in contact with the phreatic water that was always cold. Since a lower temperature meant greater pressure, that air would not have been able to rise without the suctioning power of the tower but, because of the powerful upward force it first invaded the basement in which the well was located and then saturated the house itself, while the hot air escaped into the wind. Contrary to the ventilation devices described previously, this had a powerful refrigerant that was almost inexhaustible and at a constant temperature, thus its correct definition as a passive aerator, such that even today many consider it to be superior to the most advanced air conditioners.

Notwithstanding the ubiquitous presence of modern air conditioners, and perhaps also because of the energy crisis, the tendency that was rapidly leading to the complete destruction of wind towers began to reverse. A promising natural architecture, rediscovering and reutilizing residential criteria less devastating to the environment, has brought back passive ventilation after several millennia of honorable service.

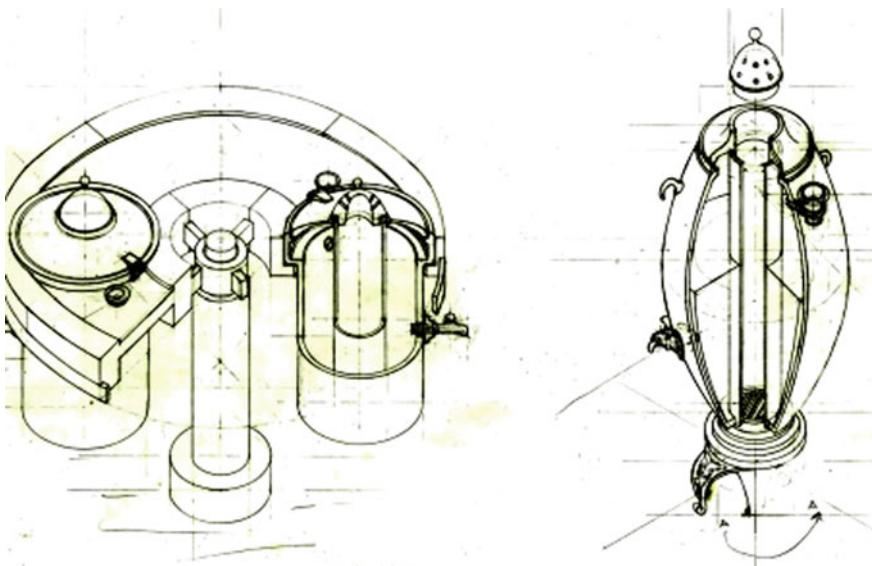
## 10.2 The Production of Ice

Pliny described the ice industry of his era in these words (XIX,19): “Cold is carefully preserved in the summer heat and man’s invention is racked how best to keep snow freezing in months that are not its own; others first boil water and then freeze it”. The quotation indicates that hot water was preferable to cold for purposes of freezing, an oddity, that the Naturalist was not able to explain but simply made reference to it. The underlying phenomenon however, far from being just another eccentric piece of information, refers to the fact that hot water can be cooled much faster than ice water! This is currently referred to as the “Mpemba effect”, from the name of a student from Tanzania who observed, in 1963, and in a purely accidental manner, that when he placed two containers filled with water into the freezer, one containing water at 35° and the other water at 90°, the latter froze much quicker!

The same conclusion was reached by Aristotle, who described the paradoxical phenomenon in his *Meteorology I, 12.17*: “Hail at times falls at the end of summer. What contributed to the rapidity of the cooling process is the fact that the water had been previously warmed; and this allows it to cool more rapidly. Thus when cool water is needed quickly, they expose it to the sun!”

If it is obvious to compare the formation of hail to that of ice, the deduction is not as obvious: for this to take place, in fact, the water must be in a closed, porous urn, placed outside on a clear night. As the water oozes out, it evaporates, but since

it cannot receive any heat from the exterior it takes the heat from itself, lowering its own temperature, as happens with perspiration, which may have inspired the process. Sources indicate that this procedure was carried out especially in Egypt, during the dry summer nights: by dawn the repeated currents of air formed a thin layer of ice in the urn. There still exists a simple procedure to obtain pure ice from dirty ice or dirty snow, a process so simple that the Romans must also have been familiar with it. Filling a basin with the dirty snow and placing a copper container filled with pure water in the center, if we add an abundant quantity of salt to the mixture, the temperature precipitates to  $-22^{\circ}$  (eutectic mixture), freezing the water. This process was introduced into Sicily by the Arabs, though there are various hints that it was already known previously. In any event, one way to obtain a great quantity of ice in the city during the summer, and Pliny did not neglect to stigmatize this, was to preserve snow in large pits, called snow-houses, located at great heights. The procedure, which was only apparently rudimentary, seems to have been practiced since the III millennium B.C., as confirmed by several logically suitable spaces found in Ur and Mari, and ceased only around the middle of the last century with the arrival of refrigerators. The reason for such longevity was the constant and varied demand for ice, to cool or preserve food or for medical uses. A need that greatly increased during the warm seasons when, with the exception of tall peaks, none was available. In Fig. 10.6 an authors' virtual reconstruction of a samovar, based on remains found in Pompeii is shown.



**Fig. 10.6** Authors' virtual reconstruction of a samovar, based on remains found in Pompeii

The ice resulting from preserving the snow found in mountain top ravines, was, in principle, one of the few pleasures of the poor, as it was only available in poor mountain villages, from Anatolia to the Apennines. Thanks to the speculative ability of the Greeks however this rapidly became a precious resource for trade: blocks of ice preserved in wooden boxes insulated with straw managed to reach the cities, at high prices. Wine cooled with snow is confirmed as far back as the 6th–5th century B.C. by the appearance of a refrigerating pitcher, the *psykter*, and the more sophisticated samovar, which poured cold water (using snow) on one side and wine warmed by embers on the other.

There are frequent allusions to this process in sources of the era, from Athenaeus to Plato. The consumption of ice increased significantly under the Romans, as it was considered indispensable for wine mixtures, to cool water for the *frigidarium* or to treat injuries.

### 10.3 Nero's Sherbert

The demand for ice increased significantly following a discovery attributed to Nero, who allegedly crushed ice and added fruit juice to make delicious sherbets. Something that soon became a popular serving for every meal, calling for great improvements in supply and transportation techniques in order to minimize losses. It seems that Nero's sherbet made its first appearance during one of Nero's sojourns in Baia, and so the ice he used could only have come from the nearby Lattari Hills, specifically Mt. Faito, over 1300 meters high. Covered by a luxurious beech forest, thus its name, this hill overlooks the inlets and coves of Vico Equense, forming a natural port. Thanks to its height and beeches, the peak of the hill was ideal to preserve snow in special, roughly made pits whose proliferation is attributable to the Romans. These artificial grottoes and deep pits were excavated among the centuries old trees so that they were always in the shade, at a moderate depth from the surface of the soil and with an access systematically facing north. The snow was preserved inside the pits, after it had been compacted and transformed into ice, eschewing any contamination with the soil or other impurities.

The capacity of each pit varied from a minimum of 5 to a maximum of  $35\text{ m}^3$ : which were rather modest volumes but perhaps purposely so to ensure better insulation. When storing the snow in the pits they first sheathed the bottom and sides with a thick layer of dry leaves, followed by a first layer of snow. This was followed by a second layer of dry leaves, more snow, and so on until the pit was full. Once finished, they covered the pit with a thicker layer of dry leaves and a final layer of soil. In the beginning of summer they reopened the pits, cut the ice into regular blocks and brought it to town as quickly as possible. In addition to these excavated snow houses, they also built others in masonry, similar to small rural homes without windows or like lime ovens, with a large hole inside to preserve the

snow after it had been transformed into ice. Whatever form it took, in the end the snow house was really a huge thermos in which the fusion of ice took place in a very slow manner.

To ensure fast transportation they used a ‘*palorcio*’, a word that, apart from its apparent similarity to Neapolitan, is not indigenous to the area. However it is wholly similar to the Italian word ‘*palorcio*’ (an Italian transport system), though not Tuscan in origin. In fact its root is in the Byzantine Greek ‘*parolkion*’, the diminutive of ‘*parolxos*’ (hawser) or, in simpler terms, a towing line between two boats, used to transfer items with great equilibrium and ability. According to our dictionary a ‘*palorcio*’ is a crude rope system, also called a ropeway or telpher: a sort of embryonic cableway, the progenitor of all funiculars! Its rope was stretched between two supports, the upper one at departure point and the lower one at the point of arrival, with suspended hooks or, if the slope was not sufficiently inclined, with suspended pulleys used to send wood, coal, forage or, in this case, ice downward.

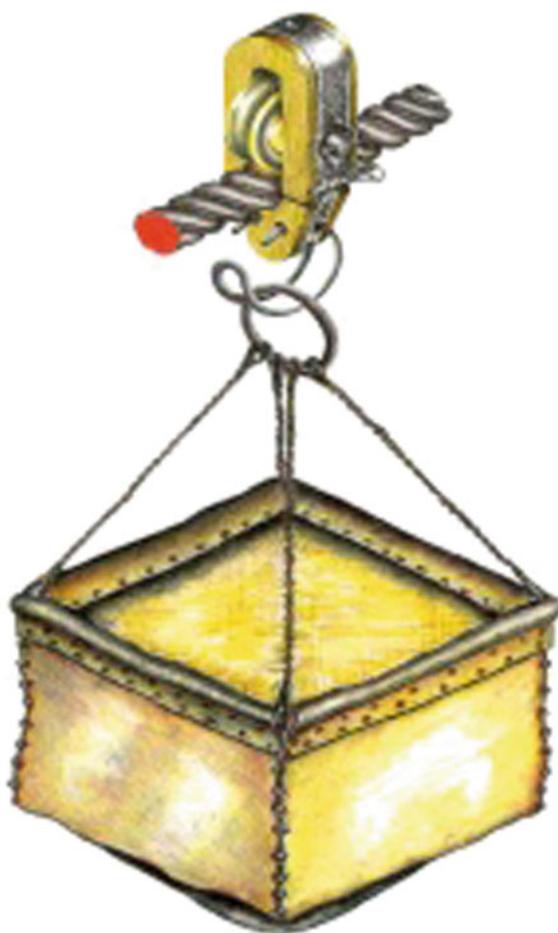
No wagon was required, no traction rope, no pull rope and, characteristically, no intermediate stand or pylon. The advantages of such a means of transportation compared to a mule track are obvious, all except for the most important factor in transporting ice—speed. In a few seconds, the containers of blocks of ice fell from the top of the mountain to the seashore, quickly ending up in the cargo holds of the fast liburnae used as supply ships.

But did the conditions for transportation by rope exist at the time? Moving objects, and sometimes persons, by rope is a very ancient practice. Seneca, for example, in his *Epistola* 88 mentions machines to lower actors and others that allowed these same actors to fly through the air. Actually they only appeared to be flying, as they were attached to a pulley sliding along a rope, much like the flight of the Angel ceremony in Venice, in which they use a cable, albeit a short one. The ‘*palorcio*’ on the other hand, was a mooring line about 200 m long and when the distance to be travelled was longer they often had to transfer the cargo or connect it to other lines. These were used to move heavy loads that were suspended on hooks, but since the strong friction generated by the speed would quickly wear out the fibers, they began to use pulleys. In a system that had no upward climbing ropes these pulleys were similar to the *pasteche* because they could be opened.

The remains of several pylons of stone that allowed the *palorcio* to function are still visible along the slopes of Mount Faito. They are 18th century structures very similar to the much older ones that had been located in the same sites during the Roman era. Current laws limit individual loads going down to 50–100 kg, an amount similar to that of the classical era.

In Fig. 10.7 the authors’ pictorial reconstruction of leather bucket to transport ice is shown.

**Fig. 10.7** Authors' pictorial reconstruction of a leather bucket used to transport ice



## 10.4 Wheat Pits

The first farmers soon realized that the harvest of a field decreased year by year, but also that it was sufficient to seed the surrounding uncultivated lands to ensure an equivalent harvest. In ancient times they did not have sufficient knowledge to explain the reasons for this phenomenon, but this did not prevent them from conceiving of and applying an effective remedy, known today as fertilization. An operation that consisted in reintegrating the *humus* of nutritive substances needed to grow vegetables. Wheat (*Triticum vulgare*), the cereal that is the foundation of civilization basically requires nitrogen, phosphorous and potassium. Durum wheat, *Triticum turgidum*, richer in proteins, and common wheat (*Triticum aestivum*) only require the phosphorous and potassium naturally present in the clayey-limey or sandy soils, the more so as potassium, concentrated in the stalks, returns after

combustion. In conclusion, those particular soils only required nitrogen fertilizers, available by the rotation of appropriate crops and, especially, by using manure and organic waste from sheep.

This last is considered to be the best because the nitrogen is released slowly, fertilizing the *humus* progressively, according to the need for growth. Thus dry and hot soil, used for pastures and nitrogenic agriculture according to biennial and triennial cycles, are excellent for durum wheat. This method became established along the entire Tavoliere plains (also known as the Table of the Apulia region), more than 3,000 km<sup>2</sup>, thanks to the practice of transhumance starting in the 12th century, reaching its maximum development following the institution of the Sheep Grazing Dogana of Foggia in 1447, when millions of sheep were brought to the plains of Puglia to spend the winter grazing in the pastures and defecating, thus regenerating fertility. But the result was a devastated countryside, land sacrificed to the attainment of enormous profits for the pastoral-cereal sector, to the point that Frederick II would not have been able to recognize the *precipua amoenitas* of his beloved Capitanate (the province of Foggia) with its great forests and vast marshes now reduced to such endless barren spaces. But the harvests were so abundant that the Tavoliere Plains became known as the wheat basket of Italy and still today, the majority of the approximately 7 tons of wheat produced annually in our nation comes from the province of Foggia.

In the 13th century this amount must have been smaller, but it certainly greatly exceeded the food requirements of Foggia, Lucera, Manfredonia, San Severo and Cerignola, leading to a flourishing commerce. However, they had to find an appropriate means of storing those mountains of wheat, a reliable system of silage that could ensure perfect conservation and of course protect it from thieves, both human and animal. The solution most likely came from the legacy of experiences accumulated in the Tavoliere by the first farmers of that region. As demonstrated by numerous studies conducted after World War II, this area of Puglia was densely occupied by Neolithic communities who created underground structures in their villages (as in the area of Passo di Corvo or Masseria Aquilone) excavated in the calcareous rock formations and that were most probably used to store cereals.

In writing of the cultivation of wheat Pliny [XVIII, 73, 306] mentions several methods for storing it. In his opinion the most beneficial was to "place them in those pits called '*siros*' (thus the word silos), as in Cappadocia, Thrace, Spain and in Africa. First of all they had to be dug in dry soil and the bottom covered in straw; the wheat was also preserved as sheaves. So that if no air reaches the wheat, they would not generate anything harmful. According to Varrone, the wheat preserved in this manner could last 50 years". In those same regions of the Byzantine empire it is likely that the wheat pits described by Pliny, and before that by Varrone, became even more numerous in the Middle Ages, encouraging their use in other provinces. Emphatically the word *Capitanata* is the deformation by metathesis of Catepanata, a province of the Byzantine Empire that included San Severo, Lucera, Foggia, Manfredonia and Cerignola, an area that was completely demolished around the middle of the 12th century by the Normans. In the meantime, pits found in the lands of the Tavoliere and the great quantity of cereal produced in the area

indicated this was the ideal location for the large scale adoption of such pits, with only slight variations dictated by the climate.

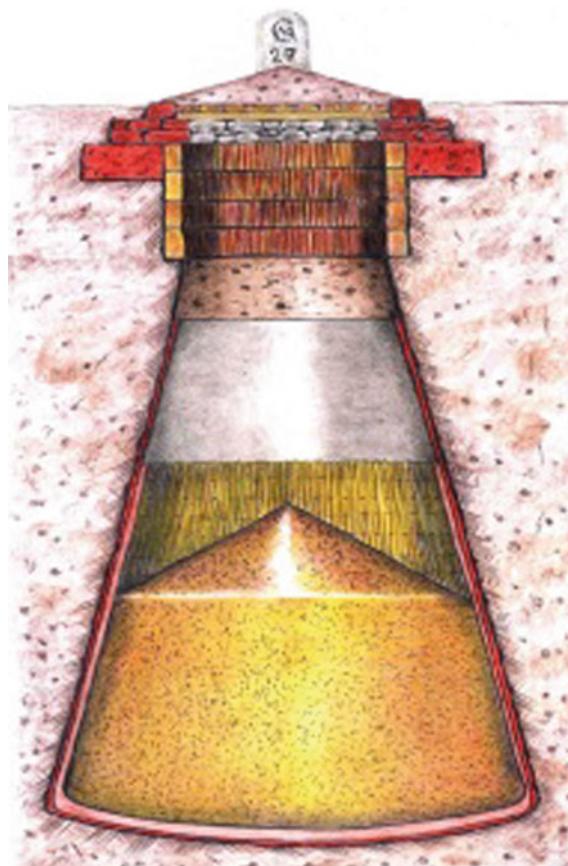
In very general terms a wheat pit is a conical excavated section, with a large base, from 4 to 6 m in diameter, located at a depth of no more than 8 meters, with a circular opening measuring about 1 m, corresponding to a maximum volume of 400 cm. An “underground trullo” that could contain between 400 and 1100 tons of wheat, corresponding to about 150 m<sup>3</sup>.

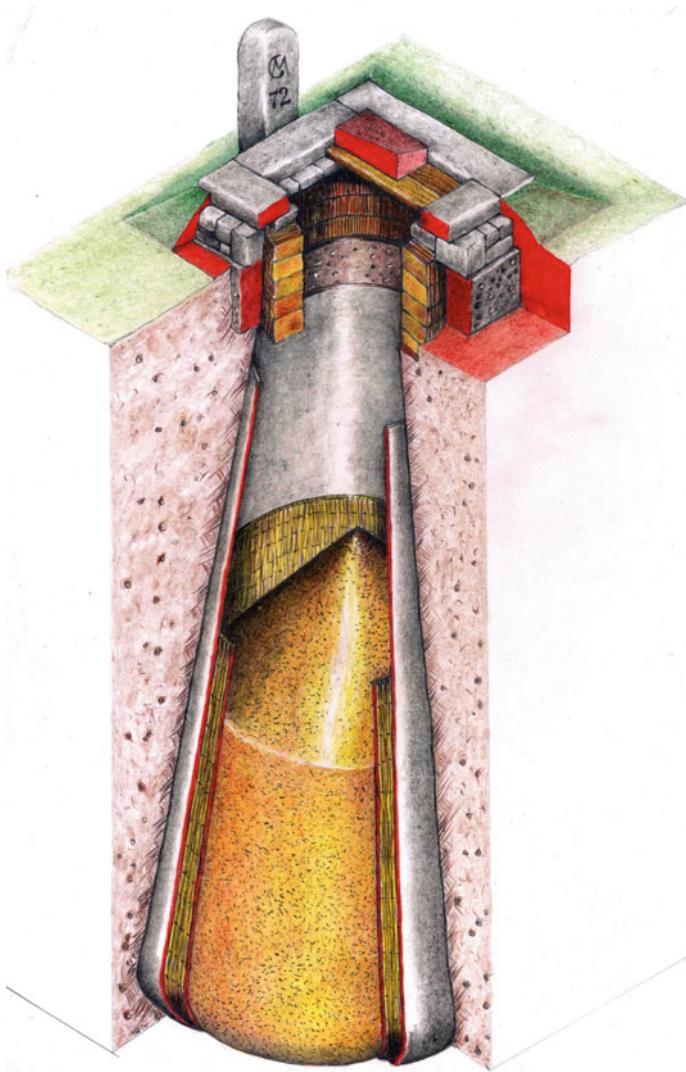
In Fig. 10.8 an authors’ pictorial reconstruction of a section of the wheat pit is shown and in Fig. 10.9 a perspective section of the same is shown.

The pit had to be completely dry and was made such as to absorb even the small quantity of vapor that issued from the grains until they were completely ripe. There was no problem of humidity or infiltration, the former because of the depth of the aquifer and the latter as it was impeded by the perfect seal of the opening that lay on a cylinder of absorbent bricks.

Positioned on a special section of the excavation, these provided support for the closing device, as complex as it was crude, placed on a cube of masonry rather like

**Fig. 10.8** Authors’ pictorial reconstruction of the wheat pit





**Fig. 10.9** Authors' perspective pictorial reconstruction of the wheat pit

a square hatch made of stone, with a small projection within. The hatch was covered by two intersecting rows of oak planks, surmounted by a pyramid of tamped earth, making it impermeable. In the middle of one side was a stone 60–70 cm high, with a monogram or number indicating the owner of the pit.

The oldest pits had no sheathing within, as the solidity of the loamy soil provided sufficient resistance. In later years however they began to plaster them, using lime based mortar, which also provided a moderate degree of absorbency. The bottom of the pit was also coated and had a slight concavity with a small well in the

center to eliminate the cleaning water. Since the cleanliness of the wheat was its greatest value for purposes of sale, they began to line the coating with straw. This insulating and protective sheath, made starting with a thick layer along the bottom to absorb any residual humidity, kept the pit completely dry.

The wheat, as indicated by its cubic amount and the size of the pit, did not fill more than half of the structure, leaving a large air bubble, making it hermetically insulated. In the days following the siling, as the grains transpired they rapidly used up the oxygen, transforming it into carbon dioxide, an inflexible and lethal guardian! From that moment on no living being could enter the pit: parasites, rodents and thieves would have quickly died. In this space made sterile by the CO<sub>2</sub>, the wheat went into dormancy and could be preserved for a long period of time: in citing Varrone, Pliny talks of 50 and even, 100 years for millet!

To empty the pit they used a special category of personnel: ditch diggers, divided into teams led by a “corporal”. When the mouth was opened, it was aired by fanning it with cloth sacks to remove the carbon dioxide that, heavier than air, stagnated lazily over the wheat. After 2–3 h they lowered an oil lamp: if the flame went out it meant that the gas was still present; if it remained lit a man would go down and begin the remove the wheat. Through the centuries the number of wheat pits multiplied and, in order to facilitate the siling and emptying, were grouped in large peripheral areas, called Pit Plains, of which today there exists only one, in Cerignola, with over 600 of the 1100 original pits. At first it resembles an abandoned military cemetery, the pits all being equal and all provided with an identical stone: but underneath, until a few years ago, lay the most essential of resource to human life.

From a historical perspective the first document that briefly mentions the wheat pits of Cerignola dates to 1225: a donation to the Teutonic Knights of Barletta:

«unam domum (...) cum duabus foveis».

“One house (...) with two pits”

The second mention dates to 1308, also a donation, with the writing:

«in certis foveis in Cidiniole» e ancora «in diversis foveis in dicta terra Cidiniole».

“in certain pits in Cerignola” and “in several pits in the mentioned land of Cerignola”

But we must wait until 1538 to find an explicit reference to Piano di San Rocco or Piano delle Fosse (Plain of St. Rocco or the Plain of Pits), in front of the Church of San Domenico, formerly San Rocco. Although it was the Capitanata region that made the most use of wheat pits, they were also found in numerous other regions of Italy, such as in Marche and Tuscany, starting from the 13th century. Pier de Crescenzi (Bologna, 1233–1320), one of the greatest medieval agronomists, for example, wrote in his *Ruralium Commodorum book XII*, that:

“some (people) make a pit and they put straw on the bottom and on the walls so that no air nor humor can get inside, except when (the pit) must be used”. In his treatise on architecture Francesco di Giorgio also writes of the wheat pits, saying that rural houses should have had “more wheat pits to preserve the wheat according to need”.

He also wrote, that “in order to better preserve the wheat they should make a pit like a cistern or one made of concrete, well-sealed on all sides; leaving a small hole and covering it with planks and solid earth to preserve the wheat, and sheathed with straw on all sides as is the custom. In this manner the wheat will be better preserved because the tufa or other soil would prevent humidity from destroying the wheat”.

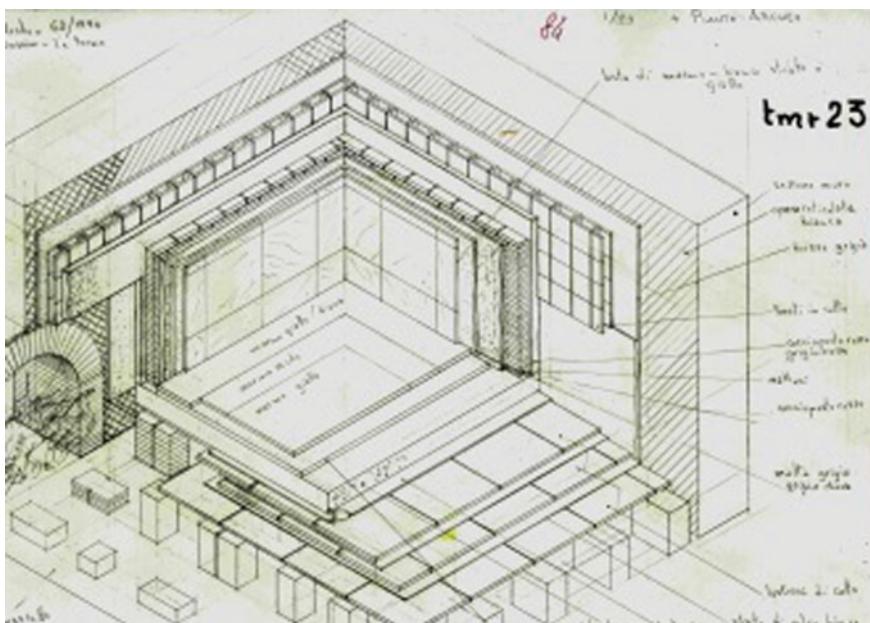
Except for Cerignola, the wheat pits have almost all disappeared, as a modern silo can contain up to 7000 tons of product! But wisely and perhaps *in extremis* those that still exist in the Puglia city, taking up most of the Piano delle Fosse, were placed under the protection of the Ministry of Cultural and Environmental Assets on July 5, 1989, pursuant to Law 1089/39. This will probably prevent their destruction, but it will be difficult to avoid negligence, contrary to the fifty or so that still continue to perform their ancient service.

## 10.5 Heating and Thermal Baths

Anyone visiting Pompeii or Herculaneum cannot avoid the feeling that he is among the ruins of a tropical city; one never touched by winter cold, for even in wintertime the temperature decreases only slightly. Which could have been true as the historical context of those homes coincided with one of the many warm cycles that have succeeded themselves over the past two millennia. Not so in other regions of the Empire, where the cold season truly did exist. In those areas the windows had glass and the houses were heated using a system that was even more logical than the modern one. It was in effect a domestic variant of the hypocaust that is so widely used in thermal baths. A wood burning boiler produced a great quantity of hot air that was made to circulate underneath the pavements and behind the plastered walls thanks to the difference in pressure with cold air. For this purpose small columns and supports, called *sospensure*, raised the pavement, while hollow bricks, installed along the walls, called *tubular parietes*, connected to the area underneath the pavement allowed the hot air to heat the walls and then vent outward.

In Fig. 10.10 a cross section drawing of the thermal baths of Pompeii is reported.

Obviously the circulating temperature of the air was relatively low, but a couple of days were sufficient to bring a comfortable warmth inside the building and there certainly was no lack of wood or labor to keep the boiler constantly in operation. It should also be noted that this same boiler also heated the waters of the domestic springs and baths, making maximum use of the installation. As already mentioned, a concept similar to this heated the water of the tubs and premises of the Roman baths. And although this was not a Roman invention it did become a distinctive characteristic of Roman life. The Romans went to the public baths not only to bathe and exercise but also to enjoy leisurely walks, entertainment, socialize, to discuss business matters, eat and drink, see performances and admire works of art. In effect, to enjoy life in an environment that, like our beaches, encouraged interpersonal relationships. No wonder that the construction of thermal baths became a specific political commitment of emperors, local influential politicians and well-off private



**Fig. 10.10** Cross section drawing of thermal baths of Pompeii

individuals. And one of the first tasks of the military engineering units, the *faber* of the legions, when a camp was made permanent.

It's obvious that these structures were also intended to meet hygienic and sanitary needs not otherwise fulfilled, at least during the archaic phase. One of these structures that has come down to us almost intact, though of medium size, are the Stabian Thermal Baths of Pompeii, providing us with some very specific information. From a historical perspective it is the oldest of the known baths, dating to the 2nd century B.C. "Divided into two sectors, one for men and one for women, located along a single longitudinal axis on the sides of a common furnace, the complex extended over a surface area of over 3500 m<sup>2</sup>, including the large courtyard with porticoes on three sides, used as a gym, as well as a large pool with dressing room and additional spaces sufficiently large to be used for indoor physical exercise". ARCHp70.

To give a better idea of the technical aspects of these large installations, we must consider the enormous requirements for water: for his thermal baths Agrippa had the Aqueduct of the Virgin built, bringing approximately 100,000 m<sup>3</sup> of water daily from Marino to the hills of the Pincio. Before being used the water was collected in huge cisterns, probably to stabilize the quantity and pressure of the flow. From the cisterns there issued a complex distribution network to bring the water to the tanks used for cold baths and to the swimming pool. The water that was to be heated passed through other pipes, to the boilers, and was then sent out to the appropriate tanks. The boiler, or hypocaust, normally made of bronze, was underneath the

center of the building in the older installations, where a great quantity of wood was brought and stored in the immediate vicinities in quantities sufficient for a month. To ensure the stability of the boiler it was walled inside a special case. Larger installations normally held three of these boilers placed in battery formation and connected to each other by bronze pipes with stop keys. The water that was removed from the first, the hottest, was replaced by the tepid water of the second and so on with significant savings of time and fuel. A special device was used to introduce the water inside the tanks, which Vitruvius described meticulously calling it a "turtle". This was a semi-cylindrical bronze container in the shape of a turtle, thus the name, that when placed inside with the convex part facing the bottom was heated directly from the exterior thus also heating the water.

The warm or cold pools were fed by running water, since it was not possible to purify water as we do today using filters and pumps. This led to a conspicuous flow of water issuing from the baths, used for many other purposes according to its temperature. In one case it appears that it was even used to operate a windmill, confirmation of the logic of the installations and the intent to minimize any loss and waste not strictly necessary.

Rooms were heated by the hot air circulation system described above using the hot air produced by the boilers for the water.

## 10.6 Energy Saving: The Sun Chimney Heating and Thermal Baths

Apart from the performance of the machines, the slaves and the use of thermal power, the true question remains the estimate of the energy balance of Roman society, sufficiently evolved and in a phase of constant advancement. What was, in effect, the influence of slavery? And what was the actual average energy need for a Roman citizen of the 1st century in Rome and its provinces? In order to assess how far removed this was from the current needs of an inhabitant of the First World, we can suggest a few significant equivalencies: the motor of a vehicle of medium cylinder develops about one hundred hp, an improper expression but an effective one that, compared to the maximum power that can be provided by an average man, corresponds to the work of about 300 slaves; the energy absorbed by one domestic water heater is roughly equivalent to the power provided by 5 men, while in order to make a hair dryer work or light an apartment we would need 4.

It is logical to conclude that the energy availability, both natural and slave, even for the wealthiest, was far removed from our own standards. Considering also that then as now energy, in addition to being finite, involved a certain cost, it must be said that with the reduction of the most convenient sources—for the era the closest ones—its cost increased progressively, triggering ancient energy crises. The consumption of wood for example, that within a few decades increased exponentially, is a case in point. To get an idea of the quantities involved, just consider that in

order to cook one kilo of bread almost the same amount of wood was required and, considering an average daily ration pro capita of at least 250 gr we must conclude that when Rome exceeded one million inhabitants, they needed 250 tons of bread per day, thus an equivalent amount of wood, and 2–300 carts to transport it. If to this quantity we add the wood burned for the baths, by private individuals for heating and to cook food, by furnaces to produce urns and bricks—which the enormous cost of transportation restricted to areas near where it was to be used, i.e. near metal shops etc.,—we estimate an overall daily amount of over a thousand carts of wood to use for burning.

A tendency that rapidly increased deforestation, with the consequence of first increasing the cost of wood, thus leading to more complex choices such as getting the supply from more remote areas or transporting it by river and, above all, architectural solutions for energy savings. In fact, in the beginning of the 1st century we begin to see the appearance of environmental heating systems that did not require an excessive amount of combustion, but were based on the greenhouse effect, and that Pliny the Younger defined, with an appropriate neologism, as *Heliocaminus*, a solution that was widely adopted in the Baths and in the homes.

In conclusion, we cannot exclude that the breakup of the Western Empire may have also been caused by the decline or grave insufficiency of energy resources, just at the time that the demand became vital. The result was a crisis of social structures and complex military institutions, a risk that seems to have reappeared, with results that are enormously more catastrophic, in our own days. Now, although it may be far-fetched to estimate how much energy was indispensable, in its various manifestations, to the immense state structure of the Empire, it is possible to identify the different types used, starting with the one most easily available in nature.

All the energy available on earth and its immediate sub soil, with the exception of nuclear power, is the result of solar warming and, from an anthropic perspective, can be divided into renewable and exhaustible. The former, exploiting the effects of radiation, is continuously regenerated, and is thus also defined as natural, contrary to the latter that, by using resources that developed in the course of geological eras and not having the capacity to regenerate, tends to be exhausted and is therefore defined as fossil. The renewable energy source was obviously used abundantly since prehistoric times, given its vast availability in the form of wind, water current, fire or falling masses, and can be labelled as “primary energy”.

The other, though not unknown—as is the case with coal and naphtha—because of the difficulties connected with its extraction was only used moderately and was limited to areas in which it was present spontaneously, mostly in the Near East. They were even less familiar with methane, apart from accidental combustions. With the exception of these experiences, in ancient times they did not go beyond the use of natural sources, in the three spheres attributable to the four elements: land, water, air and fire. Areas that, coinciding with our four states of aggregation—solid, liquid, aeriform and plasma—seem to suggest, even in the beginning, a distinction that is energy related rather than material. At any rate the quantity of energy provided by the sun and transformed into the various natural forces are immense, equal to about  $200 \text{ W/m}^2$ ; the different levels of heating originated the

winds; evaporation caused the formation of dense blankets of clouds that, in turn, led to rain and courses of water. Aeriform and liquid fluids were therefore the primary energy sources and the machines that they powered led to the debut of mechanization, through the adoption of archetypical devices, also called “primary motors”.

# Chapter 11

## The Production of Water

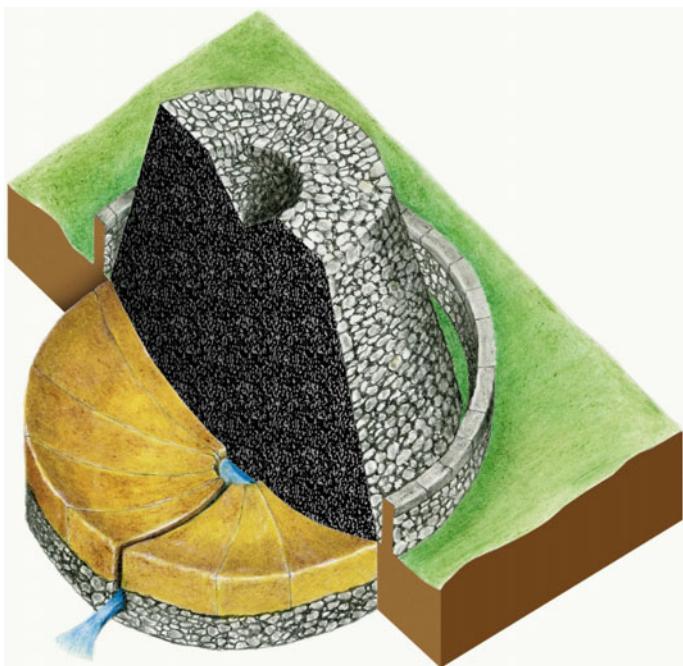
**Abstract** This chapter shows two not very widely known devices to obtain fresh water from air. These devices could explain how ancient towns could resist to long sieges without any apparent source of fresh water. Moreover, these devices are very simple to build and do not need any external source of energy, so they could be used even in the present days in emerging countries or in case of natural disasters.

### 11.1 The Air Well

The first to describe a device to extract water from the air, the air well, was in the summer of 1900, was the Ukrainian forestry engineer Friedrich Zibold. While performing a topographical survey on Mt. Tepe-Oba, in Crimea, near the ruins of Theodosia, the current Feodosiya also known in the past as Caffa, he found enormous piles of stones, each measuring over  $600\text{ m}^3$ . Only the ruins and a poor village adjacent to the Genoese colony of Caffa remained of the ancient city, founded around the VI c. B.C. along the shores of the Black Sea by the Greeks of Miletos and destroyed a 1000 years later by the Huns. The excavations that took place from 1900 to 1907 attracted international interest and brought to light various areas of the city, along with a network of terracotta pipes, about 10 cm in diameter. Some of these pipes issued from the piles of stones and ended in the many cisterns and fountains of the city, even though there was no indication of the existence of streams or other sources of water, even dry ones: an anomaly that may have led Zibold to his interpretation. There were about a dozen or so of these cone shaped piles, all about 10 m tall with a base measuring approximately 20 m in diameter, composed of small stones. Each was positioned on a concave platform similar to a dew pond, with pipes issuing from its center.

In Fig. 11.1 an authors' reconstruction of the above described piles is shown.

These artificial hills functioned in a very simple manner: the hot and humid air from the exterior penetrated inside, coming into contact with the colder stones sheltered from the rays of the sun and formed condensation on the surface of the stones. The condensation then trickled into the basin, subsequently draining into the



**Fig. 11.1** Authors' reconstruction of stone pile

pipes. According to his calculations, under optimal conditions the system could produce 50,000 L of water per day, or 4 m<sup>3</sup> per pile.

To verify his hypothesis, and with the help of local farmers, Zibold constructed a similar condenser at an altitude of 228 m, on top of Mt. Tepe-Oba. This was a cone shaped structure, 6 m tall and 8 m in diameter, composed of sea stones measuring 10–40 cm, resting on a stone basin. The experiment was successful and from 1912 to 1915 the structure produced 360 L of water per day, until the basin, whose remains are still visible today, broke down and the structure was dismantled.

Zibold's condenser led to various other projects for air wells. The most conspicuous was built in 1930 on a hill in Trans-en-Provence, France, based on a drawing by the Belgian Achille Knapen. This was a tower 14 m high and 3 m thick, very similar to a dovecote with its many openings and with an internal core of cement that remained cold, thus increasing dehumidification. However, since the lateral surface of the core was smaller than that of the stone piles, it was unsuccessful and produced no more than twenty or so liters of water per day.

A much more interesting device was patented in the 1950s by Rumanian engineer Henry Coanda; referring to a well-known principle of thermodynamics the inventor explained it in these words: "It is known that the air contains water and according to my invention the energy for precipitating this water vapor can be taken from the air itself in motion. It is known that for a given temperature a given volume of air may contain no more than a certain quantity of water vapor. When it

contains this quantity it is said to have reached its saturation point. Moreover, this point varies with the temperature, and the cooler the air, the less water vapor it may contain for a given volume.

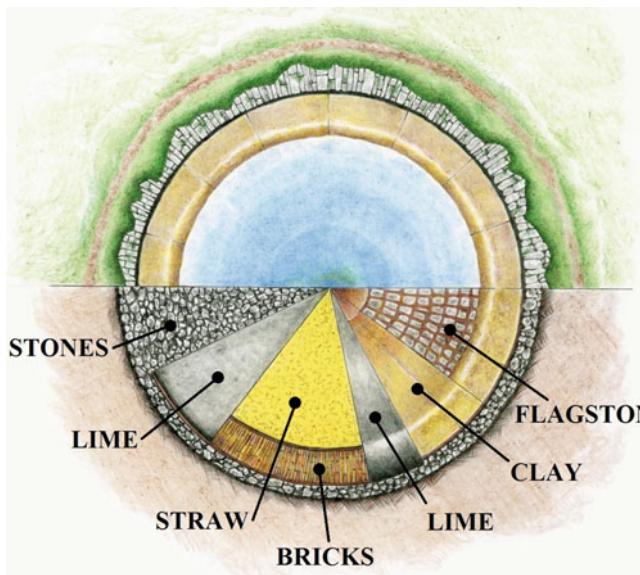
Consequently, when a relatively warm volume of moist air is cooled to a sufficiently low temperature, it yields the water it contained in excess over the quantity permitted by the saturation point at the temperature to which it has been cooled. In a continuous process of producing fresh water, it is necessary to absorb the heat derived from the warm moist air at a speed corresponding to the rate of cooling...”. He also recommended that the condenser be placed underground so that the soil could absorb the heat. “For example, 1 m<sup>3</sup> of air from a wind whose temperature is about 40 C. can contain up to about 50 g of water vapor; if the Wind is forced to enter a certain space ...a radiator in which a fluid circulates at the temperature existing 7 or 8 m below ground level, that is of about 11 °C, this wind will immediately precipitate on the radiator walls the portion of its water content which is in excess of that permitted by its saturation point at the cooler temperature, that is, about 40 g/m<sup>3</sup> of air, as the saturation point of air at 11 °C. is grams per cubic meter. The heat given off, which must be carried away by the fluid in the radiator, represents approximately 32 calories for said one cubic meter of air.

It is advisable to pass the fluid through a second radiator or heat-exchanger of large dimensions disposed in the ground at a certain depth. If the humidity of the warm air is definitely below 50 g of water per cubic meter, that is, if the air is far from its saturation limit, and if the device for obtaining fresh water is disposed near the sea, it is possible to use windmills to spray sea water into the warm air in fine droplets, thereby increasing the amount of water contained in the warm air through the partial evaporation of the sea water...” In the past few years other humidity condensers have been built. Quotation from *Coanda, Henri: US Patent #2.761.292; US Patent #2.803.591; US Patent #3.284.318*.

## 11.2 The Dew Basin

For centuries the ancients were familiar with at least two methods of extracting a moderate quantity of water from the air. A procedure that to our eyes may appear to be almost “magical”. But in actual fact it is something that we are wholly familiar with, especially during the summer when we note a veil of water forming around a glass filled with a cold liquid or when, after being left out during the night our car also is covered by a film of water or if we are seated in a car talking and in just a few minutes a mist forms on the glass. In all cases this is water extracted from the air in variable quantities.

The ‘Dew Point’ is the maximum temperature above which air vapor reaches the saturation point and below which it condenses into tiny drops. Water produced by dehumidification is called a ‘Dew Basin’ if produced in large basins and ‘Air Wells’ if produced in tall towers. Labeling aside, this was a method of obstructing the motion of the air using large cold surfaces to produce vapor The structures had no



**Fig. 11.2** Authors' pictorial reconstruction of a dew basin

metal parts as it was sufficient to use rough stones, clay, straw and, when available, bitumen or slaked lime.

Dew basins and air wells produced very pure water, actually distilled water, as it flowed into clay or lead pipes at very low pressure and did not therefore form any deposits. Dew basins, known since prehistoric times, were made by digging a basin, about thirty meters in diameter, which at first may seem to be larger than necessary, and about 2 m deep.

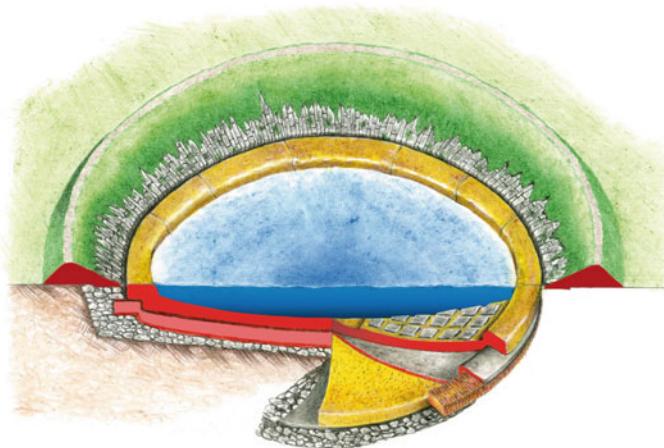
In Fig. 11.2 an authors' pictorial reconstruction, in scale, of a dew basin is shown.

The actual structure consisted of several different layers, starting from the bottom of the basin. The first layer was a loose stone foundation using crushed stones, about 10 cm thick, followed by a coating of slaked lime or smooth clay to level the surface and prevent any seepage. A second layer consisted of compacted dry straw, about 30 cm thick to insulate the basin, enclosed in a ring of bricks. The third layer consisted of lime, mixed and shaped into a spherical cap, upon which rested a 20 cm layer of wedge shaped clay called "crust", and finally, to protect the structure from the hoofs of animals, there was a final layer of flagstones.

An embankment of soil covered with clay surrounded the basin to prevent rain water from reaching the straw, as it was well known that optimal operation of the system depended on it remaining absolutely dry.

In Fig. 11.3 an authors' pictorial perspective of cross section of the dew basin is shown.

The diameter of the basin thus decreased to around 20 m, with an actual depth of barely 1.2 m at the center and a total volume oscillating between 300–600 cm, at times even less, for a cubic volume less than the aforementioned protections.



**Fig. 11.3** Authors' pictorial perspective of cross section of the dew basin

From a functional aspect even though the clay basin received the same amount of irradiation from the sun as the surrounding land, it maintained a lower temperature thanks to the insulation provided by the straw. As the clay dried due to the evaporation of water used for the mixture, it cooled and at night was significantly colder than the surrounding soil. Since the amount of vapor that the air can contain is directly proportional to its temperature, as the temperature decreased when it came into contact with the basin, the vapor would condense. The drops of water deposited on the surface slid toward the center and were deposited on the bottom. In fact, in order to facilitate the water's dropping down some of the basins had spiral incisions. During the day some of the water evaporated, but it was always less than the quantity that would condense on the following night. Hence, night after night, in spite of the slight losses and the water taken from the basin daily, the basin would fill, almost like an artesian well.

### 11.3 The Qanat

The system of underground collection of water and its flow through tunnels up to the end user, was, if not invented, at least massively used in Iran, where it is still in common use for domestic and irrigation purposes. The system, and its original name—‘qanat’—soon spread to all the arid regions of the Mediterranean area. It is important to point out an apparently obvious peculiarity: neither in antiquity nor in the modern era was this system in use in regions with sources of water that had even a minimum efficiency. This type of water supply presupposes the existence either of fairly large inhabited centers or highly productive agricultural areas, as there would not otherwise be any justification for the significant costs of constructing a qanat.

The qanat system is supported by underground channels in which the water from the aquifers flows down by the force of gravity from the slopes of the hills to the surface below. The qanats in Iran were built on such a scale as to rival the immense network of Roman aqueducts, with the significant difference that while the latter were by now archeological ruins the Iranian qanats are still in use, even after 3,000 years.

The system is in effect specular to Roman aqueducts, running underground and in tunnels while the aqueducts were aerial and had numerous rows of arches. But in both the water flowed by gravity and in the open. Contrary to Roman aqueducts the survival of the Iranian ones is not due to their validity but almost certainly to the local technological backwardness. Perhaps if the West were still in the Middle Ages the Roman aqueducts would not be considered simply as a ‘historical curiosity’ but a tragic necessity. The Romans were perfectly familiar with this method of capturing and conducting water, to the extent that Vitruvius left us a clear indication when he stated that: “it is simple to acquire water when the sources are in the open. If they are not the water must be found underground and collected ...”.

From a chronological perspective the technique used to construct underground aqueducts by means of tunnels excavated in a manner such that they conformed to the soil and were provided with vertical shafts to allow for ventilation must have been conceived in the II millennium B.C., such as the Tunnel of Eupalinos on Samos. This tunnel runs for 1 km and excavation was begun on both ends. We can only imagine the difficulties and harshness of such work, especially in order to remove the resulting debris using the ventilation wells.

In Figs. 11.4 and 11.5 photos of a qanat by the authors are shown.

As for usage we must point out that in modern day Iran there are over 22,000 qanats, forming a network of over 300,000 km, providing 75 % of the water used in that country for irrigation and for personal use. Until a few years ago the water in Teheran was supplied by a system of qanats fed with water from Mt. Ebrus. Qanats have been found in all regions that were part of the area of influence of ancient Persia, as well as in Pakistan, in Chinese settlements in the oasis of Turkestan, the

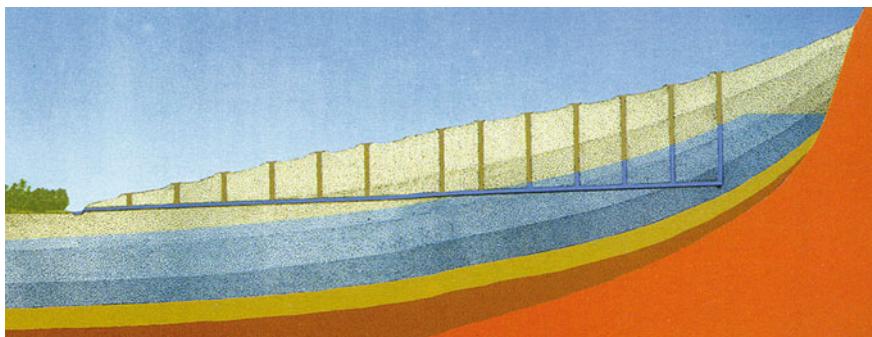
**Fig. 11.4** Qanat shaft



**Fig. 11.5** Qanat tunnel

southern regions of Russia, Syria, Arabia and Yemen as well as in Sicily and Spain because of the Arab domination in those two countries. The oasis of the Sahara desert is also irrigated by qanats.

But how were these qanats constructed? Normally a qanat is excavated along the slopes of a hill, in the aquifer composed of alluvial deposits, where there is some indication of the presence of water. It is approximately 1 m wide and 1.5 m high; the linearity of the excavation is achieved by using three lamps and develops for an average length from 10 to 18 km and varying capacity. Once the most promising area is identified they begin the excavation, usually carried out by two laborers supplied with a rudimentary winch. First they dig a well or shaft, then two others extract the excavated material, placing it around the mount, forming a small crater. In the best of cases the aquifer emerges at a depth of 15 m, but there are also cases in which they must continue the excavation up to 90 m before finding it. In the days immediately following they assess the extent of the vein of water found, making use



**Fig. 11.6** Drawing of a qanat

also of adjacent shafts: the underground passage for the qanat starts from the first shaft limiting the inclination to between 1/550 and 1/1500. The air shafts are made at a distance of approximately 50 m from each other.

In Fig. 11.6 a scheme of a qanat is shown.

## 11.4 Distillation

The first attempts at distillation reach so far back in time that we ignore its actual origins. It may have been the ancient Egyptians, or Persians, in whose sources we find several mentions of the process that was later rediscovered by the Arabs. It is just as improbable to determine what was actually distilled and why. The only certainty we have is that the premise was probably based on alchemy, perhaps to make perfumes or medications.

According to Synesius of Cyrene, 370–413, the Egyptians had been distilling wine since 4000 B.C. to produce the first alcoholic beverages, but it is more certain that this procedure dates to the 6th century B.C. in Mesopotamia, and Pakistan during the same era. It becomes a common procedure four centuries later also among Greek alchemists, especially the women scientists, working for the most part in Alexandria, among whom is Mary the Jewess, or perhaps even before that with Miriam, sister of Aaron and Moses, and inventor of the steam cooking that still bears her name; there is also mention of certain chemist called Cleopatra in the 1st century and especially of Hypatia, in the 4th century, who may have constructed the first distillation system. But it was the Arabs who brought the alembic, essential for distillation, to Sicily and then slowly introduced it to the rest of Italy. Its root is the Arabic word Al-Anbiq and indicated the impalpable powders used to highlight the outline of the eyes, while the word Al-Kulh is the root of alcohol. Many historians believe that the distillation of grappa took place for the first time in Sicily, shortly after the introduction of the alembic. With the proliferation of distilled substances it was no longer used for medical purposes but began to be used to make beverages.

In fact, starting in the 11th century there is specific mention in the rules established by the School of Salerno (see Chap. 17). The invention of new and more sophisticated alembics will later allow alchemists to produce the famous aqua ardens (fire water)—as that crystalline liquid, similar to water, was easily flammable—and aquae vitae, that is the water of life, or aquavit.

Incendiary mixtures and their applications are discussed in Chap. 20.

# Chapter 12

## Lifting Water

**Abstract** The need to lift large amounts of water from a basin to a higher level was strictly connected with the agriculture, hence with the birth of the civilization; the Code of Hammurabi dating to the 18th century B.C, in fact, made explicit reference to irrigation machines. In this chapter the early water lifting machines are presented from the shaduf till the Renaissance; Greek-Roman pumps and Islamic devices are also presented.

### Introduction

Water is without doubt the most necessary element for the life, for this reason, the devices to raise water from wells were among the first to be conceived. The need to raise water in large quantities from the bottom of a well or from a river bed, requiring extensive if not continuous time, led to the invention of some simple devices. Their characteristic, in addition, to make the construction easier, was that they could be moved by humans or by animals and even by the running water itself, obviously when relating to rivers, and even by the wind. Such machines had two basic parts: the motor and the system for picking up and raising water. The motor, of whatever type, transformed the motive power available into movement. Just like the oar which eventually led to the paddle-wheel, the goatskin suggested a wheel with many goatskins applied along its rim. By rotating the wheel, the goatskins would be immersed, filling with water which they would then discharge once they reached the top of the wheel. But to rotate a wheel bearing the goatskins, which later became terracotta cups and then wooden cases, they had to overcome a resistance equal to the weight of the water hauled, thus the more numerous the number of goatskins, the greater the quantity of water, the greater the height, the greater the effort required.

Supposing that the goatskins or buckets had a capacity of only 10 l and supposing that they were placed at 1 m distance one from the other, an extension of 10 m would have ten containers, equalling one ton of weight. With the rising speed of the chain about 20 cm/s, they could haul approximately 100 l/min. Certainly not little but since almost 10 min were required for one cubic meter the result is extremely modest.

In spite of this, the wheels operated for long periods and permitted the cultivation of soil that would otherwise have remained barren. It is no surprise, therefore, that

even the very ancient Code of Hammurabi dating to the 18th century B.C. made explicit reference to irrigation machines operated by windmills. The very opposite of those used almost three millenniums later in Holland to drain excess water.

Various devices were conceived to provide the power required to activate the wheels. Cog-wheel reduction gears of various shapes were used, according to whether they were to be used by animals or men. However, it soon became obvious that when the goatskin wheels were immersed in water, the current caused a certain amount of drag: a second paddle wheel of adequate size and moved by the water could make it rotate. At that point, the two parts of the machine were joined, becoming a mechanical system called the ‘water-wheel’. Water-wheels could be operated by animal traction or by hydraulic traction, they could have one wheel or multiple wheels, a single gradient or a fractioned gradient.

## 12.1 The Early Devices

Although there were different methods for raising water, the result was the same. From these remote devices there followed a long series of increasingly small and effective machines developed to raise water: for the bilge and, for more general use, to evacuate flooded hulls. They were called siphons and pumps and are the basis for our reciprocating motors.

Rarely was the water from large rivers suitable to drink and the water found in wells of the arid zones was even worse. Nevertheless, there was almost always water underneath the soil and it was certainly better than what filtered out; but to get at the water it needed to be raised. For this purpose they used a goatskin, which was very light when empty but extremely heavy and difficult to lift when full. To obviate this inconvenience, a branch was used, first as a pulley and later as a rocker. In the first case it was a forerunner of the pulley that transformed vertical stress to horizontal stress; as a rocker, it decreased stress by means of a counterweight and lever. The Near East had what was called a shaduf; it is present in numerous and very old hieroglyphics. In Fig. 12.1 are reported an Egyptian painting of the I millennium B.C. showing a shaduf and a pictorial reconstruction of it. Over the centuries it was perfected and became highly diversified and it is still used in many non industrialized countries. This device was also used for the medieval trebuchet a (kind of catapult, see Chap. 13), the most powerful mechanical artillery in history and can even now still be seen in the huge rockers that are continuously pumping out oil. Actually, its advent in the eastern areas of the world has been confirmed in even more remote times and with motive features very similar to those of the rocker used for wells.



**Fig. 12.1** The shaduf

## 12.2 The Archimedes' Screw

The Archimedes' screw is the one of the inventions that led to the greatest number of derivations, including the screw for drills, bottle openers, presses, propellers and so on. In its early stages it was used to evacuate water from hulls, an activity for which it was ideally suited due to the little head required.

When the difference in level to be overcome was minimal, as between the surface of a body of water and the adjacent land, another type of continuous action pump was used: the Archimedean screw. Providing only a few of its modern derivations would still be a very long list, spanning from the smallest kitchen appliances, like the meat grinder or pasta maker to large draining systems, drills, compactors, presses and so on.

There was no specific confirmation of its presence in antiquity until the discovery of a fresco in Pompeii illustrating its operation in detail, but it is likely that it was already well known by the Egyptians. Generally, it consisted of a lead nut or worm screw inside a cylinder. Not incidentally, this tradition was copied from the shell of the humble snail, perhaps by Architas and later improved by Archimedes. The criteria of the screws found ample application in such mechanics as transmission parts and devices intended to increase force: among the most notable examples, the presses found in Pompeii, with one or two screws, and numerous surgical instruments, called divaricators. After its invention the screw was put to many uses except, paradoxically, the one it has today: a device for mechanical joining.

To return to the cochlea or Archimedean screw, if placed in rotation with one end immersed, the water within would rise by continuous drop force, as acutely observed by Leonardo da Vinci, descending until it exits from the upper end of the tube. Vitruvius left us a detailed report on how to build it. Thanks to its simplicity

and reliability it was also widely used in agriculture: its validity is confirmed by the fact that it was still widely used in Egypt, without any alteration, until a few years ago. In Fig. 12.2 is reported a scheme of the Archimedes' screw used to lift water.

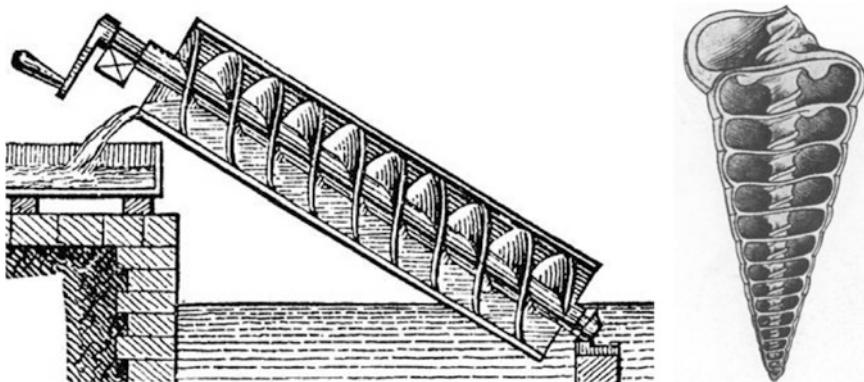
In the same Figure is reported a section of the shell of a gasteropodous the shape of which could have given Archimedes the idea for his screw.

## 12.3 Norias

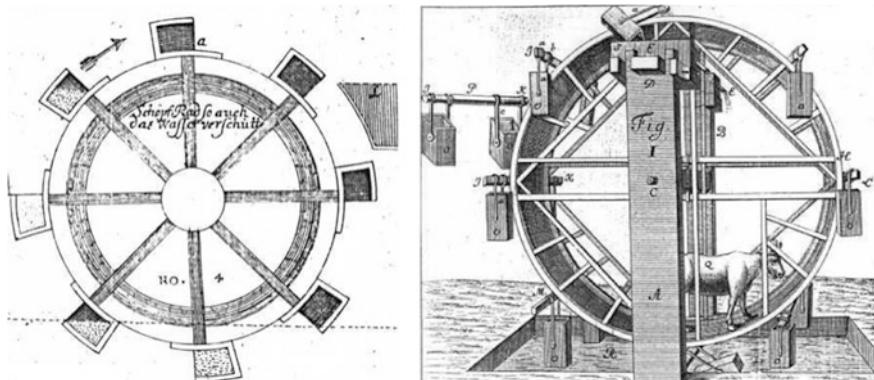
The noria was the first device that was able to lift an appreciable amount of water. These machines can be divided into two groups: one group, the scoop wheels, is constituted by wheels having some scoops or cups on their ring; another group, the chain noria, is essentially constituted by a closed loop chain with some scoops installed on some of the chain mail.

### 12.3.1 Scoop Wheel

The simplest type of scoop wheel had only one wheel, with a few cups around the rim, and used animal power. For obvious reasons, the device was used mostly in arid regions and was of little interest in temperate climates rich with running water. The height to which it could lift water was inevitably less than its diameter which for structural reasons could not exceed 10 m, and had an average lift of about 5 m. In Fig. 12.3 are reported scoop wheels designed by Jacob Leupold (1674–1727), a German physicist, scientist, mathematician, instrument maker, mining commissioner and engineer in his treatise *Theatrum Machinarum*, published in 1724–1725. Among many devices, he also designed a computing machine.



**Fig. 12.2** Archimedes' screw



**Fig. 12.3** Scoop wheels by Leupold

From classic sources the water lift devices of the city of Ostia are widely mentioned. According to sources, the city of Ostia was founded by Anco Marcio in the 6th century B.C. but tests carried out on the walls of the Castrum only date it to the 4th century B.C., thus we may presume that the first settlement may have been a simple encampment. And like all the others, it must have been located close to the shores of a river. Frontino in his *Commentari* writes that: “for 441 years the Romans were satisfied drinking the water they found on site, that of the Tiber, the wells and the springs”. There is no doubt that the same applied to the people of Ostia, at least until the activation of the aqueduct that brought water to the city from the Acilia hills.

Ostia had a surface water-table that not only made it easy to build new wells it also facilitated hauling the water out, as stated by Lanciani (A. Staccioli, *Le terme dei Romani*, Archeo n. 68, Oct. 1990). The situation was very different when a larger quantity of water had to be extracted, as was required for thermal baths. This was the reason it became indispensable to use water-wheels in Ostia, some built as a simple wheel with buckets, others consisting of several wheels, with chains of buckets. The total gradient was divided into two drops with an intermediate basin. As already mentioned, the only evidence that has reached us are the narrow lodgings built for their operation, with related housings for the pins and the axles.

Scoop wheels were widely used for two factors: the great number of inhabitants, approximately 50,000, that the city soon reached, and the water-table at a depth of only a few meters. The first led to a need for baths and industrial systems requiring huge amounts of water, the second to the ease of acquiring it from anywhere without having to build an aqueduct. In effect, anyone could obtain water by simply digging a small well and raising it to the level of the soil. To this end a water wheel with a diameter of 3 m was used, operated by one or two men by means of an axis

ending in a punch pinion that engaged the crown of a bucket wheel. For larger quantities, not infrequent for thermal baths, they used double-drop water-wheels, a pair of water-wheels separated by an intermediate exchange basin. In this case also, the motion was provided by a punch sprocket that engaged a perforated crown in the rim of the water-wheel either with the cogs on the crown or with external cogs.

Nowadays it is still possible to see scoop wheels; probably the most famous ones are those at Hama (the ancient Hamat), a city in Syria; they were (and some still are) used mainly to move water lifting devices for agricultural purposes. In Fig. 12.4 is reported a couple of these, still existing, devices.

It is interesting to observe that the spokes of the wheel are not orthogonal to the axis but tangent to the hub; this gave more rigidity and strength to the wheel.

Some water wheels operated in the water flow of a river; in this case they could have several blades on their ring so that they were moved by the water flow; in this case the same wheel was both the motor and the water lifting machine.

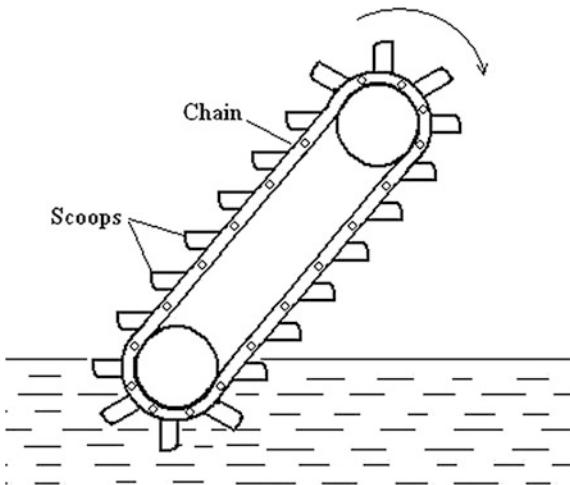
### 12.3.2 *Chain Norias*

For bigger gradients they resorted to an ingenious system that consisted of one wheel, very rarely two in which the second acted as a return, and a pair of chains side by side. Buckets or cups were affixed to the links of the chain at regular intervals. The machine was rotated by the upper wheel, made with special slots or marks and sufficiently solid to sustain the entire weight of the load. In Fig. 12.5 a scheme of a chain noria is reported.

**Fig. 12.4** Noria at Hama



**Fig. 12.5** Scheme of a chain noria



Since the length of the chain was discretionary, in theory it could reach and bear significant depths and weights. In practice, however, as each increased, so did resistance to the point that it could jam, whatever motor it was using. The wooden structure of the water-wheels did not allow them to last: the only evidence and traces we have are the slots for the axles and the incisions on the walls caused by their rotation, some of which are still visible in Ostia Antica. For greater gradients a chain noria was required: the simplest had a squirrel cage driving gear, approximately 3–5 m in diameter, fixed to the axis of a press wheel that engaged the bucket chain, often a pair of ropes.

Usually there was no return wheel, as the weight of the buckets lifted provided sufficient operating tension; the gradient, however, could not exceed 5–6 m.

As it happened for many other devices, during the Middle Ages, the studies on the norias were carried out by Arab Engineers. Among them, of particular interest are the designs by Al Jazari (1136–1206) that is also mentioned in this book for his time measuring devices (Chap. 4) and his automaton (Chap. 16). Among other water lifting machines, probably the most interesting is the one showed in Fig. 12.6.

This device is powered by a horizontal axis water wheel; the transmission of motion to the chain noria is obtained by means of two couples of orthogonal axis gears. In the Figure is also represented an ox that perhaps was just a marionette to show the motion.

Chain norias were made until 100 years ago with the same shape as those of the Roman Age; in Fig. 12.7 is reported a picture of one of these “modern” norias.

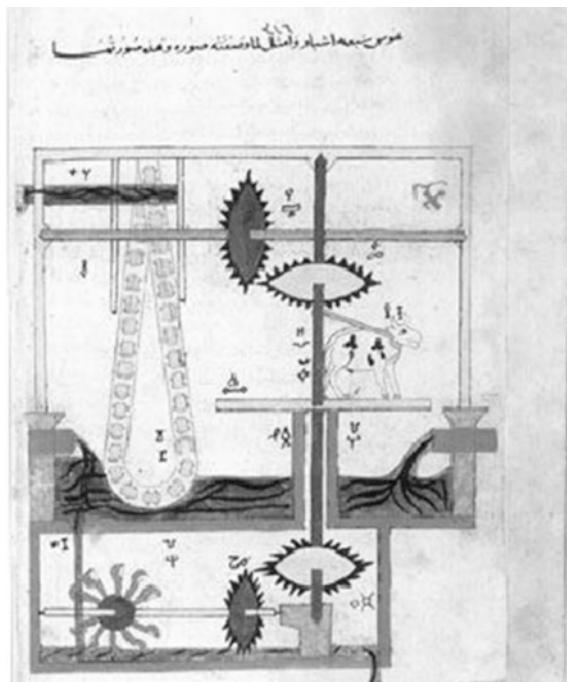


Fig. 12.6 Chain noria by al Jazary

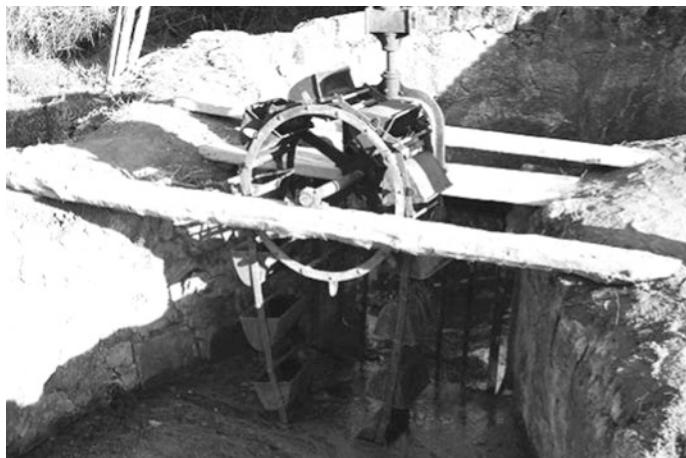


Fig. 12.7 A “modern” chain noria

## 12.4 Pumps

Contrary to water-wheels that raised water using the same mechanism as a crane, pumps raised water by varying the pressure, aspirating or compressing it. However, there was one type of pump that functioned in this manner only partially and that may justly be considered as an intermediate step between water-wheels and actual pumps: the chain-pump.

Pumps were conceived to remove excess water from on board ships and so were essential for safety, pumps were studied and improved more than any other device. First a machine to save human lives, it was soon put into universal use, as its action could be reversed. They are used today both in thermal engines, hydraulic cylinders and even the very common medical syringe.

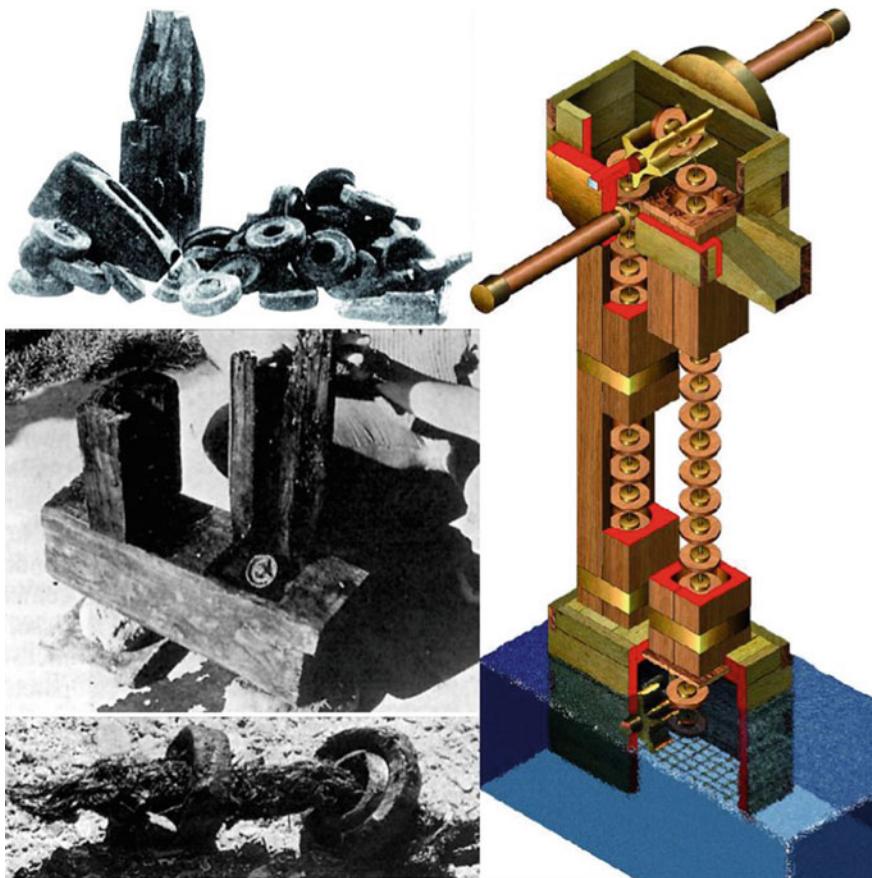
### 12.4.1 Chain Pumps

The chain-pump was conceptually similar to the water-wheel although much smaller, and was strictly for naval use. The few remains of this type of pump were found in Nemi's ships and other shipwrecks. Since it was effective in eliminating water from the bilge, it continued to be used and this explains its constant presence in all the drawings of Renaissance engineers.

It consisted of a rope a few meters long, which passed at regular intervals through the centre of a small bronze or wooden disc, almost like a giant rosary. One half of the rope was inside a wooden cylinder, with a slightly larger diameter than the discs, rubbing against it like pistons. The lower part of the cylinder was immersed in water while the upper part was secured to a press wheel that rotated the rope by means of a crank. Before entering the cylinder, the discs captured a small quantity of water that they raised and then discharged into a hopper. In Fig. 12.8 are reported the finds of a chain pump found at the St. Gervais relict and a virtual reconstruction of it.

The advantage of a chain-pump on ships was its extreme simplicity of construction and the fact that it could be activated from the main deck, thus avoiding the risk of sailors being trapped in case of sinking.

Chain pumps were used for many centuries: in Fig. 12.9 is reported a drawing from treatise on architecture, engineering and military art by Francesco di Giorgio Martini (Siena 1439–1501); some further biographical information are given in the last paragraph.

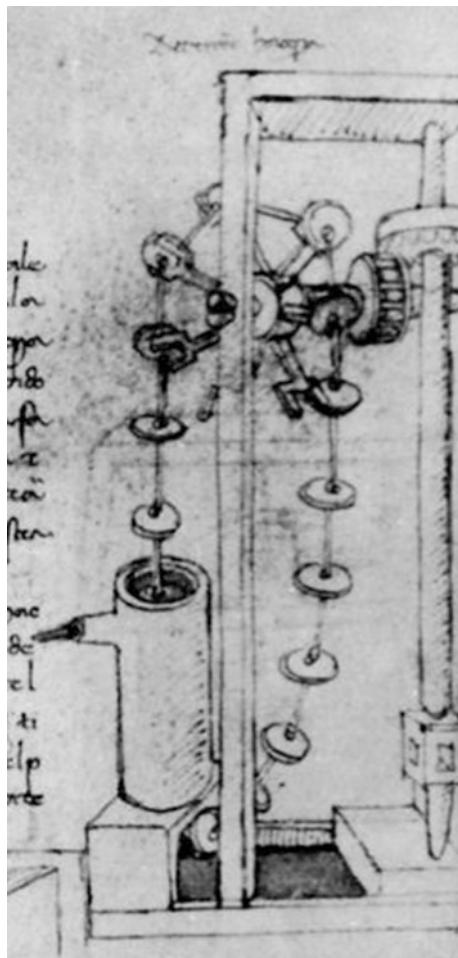


**Fig. 12.8** Chain pump: finds and authors' virtual reconstruction

### 12.4.2 Reciprocating Pumps

The water-wheel with the chain of cups could raise water to a moderate height but had no pressure and so could not project it out in jets or spouts. This effect, which may appear to be simply aesthetic but that was in fact essential for fire fighting pumps and naval evacuation pumps on medium sized ships, was attained thanks to a cylinder equipped with a piston, presumably invented by Ctesibius. With it they could discharge the water aspirated at a certain level of pressure, forcing it through a narrow nozzle and transforming it into a long jet of water. To prevent its spurting out intermittently two cylinders were added, operating alternatively so that when one piston was lifted, the other was lowered. The idea in itself was not a new one as it could be found in primitive bellows made with two bamboo canes, probably observed and studied by Alexander's scientists.

**Fig. 12.9** Chain pump by Francesco di Giorgio Martini

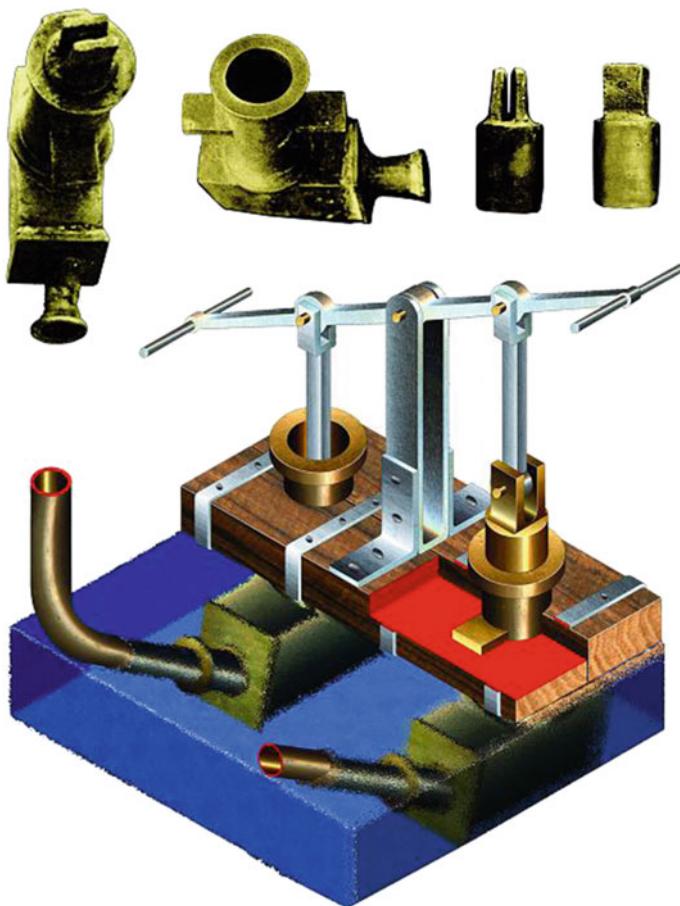


In Fig. 12.10 are reported some finds of a reciprocating pump taken from a group of similar ones found on a relict of a Roman ship wrecked in the gulf of Lion, France and a virtual reconstruction of the pump.

This machine, later defined as a double-acting pump, was for the ancients simply the ctesibica machina and could provide a jet of water that was not yet perfectly continuous but pulsating, an inconvenience later obviated by a stabilizer, in actual fact a compensation box with check valves. Because of its capacity to launch jets of water at a considerable distance this pump was used to put out fires and, very probably, also to set them.

An interesting application of the Greek-Roman era of the reciprocating pumps is represented by the Valverde Pump.

Ctesibius was well aware that his invention was extremely versatile: in fact, he also used it to build a pipe that could aspirate water to be thrown onto flames, to



**Fig. 12.10** A two cylinder reciprocating pump; finds and authors' reconstruction

play the organ, to launch stone balls and even as a medical syringe. No surprise that the Byzantines also used it to launch jets of pyrophoric mixture, perhaps benzene, toward enemy ships.

Around the end of the 19th century, in the depths of an ancient and abandoned Spanish mine of the Roman era, located in Huelva Valverde not far from Barcelona, an incredible relic was discovered. This was a sophisticated bronze mechanism, perfectly preserved, consisting of two cylinders with related pistons and valves, a cylindrical box with two valves and a long tube that could rotate at 360°. At the extremity was a mechanical contrast sprinkler that could also rotate at 180°: an omnidirectional system.

After cleaning the device, which consisted of 26 pieces, all of excellent bronze with the external surfaces covered by a layer of zinc to preserve it from corrosion, it was sent to the Archaeological Museum of Madrid, where it is currently kept in a

separate display case. With the exception of the curious hinged tube, there is no doubt that this machine was made by Ctesibius.

The machine consisted of two cylinders each approximately 26 cm high with an internal diameter of 8.5 cm, a compression box measuring 16 cm in diameter and 4 cm high and a hinged tube almost one meter long, ending with a single Y shaped nozzle.

There are four valves, of two types. The cylinders have short protrusions for connection to the support, as does the compression box, typical of Roman piston pumps. One detail indicates that the technology of the pump was Roman: the housing for the rod pin is found on the head of the pistons rather than inside, like the modern ones, although they too are hollow. The precision is extraordinary, obtained by lathe with a tolerance of 0.1 mm in respect of the cylinders.

It is obvious that the box acts as a stabiliser to suppress the pulsation of the jet of water; also obvious is the function of the Y shaped terminal as a contrasting nebuliser. An image of the pump of Ctesibius, complete with equaliser and nebuliser is found in a Renaissance re-edition of his *Pneumatica*. Nothing was found of the container and the equaliser as they were dissolved by the humidity of the mine. We imagine that they resembled a modern back-carried sprinkler, the only difference being its location on the chest rather than on the back. The discovery led to numerous interpretations, but each clashed with the evidence: the relic appeared too small and too complicated for a water pump or fire extinguisher; the hinged tube too sophisticated to direct a small jet of water to the right or left it would have been sufficient to simply slightly deviate a small hose. And why assemble two cylinders, a compensation box and four valves to evacuate the same quantity of water that a bucket could have removed in less time? Why a zinc layer when bronze resists salt water for millenniums?

A realistic theory is that this may be the remains of a Byzantine flamethrower. According to the Alessiade written by Princess Anna Comnena, daughter of the Emperor Alessio Comneno (1081–1118), the terrifying Greek fire was projected by means of the strepta and by tubes, directed towards any point desired, from right to left and from top to bottom. Consequently, one can easily imagine that the tube must have had a universal hinge, a flexible tube. There is also the fact that the word flexible normally translates into the Greek word strepta. But such an interpretation provides no explanation for the pressure needed for its projection. A pump would be required, as well as a nebuliser located before the launch nozzle to enhance performance. In Fig. 12.11 are reported the finds, a virtual reconstruction of the pump acting as a flamethrower and some orthogonal views.

It is well known fact that for fire eaters to transform a sip of gasoline into a fiery cloud, they must expel it through closed lips, transforming it into an aerosol, before lighting it with a torch. Translating strepta as twisted, folded or angled, a perfectly suitable definition for an angled expulsion nozzle, we would have a nebuliser for the pressurised liquid conveyed by a double-acting pump, that is, by a siphon. Not all scholars believe that this siphon was the pump of Ctesibius: for some the word, in Greek *sifonon* (*σιφώνων*), simply means tube. The objection, valid for Greek and for decadent Latin, does not apply to refined Latin, in which the usual and

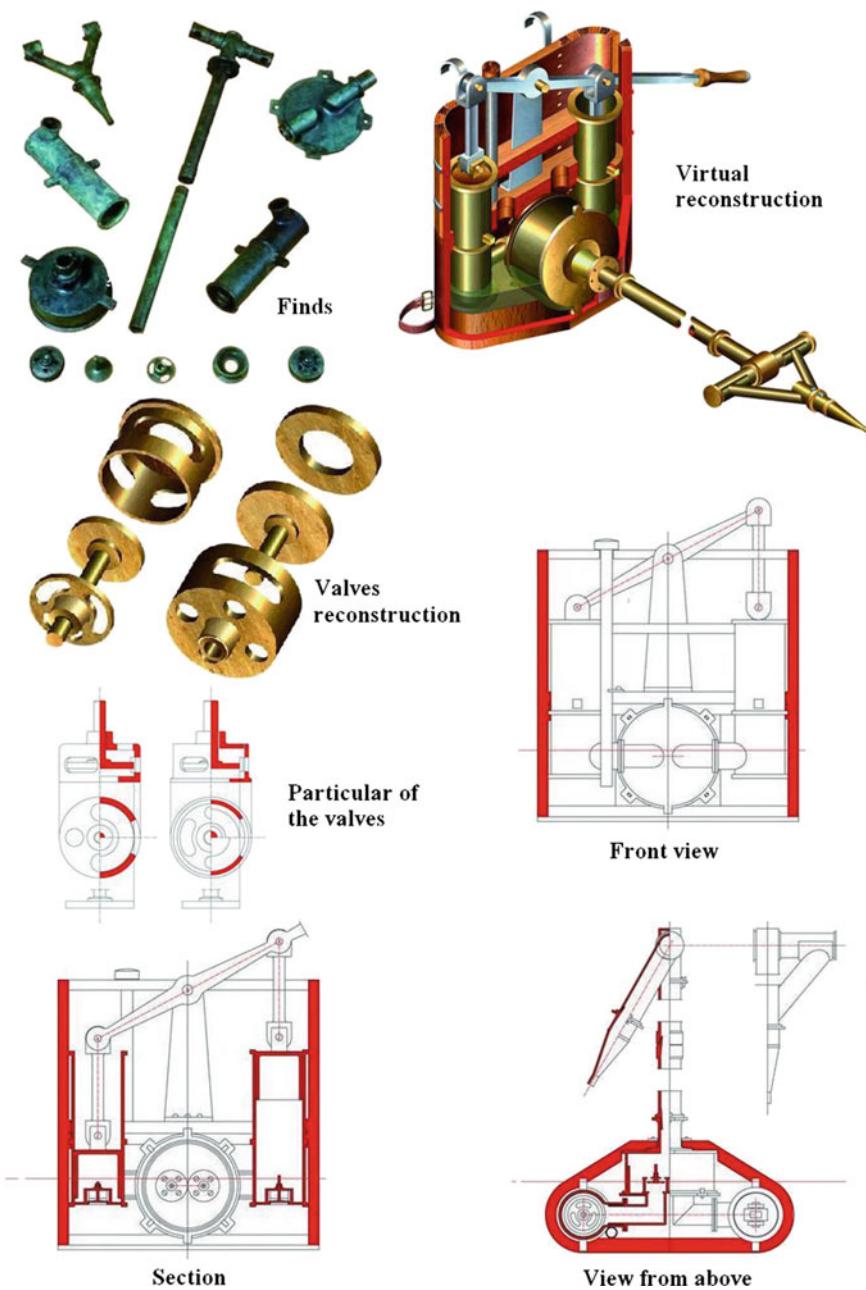


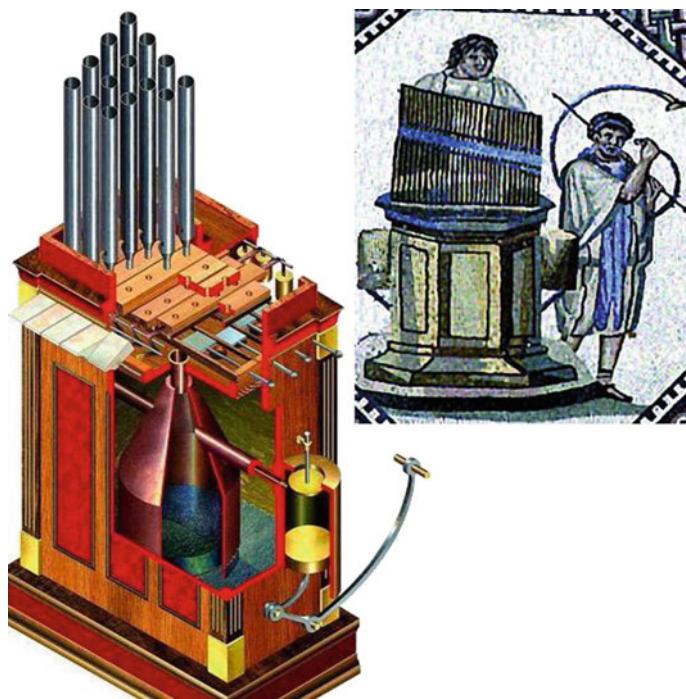
Fig. 12.11 Pump of Valverde; finds and authors reconstruction

specific name for tube is fistola, while a siphon defines a double-acting pump. As for Greek, the word siphon indicates both tube and double-acting pump. In favour of this latter accepted meaning, however, intervenes the term sifonizo = inspire, like a siphon, an action that no tube can effect unless it is connected to a pump! Furthermore, both Hero and Pliny the Younger call siphon a double acting fire extinguisher, the same name normally given to a bilge pump.

The similarity of a siphon flamethrower with a discharge or fire extinguishing pump ends here, specifically because of the need for a nebuliser before firing. It is the custom for the name of a component part to describe the entire device: i.e., because it has a turbo compressor an entire motor is called turbo. No surprise therefore that the use of an angled nebuliser is at the origin of strepta, that is angled.

Although pumps were already highly advanced, the described ones represent a fine example as they contained cylinders within them, pistons and suction and compression valves, as well as cranks and rockers, the entire repertory of instruments needed to build a steam engine. This type of pump is still used to extinguish fires.

Another interesting ancient application of the reciprocating pump is the water organ by Ctesibius, a virtual reconstruction of which is reported in Fig. 12.12; in the Figure, a particular of a mosaic showing the organ is also reported.



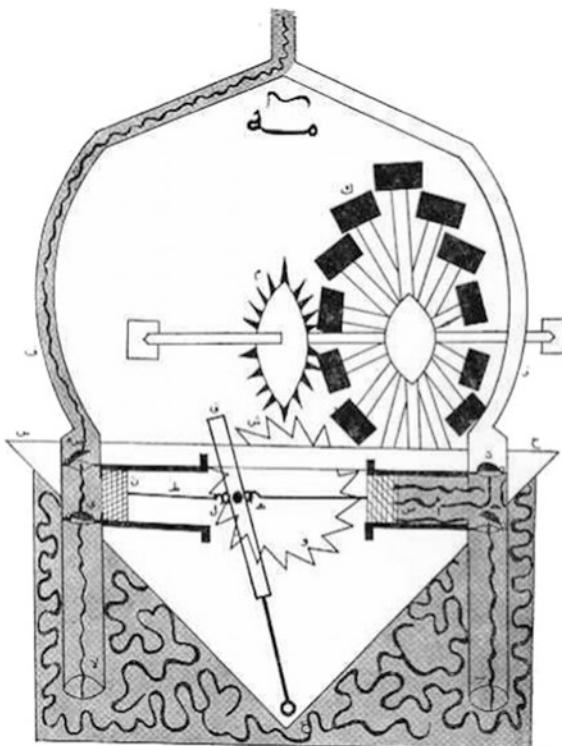
**Fig. 12.12** Water organ; authors' virtual reconstruction and particular of a mosaic

An organ, in general, is the giant perfection of a pastoral pipe: a series of canes of different diameters and lengths, tied together so that when blown each would produce a different sound. And if with the former in order to achieve a harmonic variation you needed to slide the canes along the lips, the latter, for obvious reasons needed the player to send compressed air directly into the case, following the same musical criterion. For this purpose a distribution device was invented, a true novelty of elevated mechanical complexity.

Transforming the pastoral instrument into something more sophisticated however required the common factor of introducing compressed air and a controlled distribution of this air towards a specific cane in order to achieve a specific sound. The solution was not difficult since it was simply a matter of providing metal canes, in bronze or tin, with tiny conduits of compressed air produced by a pair of bellows with a special set of keys. The only real difficulty was related to the slowness of the commands and the wide range of pressure since the pressure varied according to the quantity of air in the canes, which in turn depended on the type of music and the volume. In the worst of cases, at a certain point pressure became insufficient: Ctesibius found the solution, one that has remained unchanged up to the present time.

Using a pair of cylinders with pistons as bellows, activated alternatively by special levers, after the check valves he directed the two tubes to a chamber placed

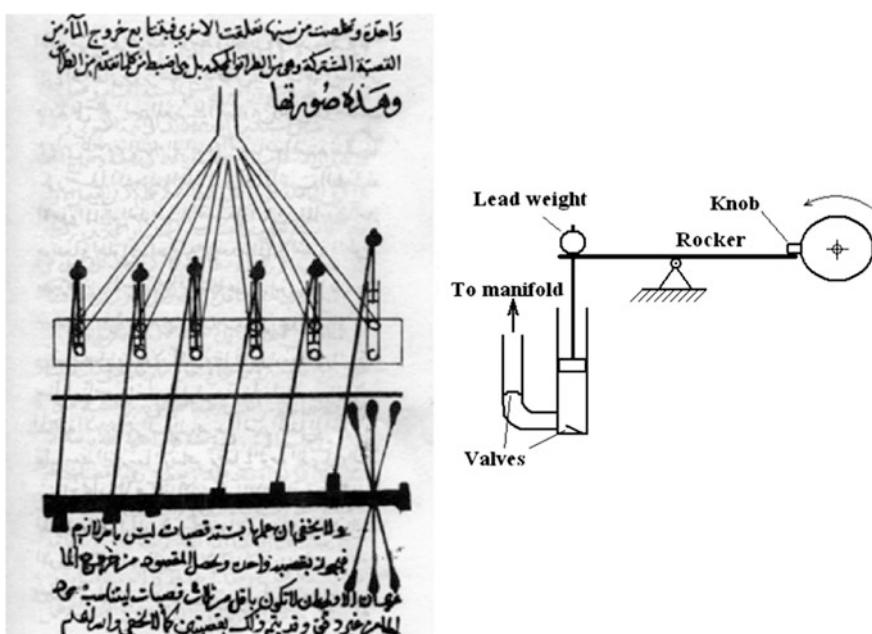
**Fig. 12.13** The two cylinders water pump by Al Jazari



inside a tank partially filled with water. From the chamber protruded a third tube that brought air to the keyboard, where it was distributed to the canes by the keys. By moving the bellows inside the chamber he could increase the air pressure, lowering the level of water. The immission of water, on the other hand, decreased pressure and increased the water level. By varying the level of the water, the pressure remained substantially constant, thus acting as a stabiliser, a bit like the boxes of the double-acting pumps. In this case, it was similar to squeezing the bladder of a bagpipe with the left arm in order to maintain a constant pressure.

As it happened in many other fields of scientific knowledge, during the Middle Ages, the studies and the inventions on water pumps were carried on by Arab engineers; among these, once again, are particularly interesting the machines designed by Al Jazari. One of them consists in a couple of copper cylinders horizontally opposed; the pistons are moved by a water wheel through a gear train and a quick return mechanism. In Fig. 12.13 is reported the drawing of the Al Jazari's reciprocating pump.

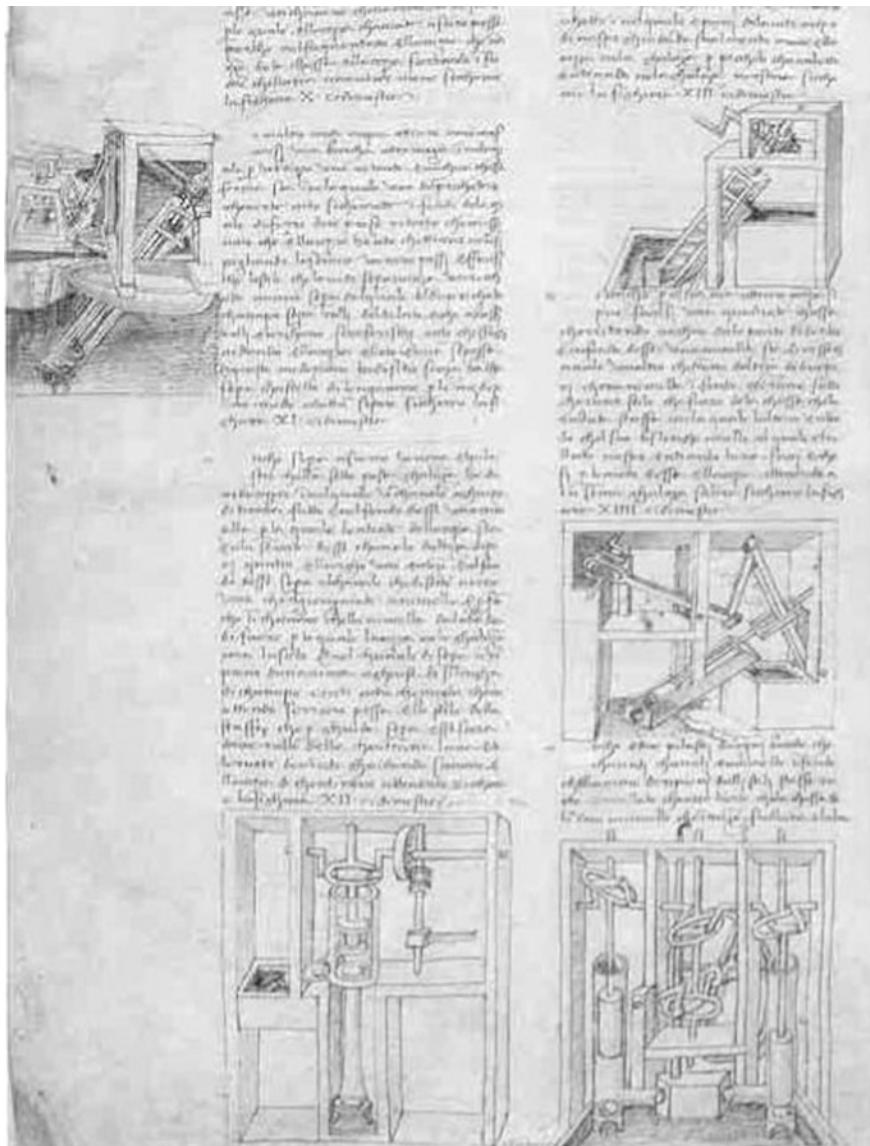
An even more interesting pump was designed much later by Taqi al Din (Damascus, Syria 1526–1585) who has already been mentioned in Chap. 4 for his mechanical clocks. He wrote many treatises among which the most famous is probably *Al-Turuq al-samiyya fi al-alat al-ruhaniya* (*The Sublime Methods of Spiritual Machines*, 1551). Very famous is his design of a six-cylinder "monobloc" pump that is reported in Fig. 12.14; on the left is shown an original drawing and on the right a schematic reconstruction of the working principle.



**Fig. 12.14** Six cylinder pump by Taqi al Din

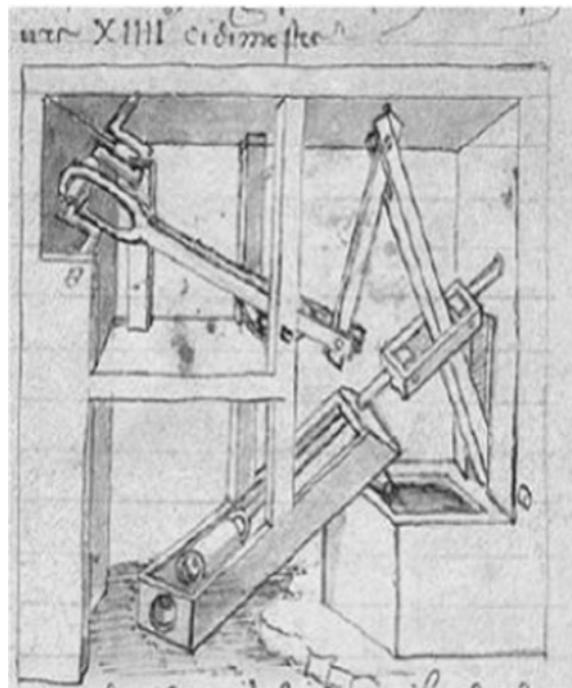
This interesting pump is essentially constituted by a six cylinder monobloc linked to a unique manifold and a horizontal shaft powered by a water wheel; the latter has six knobs each of which moves a rocker that is linked to one of the pistons rod. The unique manifold probably gives the benefit to regularize the pressure.

During the Renaissance an interesting study on water pumps was carried on by Francesco di Giorgio Martini an Italian sculptor, architect, painter and most of all



**Fig. 12.15** Pumps by Francesco di Giorgio Martini

**Fig. 12.16** Reciprocating pump by Francesco di Giorgio Martini



military engineer that worked mainly at the court of the Dukedom of Urbino. His main work is a treatise on architecture where he stated the main principles of the art of building fortifications called “modern fortification”, art of which he is considered the founder together with his brothers. A copy of his treatise was owned by Leonardo da Vinci and was widely studied and commented by the latter. Francesco di Giorgio Martini is mentioned in this book also in Chap. 11 for his self-propelled carts.

As for the water pumps by Francesco di Giorgio, in Fig. 12.15 is reported a page of his treatise on architecture and machines.

In the second column of the page represented above it is easy to recognize an Archimedes screw and two reciprocating pumps. The one in the middle of the second column seems very interesting and is reported, enlarged, in Fig. 12.16; a crack, through a quick return mechanism moves a four bar mechanism and the rocker of the latter moves the piston.

### Observations

The working principle of most of the pumps that have been described, conceptually, is still used. In addition, the reciprocating pumps are the first reciprocating machines and the first machines that require components machined with close tolerance.

# Chapter 13

## Adduction and Distribution of Water

**Abstract** After the lift of the water, exposed in the previous chapter, the subsequent need was represented by the adduction and distribution of water that is the topic of this chapter. Ancient ducts and pipes are first presented, and then some examples of Roman valves are shown, all showing a surprising modernity. Finally examples of water mining are shown.

### Introduction

The surface of a lake, more than the sea, conveyed the perception of horizontal direction and absence of current. Rivers and torrents on the other hand illustrated the close relation between inclination, current and movement of the water. It was by following these examples that ancient civilizations were able to build aqueducts, which were no more than canals with potable water. As for the very ancient cisterns, these became the complement of the aqueducts, doubling their capacity as they could be filled during the night when there was no water consumption and emptied for the day.

Contrary to pastoral societies that would lead flocks wherever there was an abundance of water and pasture, moving continuously and adapting to a nomad existence, for agricultural societies the criterion was completely antithetical. Since fields certainly could not go to the water, in some manner the water had to be channelled to the fields. This resulted in a sedentary society in which survival depended on technical abilities connected with irrigation and then with the planning of permanent settlements. From those remote days city and water became closely connected, one not being possible without an abundance of the other.

The Romans understood the essential role played by water in the life of a city. Perhaps this was why they had founded their capital along the shores of a river, in accordance with a plan that would become common to all the major cities of Europe.

### 13.1 Open Ducts

Certainly, a constant concern of all the engineers of the Roman legions was that of bringing large quantities of potable water to the cities, by enormous aqueducts that were veritable artificial suspended rivers. In effect, the Romans systematically

adopted a natural water adduction system: a channel with a continuous flow of water, provided by simple gravity. Since the surface of the water did not touch the covering of the channel, defined as open surface, this was the simplest method of bringing large quantities of water. However, since this frequently required crossing sections hundreds of kilometres long, the difficulties were conspicuous. First, the correct altitude of the section had to be determined, which in turn required a meticulous mapping, using instruments of absolute precision.

Then the inclinations had to be calculated in a manner such that the water did not flow too quickly, eliminating the difference in level, nor too slowly, settling in the channel and perhaps obstructing it. Along the section they also had to overcome gorges and valleys on extremely high structures, not incidentally defined technically as works of art, pass over hills and tunnels, and at times even rivers. Difficulties that increased exponentially as the distances to reach the water increased.

In Fig. 13.1 are reported some examples of Roman aqueducts.

From left to right and from top to bottom the pictures respectively represent: the Roman aqueduct at Maro, Andalusia, Spain; a detail of the Pont du Gard, France; the Roman aqueduct in Segovia, Spain; the last “Roman” aqueduct: the “Acquedotto Carolino”. This last one was about 38 km long and the structure in the picture is about 56 m high and 529 m long; it was built by Luigi Vanvitelli (Napoli, 1700—Caserta, 1773) a Neapolitan painter and architect, son of a Dutch painter (van Wittel). This aqueduct was built between 1753 and 1762 and fed the “Reggia



Fig. 13.1 Examples of Roman aqueducts

di Caserta” (Royal palace of Caserta) with its artificial cascades and pools that Vanvitelli designed for Carlo III di Borbone (1716–1788), King of Naples and Central-Southern Italy (Regno delle due Sicilie).

## 13.2 Penstocks

Though numerous treatises affirm that the Romans were not familiar with the pressure water pipe, the fact remains that not only did they know of it but in many cases they used it. Obviously, and perhaps this is at the origin of the misunderstanding, the segments of pipes were not of metal but of stone: but even today, the largest of these are made of reinforced concrete. Frequently the pressure water pipe was coupled with a pipeline located on several rows of arches when the valley to be crossed was of great depth. Up to a certain height this was achieved by the structure itself while from the structure to circulation level they used a pressure pipe siphon. This method gave excellent results and was used uninterruptedly for over a 1,000 years.

Even more interesting is the method adopted by technicians to determine the capacity of an aqueduct, different from modern methods as it does not consider the speed of the water. Since the inclination of the aqueducts was always the same, the speed of the water became a constant and the only variable was the section of the canal in which it flowed, that is its width by the height of the flow, a value that became the unit of measurement of capacity.

In Fig. 13.2 are reported some examples of Roman penstocks made of stone. It is believed that this type of conduct could resist an internal pressure of up to 2 GPa.

## 13.3 The Great Cisterns

As the capacity of the water sources varied, so did that of the aqueduct and the urban distribution network. To compensate for oscillations and perhaps to increase quantity upon entering the city, they built enormous cisterns.

The huge quantity of water that accumulated during the night when need was almost zero doubled the availability of water during the day. To better exploit this possibility, the capacity of the cistern had to be equal to the entire night capacity of the aqueduct to prevent any waste. Furthermore, since the large cisterns had no drains for overflows, it is logical to suppose that they were never filled completely or that their cubic volume was greater than the capacity that arrived.

Detailed construction and waterproofing techniques provided these monolithic structures with complete water tightness, extreme longevity and perfect hermetic seal. Any small fissures would have compromised their utility. One interesting aspect relates to their periodic cleaning: to this end, all the corners had been



**Fig. 13.2** Roman stone pipes

rounded, and in the centre was a small collection chamber with a conduit for bleeding.

Most of the large cisterns of the Imperial Era, some of which are still in use, such as the one in Albano (near Rome), have a very evident hole for the introduction conduit near the top, but no symmetrical one for pick up, for the obvious reason that it would have had to be near the bottom. There is no outflow hole even further up, a strange anomaly that suggests a different way of extracting the water, much more complex and doubtlessly more effective. The first thing to consider concerns the operational pressure: since Roman lead pipes were not very resistant, they had to avoid excessive solicitation.

The difference in pressure between a full and an empty cistern when hauling the water from the bottom would have been in excess of 100 kPa, a value that exceeded the maximum resistance of the lead pipes of the water network, equal to approximately 0.7 kPa. Since the majority were embedded into the ground, pick up from



**Fig. 13.3** Roman cisterns

above prevented pressure on the pipes up to the distribution frame, located at a lower level. By using this system they could also install shut-off valves at the top of the pipes, where pressure was practically zero, thus avoiding any stress on the welding. In Fig. 13.3 are reported some examples of Roman cisterns.

In the Figure are reported: the large cistern of Jerusalem (top right), the large cistern of Constantinople (modern day Istanbul, Turkey) and, on the left the Piscina Mirabilis at Miseno, Naples, Italy.

### 13.3.1 *The Piscina Mirabilis at Miseno*

One of the largest and best examples of a Roman cistern is in Miseno: the Piscina Mirabilis, reported in Fig. 13.3, on the right.

Among the few infrastructures that were in some manner connected with the base of Miseno, there survives an enormous cistern and the base of a tall building. Located a few hundred meters from each other, the two constructions are in contrasting condition of preservation: the first is practically intact to the extent that it could still be used. The second on the other hand is so compromised and mutilated that it is hazardous even to visit it and is of uncertain history. Such a dissimilar state of preservation must be attributed to their different seismic vulnerability, since one is embedded in a hill and the other rising above it, which may be the reason it was thought to be a lighthouse.

In giving the details of the cistern, we must first state that on its capacity depended, if not the complete autonomy of the base, at least its well being.

A colony of over 40,000 inhabitants, according to the Roman urban and hygiene standards, used enormous quantities of water, for food, for agriculture but especially for the thermal baths. To these were added the needs of the fleet and related shipyards, which were just as important.

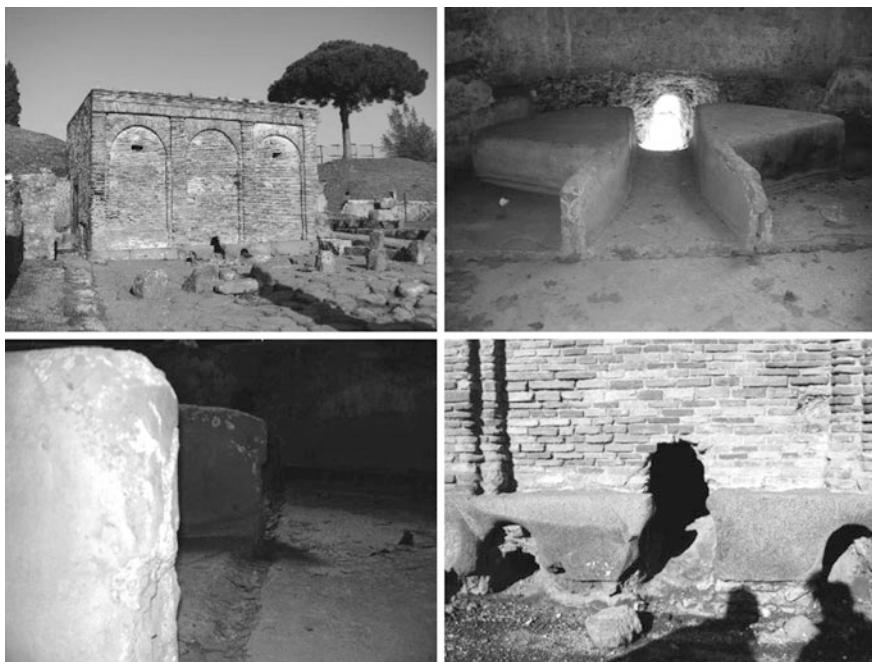
In Miseno there was plenty of fire but little water, and so a source of water was needed. This was found in the waters of the Serino, in the Sannio, almost 100 km distant, where the water was of excellent quality and abundant but certainly not unlimited. Thus an extremely long aqueduct was required that could also feed the city of Pompeii and the villas of Herculaneum en route, and a colossal cistern. Estimating the daily individual requirements as a 100 l pro capite, double the minimum amount envisaged by the UN, and the same amount for the thermal baths and gardens, approximately 8,000 m<sup>3</sup> were required, plus an amount for the fleet, bringing the total volume of water to 12,000 m<sup>3</sup>. The Piscina Mirabilis, with 48 cruciform pillars, aligned over four rows 70 m long, 25 m wide and 15 m deep, in five separate naves, provided just this amount.

It has two stairways to allow for inspections and periodic cleaning of the bottom, both of which are still usable. The evacuation of water took place through a central drain pit, approximately 1 m deep and equipped with a drain pipe. The concept is the typical one of a well-deck, similar also in that it had no pick up opening. While the opening for the introduction of water is at the top of the wall next to the western entrance, there are no openings to extract the water. Most likely the evacuation pipes were activated by small double-acting pumps. This resulted in clearer water and total autonomy among the different branches.

### 13.4 Water Distribution Systems

When the water issued from the cistern and before it entered the urban distribution network, it was divided according to its principal users. Since the quantity was proportional to the section of the canal, the distribution structure, generically called castellum aquae, was divided into geometrically equal parts. The most common, of which there is a perfectly preserved example in Pompeii, was in three sections and is called three-way water distribution system.

The flow in this distribution structure was allowed to expand into a wide, shallow tank, separated into three equal currents by masonry structures. Each part then entered the network through its own pipe: the first was directed towards the public fountains, the second to the thermal baths and the third to private users. Its hook-up however, was different from the current one: a water concession was actually a concession and its release was subordinate to specific merits, thus it was personal and temporary. It could be revoked or suspended at any time, without recourse, at least in theory and according to the information we have from Frontinus. In Fig. 13.4 are reported some pictures of the three-way water



**Fig. 13.4** The three way distribution system at Pompeii

distribution system at Pompeii. From left to right and from top to bottom the pictures respectively represent: an external view of the system; the interior showing the three way ducts; traces of the horizontal housing for the shut valves; a detail of the three outlets.

However, since the system in Pompeii used sluice gates to close off any of the sections when they needed to reduce quantity either above or below, we can assume that from a certain time onwards the principal *castellum aquae* distributed the water to the different parts of the urban network, that is by districts and no longer by type of user. The hook-ups were often discretionary and even unauthorised and were directly connected with the piezometric turrets, thus no one could determine the type and or establish the legality.

We note also the presence of a numerous secondary *castella aquae*, that in today's terminology and according to their function would be called piezometric turrets.

### 13.4.1 Piezometric Turrets

The characteristics of these accessory structures of the water distribution network, the first of a great number now winding through the city, are relatively simple. The

masonry parts unearthed in Pompeii are still in fair condition, though the metal parts of the pipes and boxes are now missing but did exist when they were first excavated and were even photographed. Since they were made of lead, this may have encouraged theft, following the serious damages inflicted by allied bombing during the Second World War.

At the time the city had a difference in level of approximately 50 m. If a shut-off valve were closed, the lead conduit that fed the public and private fountains would have had to sustain a pressure of 500 kPa, a quantity that exceeded the pipes' resistance. This serious limitation, insurmountable for the technology of the era, made it necessary to have pressure limiters, or piezometric turrets, on average 6 m high. On top of these turrets was a lead caisson or water tank, open at the top but protected by a lid, about one cubic meter in size. The feeding conduit issuing from the three-way distributor of the preceding turret emptied into this water tank and the conduit for the subsequent one would be supplied. In Fig. 13.5 are reported a picture of a piezometric turret at Pompeii and an authors' reconstruction of it in which the upper part and the underneath fountain are sectioned; it is very probable that, for hygienic reasons, the turrets had a pavilion covering on a wooden frame.

The ingenious device ensured that the operating pressure never exceeded the pressure caused by the height of an individual turret, equal to approximately 60 kPa. In later eras, when the rigid regulation governing the connections was but a distant memory, private pipes were connected directly with the water tanks on the



Fig. 13.5 Piezometric Turret

turrets, as demonstrated by the still visible remains. It should also be noted that at the foot of the turrets, or more rarely in their immediate vicinity, were all the public fountains. These were fed by a pipe connected to the bottom of the water tank and by the water that came out of it, as we presume from the obvious traces of lime sedimentation. No house was more distant than 50 m from a fountain.

## 13.5 Pipes

The concept of pressure was known rather early in the history of humanity: the Assyrians who swam underwater using a wineskin filled with air as a reserve to allow them to breathe (see Chap. 9), soon noted that it would flatten as depth increased. As for pipes, one of the very first uses was to convey air through water and fire, that is, during immersions and when working with forges.

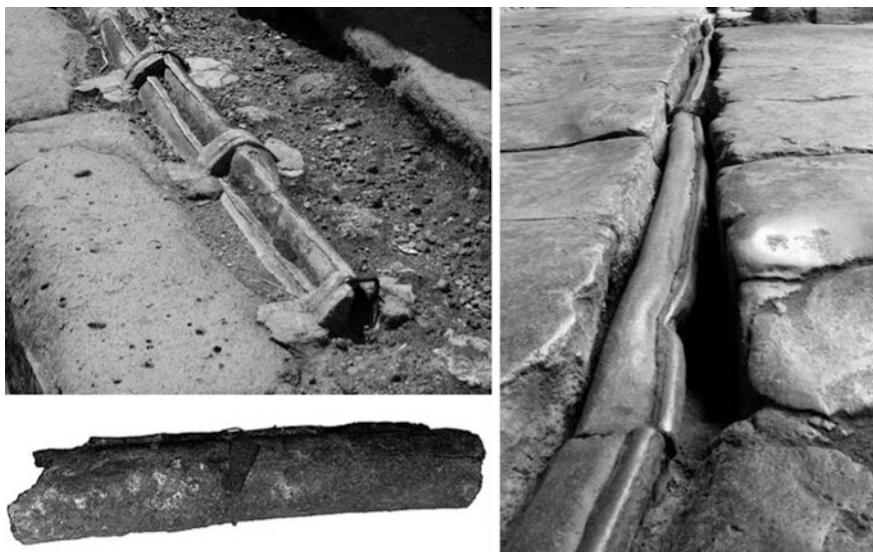
A great number of lead pipes in many different sizes were produced by numerous factories distributed throughout the empire. Even the legions made them, according to the brands found on many of these items. From a practical point of view they were made of a strip of sheet lead, approximately 3 m long, about ten Roman feet, and of a consistent thickness for each diameter. Using an iron rod the borders were bent until the long sides met or overlapped and were welded along their entire length.

We presume the welding to be autogenous, that is, by pouring melted lead along the borders to fuse them together. The same effect was probably attained by passing a crossbar of incandescent copper taken from a brazier filled with burning coal. Something of the sort was also used in the 1800 to iron clothes, when large irons were filled with a moderate quantity of embers.

Whatever the system used, the welding held sufficiently well but only allowed for moderate pressure on the pipes, apparently lower than 100 kPa, equal to a column of water about ten meters high. Not incidentally the piezometric turrets did not exceed 6 m.

But such a moderate pressure only allowed for a meagre flow inside the pipes and therefore excessive sedimentation of lime along its walls, rapidly decreasing the capacity of the small pipes and requiring frequent replacement. However, this inconvenience also had its merits: the pipe covered with lime lost much of its toxicity, something well known to the Romans. In any case the quantity of water reaching the houses that were connected was scarce, about a minute, the time necessary for 1 l to flow out. One must imagine that, since there was no meter, the supply was always open and had a water collection tank. Although the shut-off valve had the potential, it was not used as a faucet as in our houses, except in special circumstances.

Pieces of pipes without any welding were also found, ancient drawn pieces for which there is no confirmation in the sources. There were also, and these were considered infinitely better from a sanitary aspect, pipes made of oak beams, drilled longitudinally and provided with bronze joints for connections. Finally, terracotta



**Fig. 13.6** Lead pipes

pipes were also frequently used, consisting of a long series of individual embedded elements: inexpensive and hygienic, they did have two serious inconveniences, fragility and porosity.

In Fig. 13.6 are shown some lead pipes found at Pompeii and Herculaneum; they were made in segments of approximately 3 m and have numerous weldings. On the upper part of the pipes is clearly visible the longitudinal welding since the tubes were obtained by curving a metal plate.

In Fig. 13.7 are reported pictures of clay pipes (on the left) and oak pipes on the right.



**Fig. 13.7** Clay pipes (*left*) and oak pipes (*right*)

**Table 13.1** Roman lead pipes dimensions

Latin name	English name	Diameter in mm
Fistula quinaria	5 Finger pipe	23
Fistula senaria	6 Finger pipe	28
Fistula settenaria	7 Finger pipe	32
Fistula ottonaria	8 Finger pipe	37
Fistula denaria	10 Finger pipe	46
Fistula duodenaria	12 Finger pipe	55
	15 Finger pipe	69
Fistula vicenaria	20 Finger pipe	92
	25 Finger pipe	115

From the Figure it is possible to observe the male-female coupling of the sections of the clay pipes and the metal joints of the oak ones.

### 13.5.1 Dimensions of the Lead Pipes

According to Chap. 26 of his *De aquae ductu urbis Romae*, the person responsible for the capital's water supply, the Senator Sestus Julius Frontinus, on the basis of prior experience in the sector around the end of the 1st century A.D., provided us with the standard measurements for lead pipes. These do not refer to their diameter however, something that would not have much meaning since their geometric sections were not circular but pear shaped, in accordance with the previously described building procedures. Also, the measures reported by Frontinus refer to the width of the lead sheets that once curved allowed for construction of that particular pipe, corresponding to a specific maximum diameter as we know it. We have no archaeological evidence of any larger diameter pipes, as not even very modest fragments have been found. Which does not mean that they were never produced or used but that they were probably more easily destroyed, as they were profitable scrap material. In Table 13.1 are reported the dimensions of the Roman lead pipes, expressed in Roman digita (fingers) and in millimeters.

## 13.6 Valves

All over the Roman Empire the urban water system used bronze valves that were produced in series according to standard measures that were the same in every part of the Empire. Their structure was extremely simple and highly rational, consisting of two parts defined respectively as male and female, resembling the spigots on barrels. In the following the two main types of valves are described.



**Fig. 13.8** Roman shut off valves

### 13.6.1 Shut off Valves

In Fig. 13.8 are reported some shut off valves found at Hercolaneum and an authors' virtual reconstruction of them.

To better describe these shut off valves, the former, called male or rotor, was made in a truncated cone shape, with a central hole. After it was assembled, the upper extremity protruded from the female, and provided a square housing into which the control lever was introduced. This was obtained by fusing a piece of bronze, subsequently corrected with the lathe and burnished. It required no gaskets as it was sufficient to simply push it in to attain a perfect seal. The second part, defined as female or stator, was a cable section with an entry and an exit, for connection respectively with the aqueduct and the user. The central cavity, bored with extreme precision into a truncated cone, of a diameter appropriate to the male section, acted as its housing. Once the rotor was inserted into its correct position, it was blocked by an arrest element at the base, so that it could rotate freely in both directions, but not exit. Thanks to their special design the shut-off valves could be connected to two tubes at  $180^\circ$  and at  $90^\circ$ , and the opening closed by a special bronze plug.

Verification of the excellent quality and extreme longevity of these shut-off valves, like the pipes produced in eight standard sizes, is confirmed by the observation that almost all the specimens found only needed a little cleaning to function perfectly.



**Fig. 13.9** Single control Roman mixer

### 13.6.2 Single Control Mixers

A few of the most sumptuous and luxurious Roman villas had their own private thermal baths and related water systems. In the ruins of some of these villas excavations unearthed a rather singular and modified shut-off valve, of a highly sophisticated concept; one of these, found at Köln, Germany, is reported in Fig. 13.9 with a virtual reconstruction and a scheme of the working principle.

Although similar to the ones already described, its function differed somewhat, as it had two tubes at opposite ends of the female connection element, one with cold running water and the other issuing from the boilers, supplying hot water. The hole at the bottom, normally closed by the stopper, was left open and was often shaped like a wide open mouth. The rotor also was different as it had two holes located close to each other. Positioned in the female element in the usual manner, it could vary the quantity of cold and hot water according to the direction in which it was rotated. This made it possible to select the temperature of the water issuing from the mouth, much like our own single control mixers.

## 13.7 Hydraulic Mining

A very interesting mining technique was developed by the Romans; it was called “*ruina montium*” (mountain crumbling) by Pliny and was based on the use of pressurized water.

To assess the advantages of this method we must remember that the extraction of gold from its minerals becomes economically feasible when the concentration of metal exceeds 0.5 ppm (0.5 g/ton). This means bringing to light one cubic meter of rock, of varied hardness and consistency and then shredding it finely to achieve at the most, 2.5 g of gold, a fragment barely larger than the head of a match. If we also consider the fact that the rock had to be broken down by hand, using chisels and mallets, dragged to the bottom of wells and then lifted up no more than 30 or so kilograms at a time, one can understand the extreme slowness of mining. A realistic illustration of this activity was left to us by Diodorus Siculus [lib. III]:

12. At the extremity of Egypt and in the contiguous territory between Arabia and Ethiopia, there is a region containing many large gold mines, where the gold is extracted in great quantities with much labour and at great expense. For the earth is naturally dark and contains deposits and veins of white marble that is unusually brilliant; it is here that the overseers of the mines recover gold with the aid of a multitude of workers. In fact, the kings of Egypt condemn to the mining of the gold those found guilty of some crime and captives of war as well as those who have been unjustly accused and thrown into prison because of the anger of the kings, and in addition to such persons occasionally also all their relatives; by this method not only they inflict punishment upon criminals but at the same time secure great revenues from their labour. Those condemned to this punishment, a great number and all bound in chains, work unceasingly day and night, with no rest and no means of escape; they are watched by guards taken from among barbarian soldiers who speak a different language so that no one, by conversation or friendly contact, can corrupt the guards.

The gold is taken from the hard earth by first burning the earth with fire and after it crumbles they continue to work the earth with their hands; the soft rock which can be collected with little effort is crushed with a sledge by myriads of unfortunate wretches. The entire operation is supervised by a skilled worker who distinguishes the stone and brings it outside; among those assigned to this work in the quarries, those who are stronger break the rock with iron hammers, using not skill but only force; they also dig tunnels in the stone, not in a straight line but wherever the gleaming rock leads them. Now these men, working in the dark, because of the narrowness and winding of the passages carry lamps bound to their heads; most of the time they change the position of the body to follow the particular character of the rock, and throw blocks of stone to the ground as they cut them; they labour at these tasks unceasingly, under the sternness and blows of the overseers.

13. Those who have not yet reached maturity, upon entering the tunnels and the galleries formed by the removal of the rock, laboriously collect the pieces of rock and bring them outside in the space in front of the entrance. Then those under the age of thirty take these stones and with iron pestles pound a specified amount until they have worked it down to the size of a vetch. Then the older men and these small rocks and place them into mills of which a large number are present in a row, and taking their place in groups of two or three at the handle of each mill, they grind the amount of stones given to them to the consistency of the finest flour. And since no opportunity is given them to care for their bodies, and having no clothing to cover themselves, no man can look upon these unfortunates without feeling compassion for them, because of the great hardship they suffer. In fact, no leniency of respect is given to any man who is sick, invalid, aged nor to any woman who is pregnant, but all without exception are compelled by blows to continue their work, until they die of ill treatment in the midst of their tortures. Consequently, the poor unfortunates believe that, as their punishment is so severe in the present no future can be more fearful than the present and thus view death as more desirable than life.

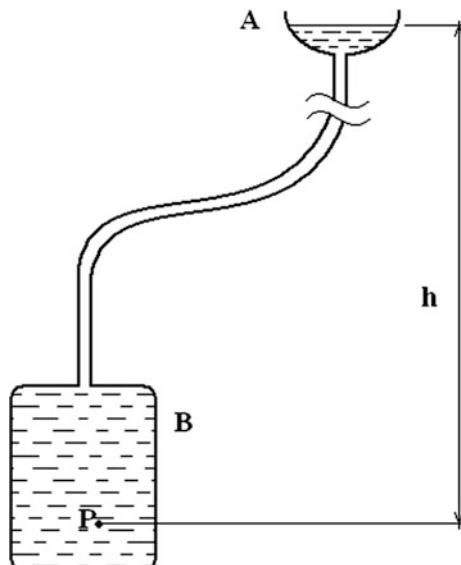
14. At the end of the process the skilled workmen receive the stone which has been ground to powder and complete the treatment; they sieve the marble on a wide inclined table, pouring water as they work; when the earth flows away by the action of the water running on the inclined plane, what contains the gold remains on the wood because of its weight. Repeating the operation many times, they rub the stone with their hands, and then pressing lightly with sponges they remove any porous or earthy matter, there remaining only pure gold dust. Then finally another skilled workman takes what has been collected and places it by fixed measure and weight into earthen jars, mixing with it an amount of lead proportionate to the mass, grains of salt and lead, finally adding barley grain; a tight lid is then placed upon the jar and sealed with mud; this is then cooked in a furnace for 5 days and five nights and at the end of this period, when the jars have cooled off, no trace of the other matter is found but only pure gold, though there has been a little waste.

Apart from the obvious harshness of the forced labour, there was a very low level of productivity, a detail that suggested to the rational mind of the Romans moving the activity from the tunnels to the open air. It thus became necessary to have the gold bearing mountain collapse under its own weight, or implode, using the very risky expedients of siege warfare: mines, obviously non explosive ones.

### **13.7.1 *The Technique of “Ruina Montium”***

The principle is known as Pascal's barrel, schematized in Fig. 13.10; briefly: if an upper tank A, at atmospheric pressure, is linked to a lower tank B by means of a penstock, the (hydrostatic) pressure in the lower tank B is  $P = h \times d \times g$ , where  $h$  is the height difference between the upper tank and the lower one,  $d$  is the mass per volume unit of liquid and  $g$  is the acceleration of gravity.

**Fig. 13.10** Pascal's barrel



The phenomenon could appear as a paradox: if the lower tank were a barrel, it could be easily cracked by means of a small pipe (no matter its diameter but only its length), vertically disposed, linked to it and filled with water.

The technique of *ruina montium* can be described as follows:

The miners excavated numerous very narrow tunnels converging in a single site where they also excavated a large cavity. The characteristic of this cavity was that one of its longer walls was close enough to the external surface of the mountain, perhaps 10 m at the most, and at a moderate elevation from the foot of the mountain. The works completed, during which they also recuperated the mineral extracted (the excavation work thus already producing a profit) they proceeded to open the sluices of the large upper basin that had been filled using the water pipes installed previously and destined to be used for very many times still, for other procedures. The pipes, measuring between 1 to 2 m<sup>2</sup> and slightly inclined, were similar to (though much cruder than) the Roman aqueducts, with some sections in galleries and others on bridges that ran along the sides of the nearby mountains at times even for hundreds of kilometers.

When the water sluices were opened, the water ran into the cavity and rapidly filled it. Once full, the difference in level between the height of the introduction and the cavity caused the pressure to be equal in all points of the cavity. In other words, if the difference in level was barely 10 m, it would have caused an average pressure within the cavity of approximately 10<sup>5</sup> Pa; that is, every square meter of the surface of the cavity would have had a force of approximately 10<sup>5</sup> N. Considering for ease of calculation a cubic cavity of 10 m per side equal to a surface of 600 m<sup>2</sup>, the total thrust would have been 60 MN (6,000 metric tons force), a force that was more than sufficient to fragment a wall of rock 10 m thick, causing it to literally shatter into the air. Large blocks of stone, of a thickness equal to the force of the layer would have shot out like corks, causing the entire mountain formation to lose stability and to collapse in a manner very similar to the effects caused by a mine.

In Fig. 13.11 an Authors' pictorial reconstruction of natural phenomenon is shown.

### 13.7.2 Historical References

Pliny the Elder, former Procurator of Spain, a rich mineral region, provided the following description around the middle of the 1st century, (bk.XXXIII, 21):

The third method of obtaining gold surpasses the labours of the Giants; mountains are excavated by the light of torches, fixing the times of rest and work and for many months not seeing the daylight. These excavations are called *arrugie*; its tunnels often falling and burying the miners to the extent that it is less dangerous to search for pearls at the bottom of the sea, so dangerous have we made the earth. Thick pillars are often left to support the overlying mountain. In mining either by shaft or gallery, barriers of silex are met, which have to be shattered using fire or vinegar. But often, since the fumes and exhalations would suffocate the miners in those shafts, these formations are broken up using iron hammers



**Fig. 13.11** Authors' pictorial reconstruction of natural phenomenon

weighing 150 pounds [45 kg] and the fragments are carried out on the shoulders of the workers, each man passing them on to their neighbors in the dark; and it is only those at the end that see the light. And if the formation is too long, they break it from the sides and dig around it. And yet excavating in these rocks is considered easier. In fact there is a kind of earth, a kind of clay mixed with gravel (called *candida*) that is almost impossible to break. This is attacked with iron wedges and with hammers, and it is thought that there is nothing harder except perhaps the greed for gold. When the labours are done, they demolish the pillars, starting with the last. The coming downfall is perceived by the sentinel set to watch on the peak of the mountain. By voice and by signals he orders the miners to abandon the tunnels and takes flight himself. The mountain rent collapses under its own weight with a crash and a movement of the air that no human mind can imagine. The miners gaze upon this downfall of nature as spectators. In spite of this, there is no gold, nor did they know that there was when they were digging. To undergo such dangers it was sufficient to have the hope of obtaining what they desired.

The ideal solution would have been to use explosive mines. The pressure of the water provided this very potential for by using it correctly the water became in effect what has been defined as hydraulic mines. The plateau of Las Medulas in Spain with its special geologic nature was ideal for this particular method. On the one hand, the percentage of gold was obviously lower than the amount mentioned at the beginning, frustrating any possibility of working in a tunnel, on the other the relative hardness of the rock would have exalted the results of the hydraulic mines. All that was required was to bring large quantities of water to the right elevation.

Pliny gives a precise description of this technique providing a detailed explanation of the origin of the lunar landscape of Las Medulas in bk.XXXIII, 21:

There is another labour equal to this one entailing an even greater expense, because to attain this ruin of the mountains, they must bring rivers from mountain heights to wash away the debris, often from hundreds of miles away.

There begin to appear feed channels that Pliny, a reliable witness, said at times extended for more than a 100 km. The reasons are as explained above and the fact that it was impossible to find water in such a sterile and dry mineral zone.

These are called *corrughi* I believe from the word *corrivatio*, and certainly they require great work. The fall must be steep that the water may be precipitated, so that it may take away the debris from the most elevated points.

In mentioning the weight of the fall, Pliny introduced in an improper but not erroneous manner the concept of water pressure. In other words they had to first assess the pressure of the water, or the difference in level, and then proceed to the canalizations required to bring the water.

If there were valleys or crevasses, they joined them by channels that they excavated. In some places they had to cut through the rock to make room for the pipes or channels. This was done by suspending the workers with ropes and anyone seeing them from afar believed that they were some sort of bird. Thus suspended they take measurements and trace lines for the course of the water even where there is support for their feet.

The route is carefully studied and for obvious reasons runs along the sides of the mountains that since they are much sharper near their peaks than the slopes, the work of the teams can only proceed with the men harnessed. Thus they trace the directions to be followed, with the appropriate inclinations and prepare the layouts on the site.

with their hands they test the soil to see if it is soft or solid enough to support the beams. This type of soil is called *urium*. They carry the water over stones and gravel and avoid this urium. At the head of the fall they make enormous reservoirs at the very brow of the mountain, a couple of hundred feet in length and breadth [m 60 × 60] and ten feet in depth [m 3 for a total cubic capacity of 5,400 cm] In these reservoirs they place five sluices, about three feet square and they open the floodgates as soon as the reservoir is filled, and the water pours out with such force as to roll forward all fragments of stones... because of this Spain has earned great profits.

The explanation provided by Pliny is typically Roman, very approximate. The most obvious aspect is certainly correct: it would have been impossible not to see those enormous basins, exceeding approximately  $6,000 \text{ m}^2$ , fed by that network of extremely long canals. But when the sluices were opened, where did the water go? Certainly not down the slopes of the hill, where as violent as it might have been it would not have caused great detritus. Nor was it drained into open canalizations, in which case within a few hours everything would have returned as before. It went into the previously excavated galleries, all leading towards the flank of the mountain but without exits. Galleries with no exits and that ended in a sort of

accumulation chamber, the hydraulic equivalent of the combustion chamber in mines. This chamber, which could also be a gallery running parallel to the side of the mountain, but internal to it by about 10 m, rapidly filled with water as soon as the sluices were opened, attaining the same pressure as that of the difference in level. As the air became compressed because it could no longer flow out and when the pressure on the interior wall of the chamber reached a value just above that of the resistance of the rock, the rock split violently and instantaneously open, depriving the slope above of its support. Its weight at that point caused the slope to collapse and given the weak resistance to the traction of the rock, coincided with the vertical one, thus giving the cut its easily recognizable perpendicular characteristic. In this case the tremendous noise and the movement of air already evidenced by Pliny was even greater. When the mountain collapsed, the compressed air within the cavity was immediately expelled and together with the movement of air produced by the collapsed rocky mass, caused the violent gust mentioned by Pliny.

Since only a modest fraction of the approximately 6,000 m<sup>2</sup> of water accumulated was needed to produce the implosion, once the side of the mountain had split open, the remainder flowed violently out of the galleries to the exterior, dragging in its impetuous race all the fragments of broken rock. As these fragments struck the walls they further eroded them, making them wider, and dragged to the bottom a mass of shredded rock even greater than that of the explosion. Thus within a few minutes there accumulated a quantity of rock equivalent to several years of work and the activity at that point was limited to grinding and selection.

In Fig. 13.12 an Authors' pictorial reconstruction of the mining work is shown.

During the Renaissance era the technique had been forgotten. For example, works of demolition to open gaps in enemy walls were performed by excavating underground cavities, which were then propped up. A collapse was caused by simply setting fire to the wooden props.

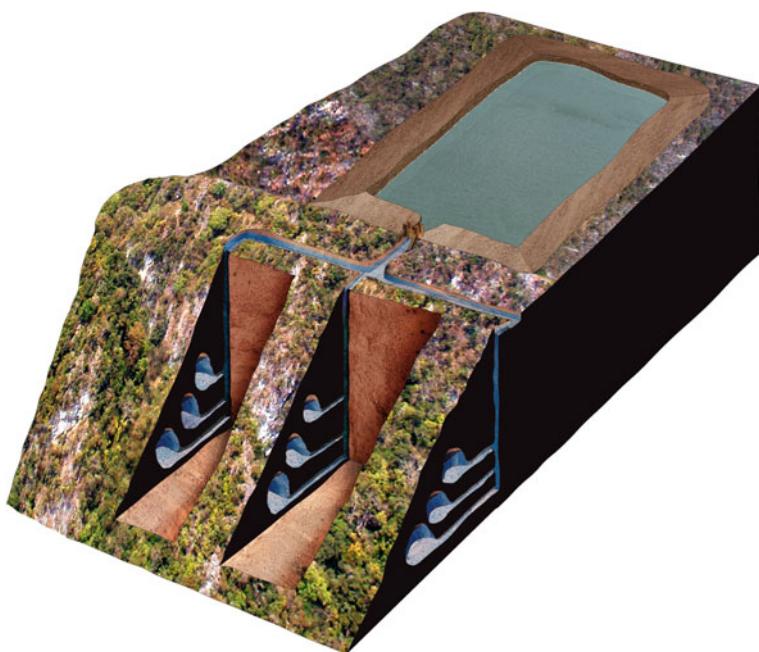
Mariano di Jacopo, known as *Taccola*, conceived and designed the use of barrels of gunpowder located at the bottom of the gallery. A few years later Giorgio Martini applied that concept to attack a wing of the castle of Castelnuovo, called also "Maschio Angioino", in Naples around 1494. From that day on the word mine became synonymous for explosion.

## Observations

Many of the inventions and applications associated with the use of water presented in this chapter are doubtless significant but are also very well known. Some of the Roman aqueducts, for example, are still preserved today and are part of our landscape.

Less well known are some *devices* such as *single control mixers* which reappeared in our homes as "novelties" not very many decades ago and that demonstrates how, approximately 2,000 years ago, hot and cold running water was already in use.

Even more surprising is the mining technique *ruina montium*; this shows that mines existed even before the discovery of explosives, in fact the English word



**Fig. 13.12** Authors' pictorial reconstruction of the mining works

*mine* comes from the Latin *mina* which in turn comes from the verb *minuere* = to remove, extract in the sense of excavating a gallery.

Yet another aspect regarding this mining technique is worthy of note: the photographs provided to this end are proof of the first documented environmental devastations caused by man, and that are still visible more than 2,000 years later.

Finally, it should be noted that this technique was most likely suggested to Roman mining engineers by the observation of nature rather than possession of a hydrostatic knowledge. For this phenomenon occurs naturally; and the authors were able to verify this from information regarding a rather recent event that had occurred in the Italian region in which they live: In the early afternoon of 4 November 1922 a deafening noise spread through the valley of a small town huddled on the southern slopes of the massif of the Matese mountains, in the south central Apennines. When they were finally able to examine what had happened, they saw that at a height of approximately 700 m the slopes of Mt. Erbano, made of solid calcareous rock, had been shattered and expelled into the air, falling back down to a height of 675 m, with a front of approximately 80 m. The vertical thickness of the exploded wall was about 15 m, making it resemble a gigantic claw-mark, capable of removing approximately 40,000 tons of rock. Water continued to flow abundantly and violently through the remnants for several days, issuing from a sort of mouth no larger than a square meter, located at the base of the apex of the cut. It was clear that the water itself had produced the explosion, leaving

one to easily imagine the tremendous pressure it must have had to produce such a disaster.

In reality, as Pascal had already demonstrated centuries before, a relatively small pressure was sufficient, on condition that a moderate sized cavity was inside the mountain with sufficient water to fill it completely. This karst phenomenon was very similar to the roman mining technique defined by Pliny the Elder as *Ruina Montium*, used in his era to demolish entire auriferous mountains in order to extract the precious metal.

# Chapter 14

## Underwater Activities

**Abstract** In this chapter some examples of underwater activities are presented, starting from the immersion of Alexander the great up to the Renaissance. Ancient devices for scuba divers and ancient diving bells are also shown.

### Introduction

The solution to the need for air in order to remain underwater dates back at least to the 7th–6th century B.C. Later special pneumatic chambers were built that were described by Aristotle. As for the snorkel, this idea came from the elephant who could walk on river beds by keeping his proboscis outside of the water. The rest was learned slowly and without too much difficulty since the first diving-suit and the first underwater military units are from the Roman Era.

### 14.1 Scuba Divers

The first example of scuba divers is found on some rather singular Assyrian bas-reliefs dating to the 9th century B.C. clearly show men swimming in water, breathing from large leather bags filled with air. In Fig. 14.1 are reported a 9th century B.C. bas-relief with Assyrian invaders swimming underwater using a wineskin and mouthpiece. Though it is not possible to determine whether they are on the surface or slightly below the water, given the significant floating thrust of the windbag, the latter appears improbable. On the other hand, if they were in the air, we fail to understand the need to hold the small tube in their mouth that is connected with the bag! It is thus logical to conclude that by using the bag they were able to float and were perhaps hidden from view, swimming barely under the surface of the water. In any case, the concept of using a large bladder as a reserve of air like today's tanks is unquestionable. In Fig. 14.2 is reported an Egyptian illustration of a diver using such a respirator to place fish on Marc Anthony's fishing line, as ordered by Cleopatra, to make him happy. The irrelevance of the depth and perhaps the brevity of the little tube led to the development of a different



**Fig. 14.1** Assyrian bas-reliefs showing scuba divers



**Fig. 14.2** Egyptian illustration of the fishing episode related to Mark Antony

system to remain underwater: a helmet equipped with a tube, through which one could breathe, as the extremity was kept outside the water by a float, a precursor of the snorkel, properly called a nozzle or aerator, used frequently on the masks of our own divers.

The maximum depth allowed by these nozzles or nosepieces usually does not exceed 50 cm, as breathing at around 1 m becomes laborious and, at greater depths, impossible because of the pressure. Some Roman writers mention something of this type, also stating that the helmet was not sufficiently impermeable. In any case, during the imperial era there was no dearth of civilian and military divers, united in a special corps, tasked with retrieving sunken objects or carrying out interventions under the float line. There is also no lack of references to actions of sabotage.

Flavius Vegetius also mentions the existence of a military corps of underwater raiders existing in the times of the emperor Claudius, during the first half of the 1st century A.D., called urinatores or urinantes, from the ancient Latin verb urinari, that means to immerse. Testifying to its existence, Pliny mentions their curious habit of

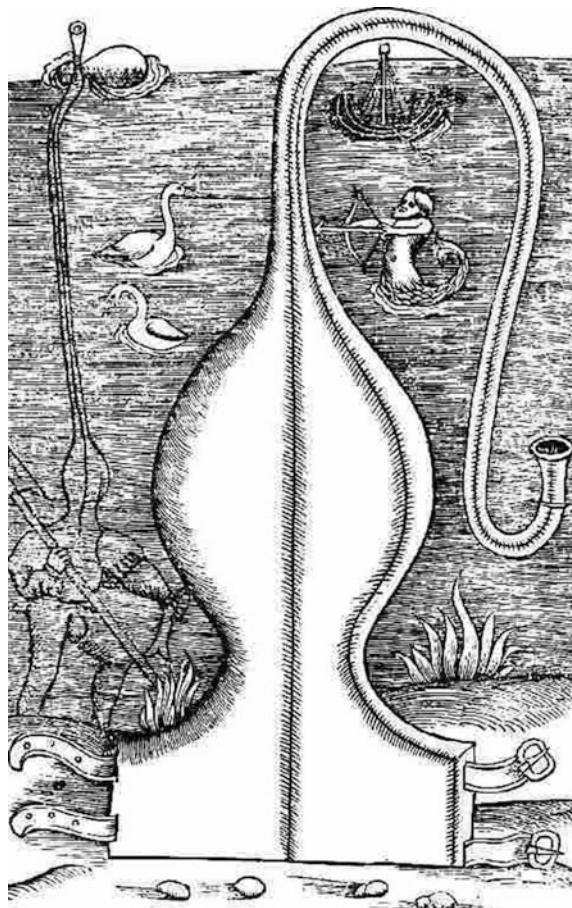


**Fig. 14.3** Imperial era funeral stone commemorating the military divers

immerging with their mouth filled with oil, which they then spit on the bottom in order to make the water more transparent. According to the few descriptions in our possession, they also wore a cap or a sack, much like the helmet of skin-divers, ending at the top in a rubber tube, that a float kept outside of the water and that was probably equipped with a valve to prevent the entrance of any water. In Fig. 14.3 is reported an imperial era funeral stone commemorating the military divers called urinatores.

In Fig. 14.4 is reported a diving helmet described by Flavius Vegetius, with a snorkel tube.

A precise drawing of such an underwater guard is also found in the notebook of Kyeser, a celebrated military engineer of the 15th century.

**Fig. 14.4** A diving helmet

## 14.2 Diving Bell

According to legend, Alexander the Great is considered, among other things, to be one of the first submariners in history. He supposedly enjoyed occasional underwater excursions accomplished in a strange submarine, as mentioned by numerous medieval illustrations. What appears to be a reliable episode is probably the basis of this heroic feat: in 325 B.C., during the siege of Tyre, the commander, in the company of Nearco, his friend as well as commander of the Macedonian fleet, performed immersions inside a pressure tank to examine enemy underwater obstructions. These may have been poles inserted into the bottom, or taut chains, or even sunken stones: in any case they were insidious obstacles placed there to break through the keels of the ships that attempted to approach the walls to attack with their artillery. According to other legends, this vehicle was not actually a tank but a sort of large caulked barrel, reinforced with bronze plates and with glass portholes,

similar to a bathysphere, at the time defined as “skaphe andros”, which translated literally means man-hull or man boat. In Fig. 14.5 are reported two depictions of the immersion of Alexander the great, found in medieval codes.

We also know that some of his soldiers, completely immersed and breathing through a rudimentary tube called a lebeta, probably connected to a goatskin, attacked the city defences, probably the same that had been inspected by Alexander.

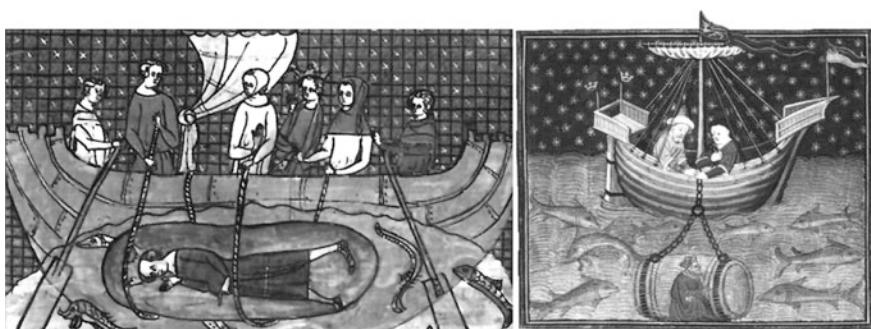
Further confirmation of this story is provided by the significant and well known observations on underwater activities and pressure by his teacher, Aristotle. The mythical philosopher observed that: “like the divers who are provided with instruments to breathe the air above the surface of the water and in such manner remain long submerged, thus the elephants have been provided with their long narices by nature, which they raise above the water when they must cross it”.

Aristotle also describes the pressure tank in his work “Problemi” (Problems, 4th century B.C.) where he suggests using the air contained in large overturned vases to breathe underwater: it appears that he may have built something of the sort or at least reproduced it.

In general, a pressure tank consists of a metal container, usually of bronze, similar to a jar. Suspended at the top by ropes it is slowly sunk into the water: as the water enters from the bottom, it stops when the air inside the container forces it to its own pressure. At that point, one can remain inside the container, or return to it to breathe, until all the oxygen is used up. The time that one could remain within varies with the size of the jar and the depth reached, but it is not very long.

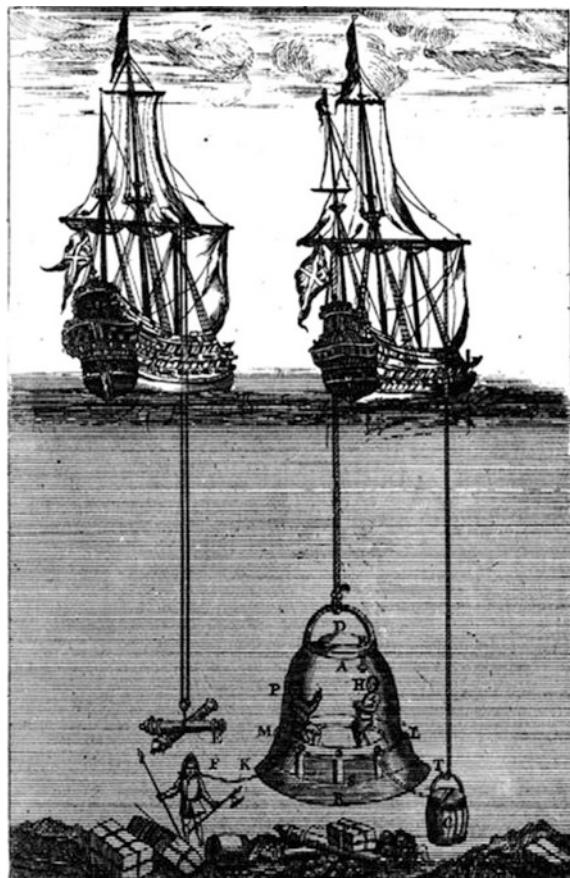
Using this jar it was possible even in the classical era to retrieve sunken objects and to work on underwater structures. It is probable that in order to increase their range of action, the divers remained connected with the container by means of a tube with a nozzle.

The idea of a diving bell was developed during the Renaissance and also some centuries later: it is reported that in 1531 the Italian Guglielmo de Lorena designed and used a diving bell to recover sunken ancient Roman ships from the bottom of a lake. It is also reported that few after the sunk of the Swedish galleon Wasa in 1628



**Fig. 14.5** Depiction of the immersion of Alexander the great

**Fig. 14.6** Diving Bell  
designed by Edmond Halley



(sunk shortly after the launch because of its instability) about 50 of its guns were fished out from a 32 m sea bed by using a diving bell.

Around 1690, Edmond Halley (1657–1742) the famous English astronomer, geophysicist, mathematician, meteorologist, and physicist (who gave his name to a comet) designed a diving bell that is shown in Fig. 14.6.

From this last Figure the working principle of a diving bell is clear: when the bell is immersed, because of the hydrostatic pressure, the water level under the bell will rise as the depth increases; hence the pressure of the air in the bell itself and the pressure of the water, at any depth, will be the same. In this way, to any scuba that operates outside the bell, compressed air will be supplied to breathe at that depth simply by connecting his diving helmet to the diving bell.

# Chapter 15

## Transports

**Abstract** In this chapter the transport devices and some details of them, such as suspensions and rolling bearings of Roman carts are presented. Several examples of authors' virtual reconstructions of Roman carts are shown; the latter are based on Roman bas-reliefs. Examples of rail systems during the Roman Empire and even earlier are also shown. Then early self-propelled carts are presented from the Hellenistic era to the Italian Renaissance. Early examples of cableways and of paddle boats, from the Roman era to the Renaissance, are also presented. The last part of the chapter concerns the dawn of the flight in the antiquity.

### Introduction

The developing of a transport system is another important step towards modernity. Horizontal transport devices are represented by carts and ships; some of them show a design whose modernity is surprising.

Probably it is also surprising that ancient engineers reduced the friction between hub and shaft using the ancestors of the ball bearings; they also conceived a rail system and they had some knowledge about the possibility even of flying.

### 15.1 Roman Charts

The Roman four-wheeled carts, whether to transport passengers, agricultural material or merchandise, be it solid or liquid, normally had a fixed forecarriage. The front and rear wheels, according to the illustrations available, had the same diameter and were higher than the caisson, so that their axle could not turn underneath it. An additional detail confirms this fact: the horses appear to be tied almost in contact with the coachman, a location not reconcilable with the steering wheel as they should have been at a certain distance to facilitate steering.

An apparent anomaly that is strangely ignored in museum reconstructions and that is the result not of the inability to conceive of a steering forecarriage, which certainly had to exist, but of its inability to support such a weight. An axle crossed



**Fig. 15.1** Fast private cart with folding tops

by a pin was fragile and the only support it had in making narrow turns could easily break off. Thus the reason why vehicles for heavy loads were later built with a double forecarriage and four steering wheels.

In general, the Romans were not great wagon makers. They simply copied them from the Nordic peoples and adapted them to their excellent roads and their many needs. They had such a vast range of wheeled carts, that some even resembled modern day trucks and busses. There were farm carts pulled by braces of oxen, freight carts to transport heavy objects, barrel carts for oil and wine, container carts with high sides to move soil or sand and even stage coaches for the public with seats on top, fast private carts with folding tops and sleeping wagons with leather pavilions and with 4 or 6 cots.

In the Figs. 15.1, 15.2, 15.3 and 15.4 are reported Roman carts: a private cart with folding top, a barrel cart, a cart used to transport dignitaries and their followers, a sleeping wagon respectively. In each of the Figures, a bas relief showing the cart, an authors' virtual reconstruction and a technical drawing are reported.

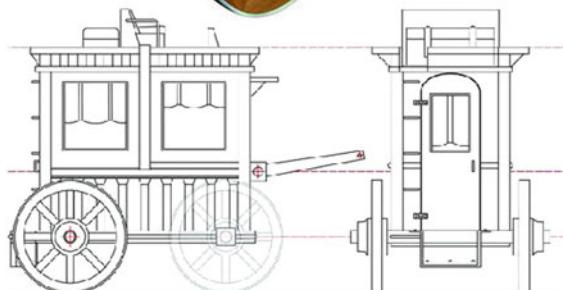
From Fig. 15.1 it is interesting to observe the presence of a brake that is evident in the bas-relief. In some illustrations we can also clearly distinguish a brake, similar to the ones still used on railroad freight wagons. Located between the wheel and the caisson, the brake made it impossible to steer the forecarriage, this is the reason why such freight wagons had fixed axles. In Fig. 15.2 can be observed the seat on the top of the chart and in Fig. 15.4 are represented some leather belts that have the function of suspension; these last two particulars are very similar to those of the stagecoach in 19th century.

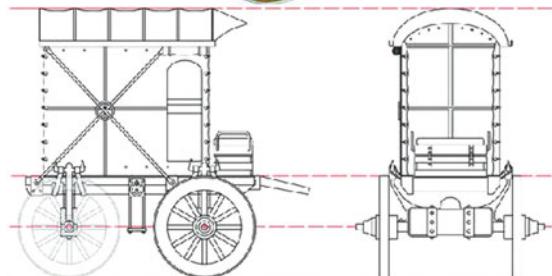
**Fig. 15.2** Barrel cart

In Fig. 15.5 a particular of a bas-relief showing the brake and in Fig. 15.6 a particular of the suspension are reported.

Several bronze supports for the robust coupled leather straps or belts have been found, some of significant artistic value. The belts acted as suspension, isolating the caisson from the axles, decreasing most of the vertical stress and the tremendous

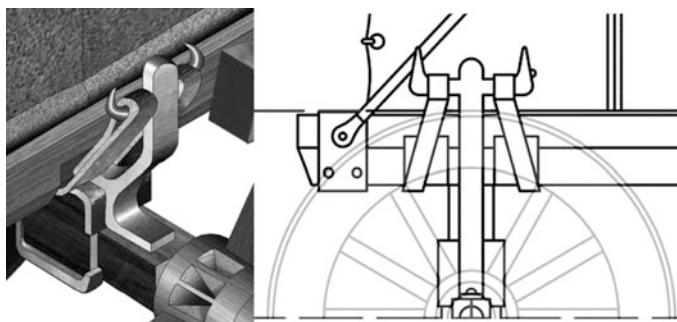
**Fig. 15.3** Cart used to transport dignitaries



**Fig. 15.4** Sleeping wagoon



**Fig. 15.5** Particular of the brake



**Fig. 15.6** Particular of the suspension

horizontal vibration, thus permitting if not a tranquil at least a less difficult voyage. Regarding a suspension system, an early type was found in Egyptian battle chariots, sometimes using actual suspension belts, others with cane arches similar to a crossbow and at times even elastic wheels with four spokes. This latter system may also be defined as a wheel-shock absorber, also used in some trains from the 1930s. In Fig. 15.7 are showed some supports for suspension belts on Roman sleeping wagons.

Thanks to the suspension and the seamless installation of the paving stones, carts were able to travel relatively comfortably and without great difficulty, in spite of the rigidity of the forecarriage.



Fig. 15.7 Supports for suspension belts

### 15.1.1 *Horse Shoeing*

It can be assumed that shoeing the animals had a dual purpose: I first was to protect the animal's feet from injuries caused by sharp items, arranged on the ground accidentally or intentionally during the wars; the second is to limit the consumption of the nail which constitutes the socket. This consumption is due to heavy use of the animal, which nature had certainly not expected. In this regard, we remember that the people who made extensive use of horses (Mongols, Berbers, Persians, Native Americans, etc.) possessed several horses for each rider.

An ancient example of metallic protection for the hooves is represented by iron full plates connected to the socket said hipposandal (in Latin soleae ferreae). Examples of such objects have been found among the remains of a Roman villa near Neupotz, in Germany and in other Gallo-Roman relics.

An authors' pictorial reconstruction of the hipposandal is shown in Fig. 15.8.



**Fig. 15.8** Pictorial reconstruction of the hipposandal

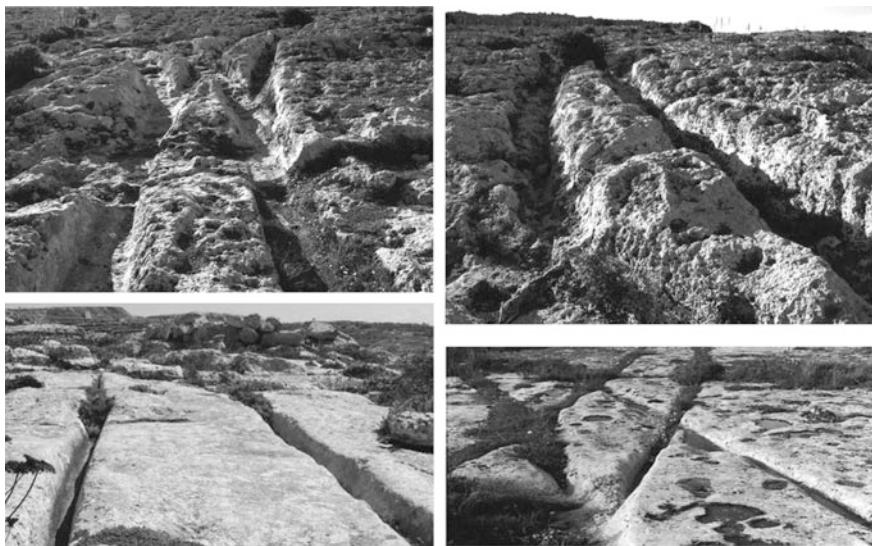
## 15.2 Railed Cargo

Large and bulky cargo was normally transported by water. This was problematic especially in shipyards that dealt daily with the problem of moving immense weights. One of the most interesting solutions involved carving rails in stone. A solution that allowed them to transfer ships from the Aegean to the Ionian, over the Isthmus of Patras, called Diolkos, in the 8th century B.C.

For many scholars, the evolution of tamping earth tracks into paved roads was spurred by the need to support the concentrated weights of wheels. This same need may have suggested an alternative solution, ideal for bulky weights: parallel grooves that could contain the rim of wheels, cut directly into the rock or in paving stones. This may explain the numerous and well preserved enigmatic primitive tracks found on the island of Malta, called cart-ruts or carved devices for guided wheels. The grooves were cut into the ground at a distance of 1.40 m one from the other and about 10 cm deep, extending over a 100 km. In Fig. 15.9 are reported pictures of those tracks at Malta.

Another stimulus may also have been their megalithic aspirations, felt very strongly in Malta. In this case it would be logical to presume that the vehicles used to transport enormous blocks would be very similar to those attributed to the architect Eleusis, and to his colleagues Chersifrone and Mutagene, to build the temples of the 6th century B.C. The idea is thought to have survived for over a millennium, an implicit confirmation of its excellent validity.

These structures were divided into railed cargo system and false axle system, both used for heavy cargo and always of large size and with a low barycentre. Even a glance reveals that they were the ideal complement to cart-ruts. The railed cargo consisted of two robust metal treads embedded around a block by means of wooden wedges that exceeded the maximum width of the block by at least one palm, allowing the assemblage to move forward in the grooves without becoming jammed. In Fig. 15.10 a reconstruction of the railed cargo is reported.



**Fig. 15.9** Parallel cuts into rock in Malta

The false axle system was reserved for longer items to be transported and will later be known as Eleusis' heavy cart. This consisted of two thick wooden axles with an iron axis and enormous wheels at both extremities that were packed and rimmed. Upon every axle was a piece of oak that lifted the longitudinal beam to which the colossal structure to be transported was tied by numerous cords. Even though the axles were independent, once the cargo was fixed, they became a veritable cart, completely suitable to the wheel-guide grooves.

This solution remained unchanged up until the last century. In Fig. 15.11 is reported a reconstruction of the system conceived at Eleusis to transport bulky cargo, according to Vitruvius' description.

These cart-ruts or grooves have also been found in other parts of the classical world, such as Delphi, where there is a singular specimen.

The Romans were obviously very familiar with these systems but only used them sporadically, not only because of the excessive inclination of the roads that could not be reduced in any way, but also for another, more important reason. The most grandiose example was the project accomplished prior to cutting a canal through the Isthmus of Corinth, called *Diolkos*, which means *dia = from the other side* and *olkos = transportation*. This was a track or portage road 6.5 km long, constructed along the western coast of the isthmus, used by ships loaded on special undercarriages to cross from the Ionian to the Aegean sea. The original construction of the *Diolkos* dates to around 600 B.C. and was used for more than a 1,000 years.

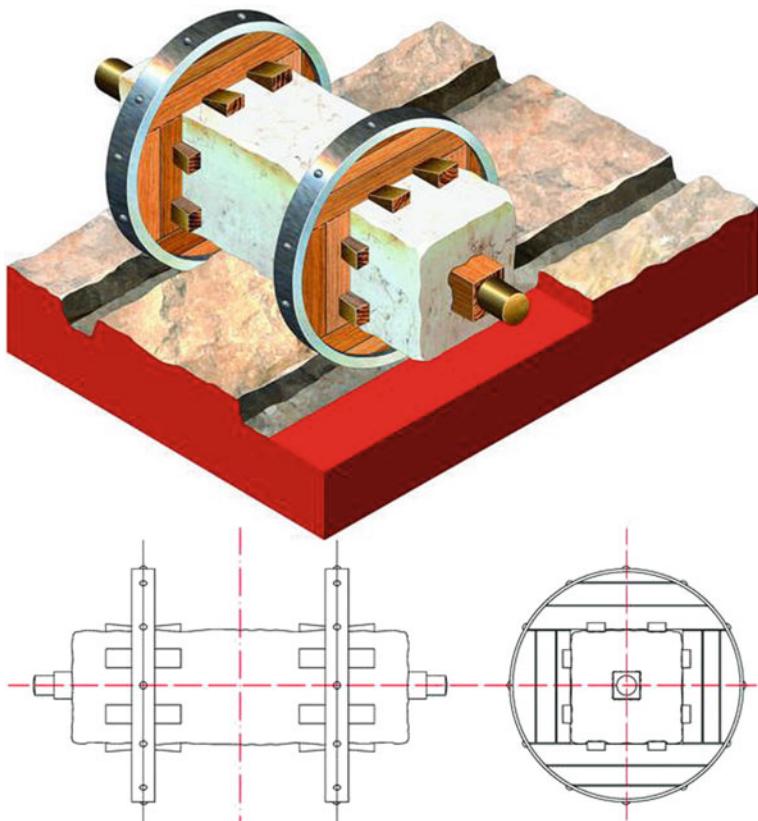


Fig. 15.10 Reconstruction of the railed cargo

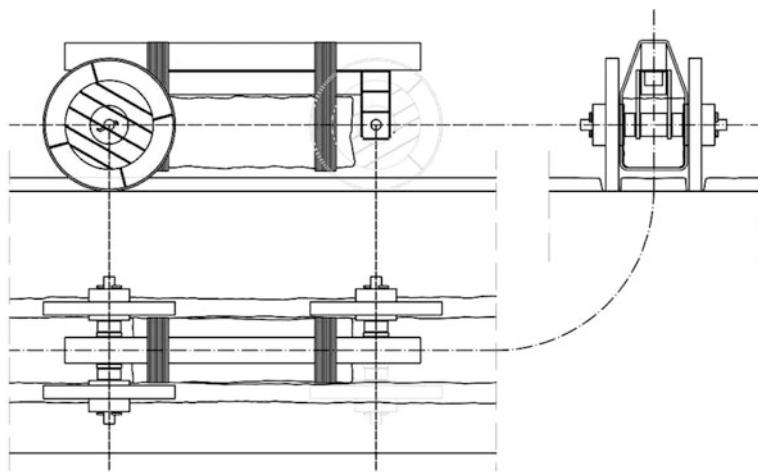


Fig. 15.11 False axle system

The Diolkos was the first long distance heavy transport guided wheel system prior to the advent of the railway. By using the Diolkos, ships reduced the time required to sail between the Aegean and the Ionian seas. It consisted of a very long hauling platform, with parallel and equidistant wheeled carts that could bear the weight of an entire ship.

### 15.3 The Rails of Pompeii

Numerous systems similar to the Diolkos were made, some even for the streets of Pompeii. But their rigidity, which because of the width of the paved roads created no problems in turning when outside of the city limits and along the loosely packed dirt roads, did become a problem when travelling along the rigidly orthogonal layout of the cities. A walk through the streets of Pompeii provides evident confirmation: not incidentally the only remains of a vehicle that have so far been identified belong to a two-wheeled cart. Four-wheeled carts found it almost impossible to turn because of their very fixed axle and the narrow crossroads. The drivers had to take a road that would lead directly to their destination, which explains the significant number of posterns on the Greek and Roman walls surrounding the cities. Thus once a cart entered the city, it advanced straight forward without turning: however, since the roads were not only narrow but also rugged and with high shoulders along the sides and even higher crossings, the risk of wheels crashing against them and being severely damaged was not a remote one.

To resolve this problem, they resorted once again to cart-ruts, of which we find eloquent examples in Pompeii, at times even lining the roads for hundreds of meters and frequently adjacent to the crossings. This was not an irrational choice, as modern day guided wheel vehicles such as trams and trains for example are also preferable exactly for the same reason—a track facilitates transit in areas not much larger than the vehicle itself, eliminating excessive oscillations and reducing the rolling resistance movement.

Technically, the use of such grooves presupposes a uniform distance between the wheels of the vehicle, the ancient equivalency of the distance between two tracks, now called *gauge*. Roman engineers updated the fortuitous gauge of the Greeks to coincide with a *double step*—1.480, which now coincides with the *Stephenson gauge*, equal to 1.435 m. Today this is still the track gauge for the most advanced countries in the world and for high speed trains travelling over 500 km/h. In Fig. 15.12 are reported pictures of some tracks at Pompeii.



**Fig. 15.12** Rail tracks at Pompeii

## 15.4 Ancient Self-propelled Vehicles

The fact that a cart moves as its wheels rotate was well known in antiquity. Not so the opposite criteria, that by rotating a wheel the cart would move by itself. This deduction was not reached until the 4th century B.C. when they were attempting to prevent the massacre of soldiers pushing siege towers underneath enemy walls.

The siege tower and their propulsion systems are presented in Chap. 18.

### 15.4.1 *Hero of Alexandria*

Hero of Alexandria designed and built a lot of devices, almost ninety reached present days. Among these device, many were automatic and represent the precursors of the automation. Some of them will be presented in Chap. 21 that is about automata and automation.

Hero in the 1st century A.D., used counterweight motors to move figurines representing animals in a sort of theatre in which the actors were automata moved by this kind of motor and by a device that permitted, among other things, to program the

law of motion of the automaton itself. To this end it could be interesting to report the following piece from the Heron's treatise *Perì Automatopoietiches* (Περὶ αὐτοματοποιητικῆς = about automatics) in which, figurines mechanically moved in an automata's theatre, are described:

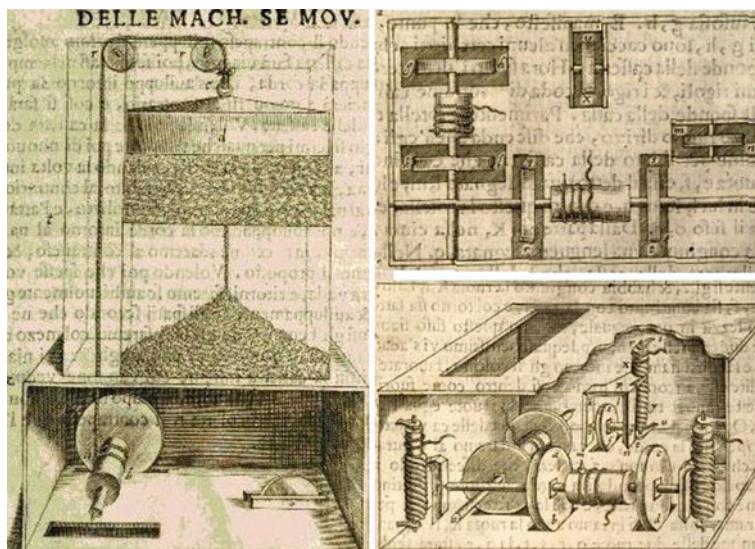
δύνανται δὲ καὶ ἔτεραι κινήσεις ὑπὸ τὸν πίνακα γίγνεσθαι, οἷον πῦρ ἀνάπτεσθαι ἢ ζώδια ἐπιφανίεσθαι πρότερον μὴ φανόμενα καὶ πάλιν ἀφανίεσθαι. καὶ ἀπλῶς, ὡς ἂν τις ἔληται δυνατόν ἐστι κινεῖν μηδενὸς προσιόντος τοῖς ζωιδίοις.

Also other movements under the platform (of the theatre) can be present, like to light a fire or figurines representing animals that before were not visible suddenly appear and then disappear again. And simply, as if one could touch them, it is possible that they move without anyone approaching the figurines representing animals.

In this and in other pieces automata are described that move without any action from outside.

The treatise by Heron was translated during the Renaissance by Berardino Baldi, abbot of Guastalla, (Urbino, 5 June 1553–12 October 1617); in his work he describes, among other things, some examples of mobile automata moved by a counterweight motor. In Fig. 15.13 drawings from Baldi's work are reported.

In the left part of the Figure the working principle of the counterweight motor is evident. In the right part, of the Figure a system used to change the cart's direction is shown: two driving axles are used, each one is perpendicular to the other one. In the same way, also the axles of the idle wheels are perpendicular. During the running, two driving wheels and an idle wheel stands on the ground while the other wheels (which axles are orthogonal to the first ones) are lifted up. To this end it is



**Fig. 15.13** Baldi's drawings of Heron's self-propelled automata

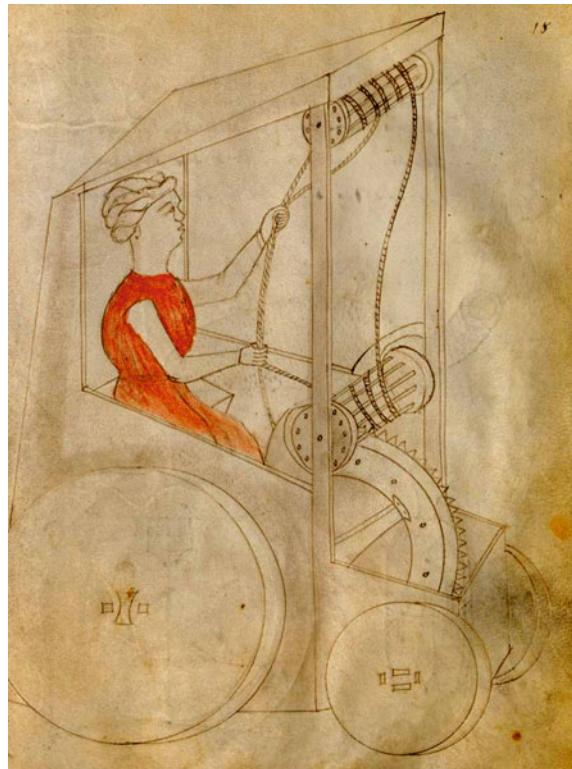
interesting to observe that the castle (or rook or tower) of the chessboard (that probably symbolize a siege tower) moves on the chessboard just in the same way; it is well-known that the chess is a very ancient game that is described in Indian writings of the 1st centuries A.D.

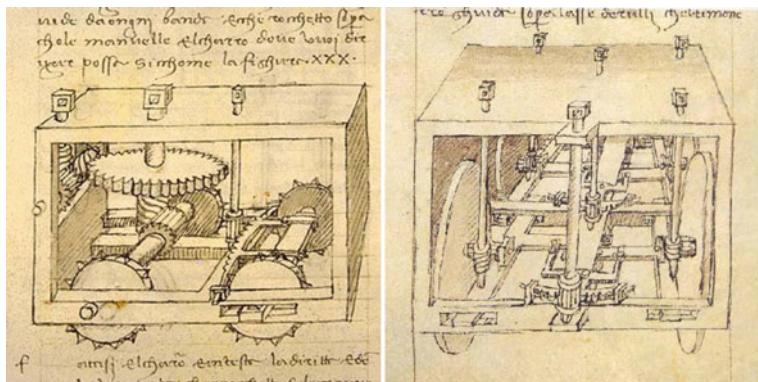
### 15.4.2 Giovanni Fontana

Giovanni Fontana (Padova 1395—shortly after 1458) is an interesting physician and engineer who invented interesting devices that are described in his treatise “Bellicorum instrumentorum Liber” (Book on War Devices). Some of these inventions are also described in this chapter (paddle ship and rockets) and in Chap. 21 among the automata.

Fontana also designed an interesting four wheeled cart powered by ropes connected to gears. In Fig. 15.14 a drawing from Fontana’s treatise is shown.

**Fig. 15.14** Giovanni Fontana’s self-propelled cart





**Fig. 15.15** Francesco di Giorgio Martini's cart

### 15.4.3 *Francesco Di Giorgio Martini*

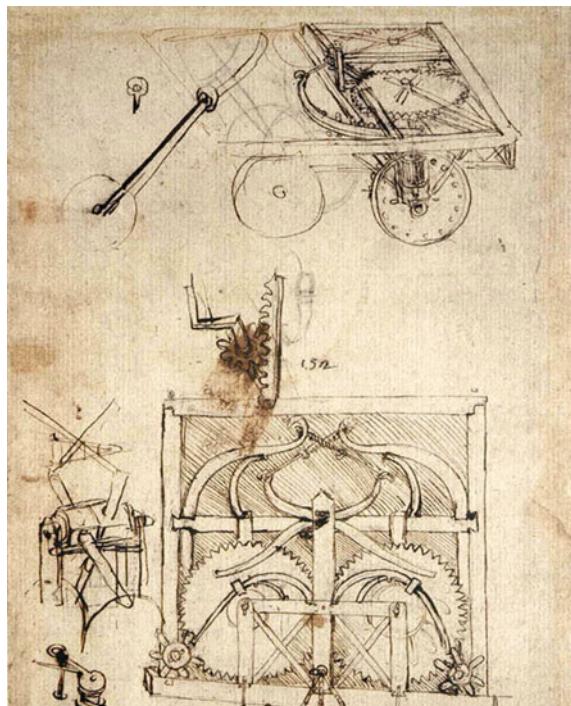
Francesco di Giorgio Martini (Siena 1439–1501) was an Italian painter, architect and engineer who designed many mechanical devices mostly reported in his treatises on Architecture, Engineering and Military Art. In Fig. 15.15 a page showing carts by Di Giorgio Martini is reported. From the drawing on the left it is possible to recognize the transmission to the driving wheels obtained by worm gears and from both the drawings the steering mechanism by rack and pinion similar to the one of modern vehicles is clearly visible.

### 15.4.4 *Leonardo Da Vinci*

Leonardo Da Vinci (Vinci 1452—Ambroise 1519) left thousands of drawings so that he is probably the man to whom they are attributed to the greater number of inventions. In Fig. 15.16 a drawing of a self-propelled cart is shown.

The “motor” is represented by leaf springs. It can be interesting to observe that the cart was studied and sometimes reconstructed by several researchers (see e.g. G. Canestrini 1938, Jotti da Badia 1939, A. Uccelli 1939) who concluded that the cart could just cover few meters. More recently M. Rosheim (2000) suggested that the real motor is constituted by a clockwork motor not visible in that drawing but drawn by Da Vinci elsewhere.

**Fig. 15.16** Leonardo Da Vinci's cart (Cod. Atl. F. 296 v.)



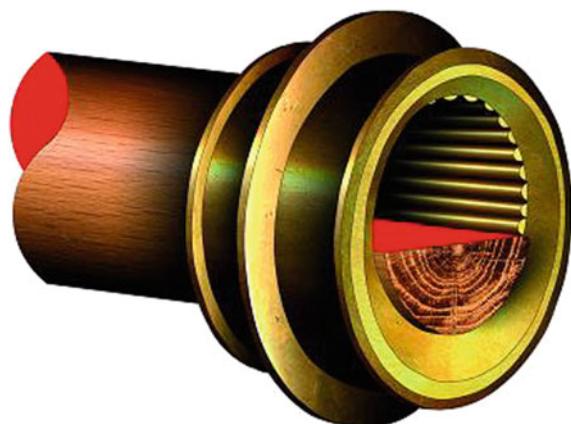
## 15.5 Early Ball Bearings

One of the problems the ancient engineers had to handle in lifting machines and carts was the friction between shafts and hubs. Probably the problem manifested itself for the first time in the prehistoric pottery lathe since it was necessary to make some crude bearings to reduce the friction of rotation: these were stone rings lubricated with mud.

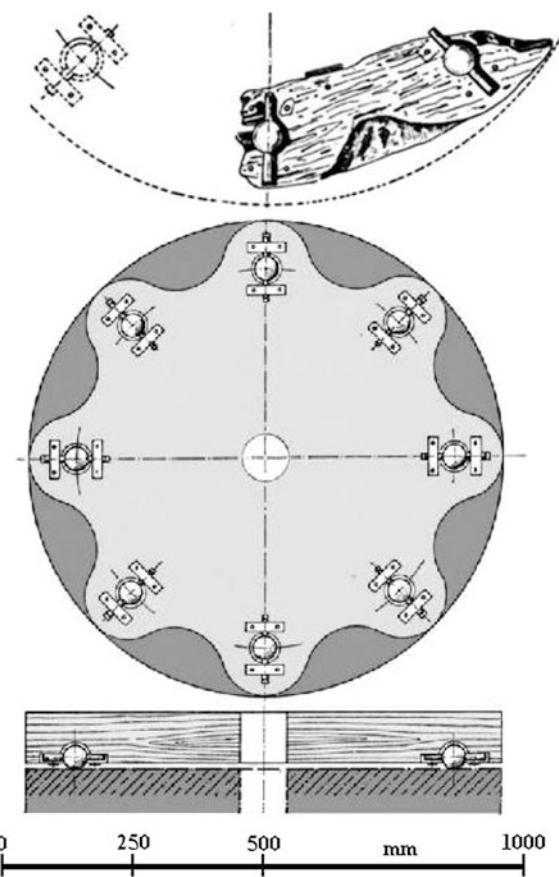
The problem was more serious with the hubs required for wheels on war chariots, for without a valid support they quickly burnt out. The remedy was a legacy of the Celts and consisted of a series of rolls placed between the hub and the axle, installed in such a way that they could not fall. In Fig. 15.17 is reported an authors' virtual reconstruction of a roller bearing of the hub of a Celtic cart.

This same criteria must have been used by the Romans since several roller bearings and ball bearings, though much larger, were found on the remains of Nemi's ships. They were installed on two horizontal circular platforms, with the lower one fixed and the upper one rotating and appeared to be a mobile base for valuable statues. But we cannot exclude the possibility that they may have been the base for a flexible crane used for loading operations. In Fig. 15.18 is reported a drawing of the thrust ball bearing of the spherical platform installed in one of the

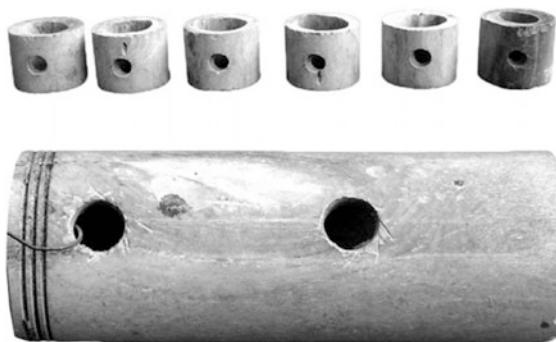
**Fig. 15.17** Virtual reconstruction of a Celtic roller bearing



**Fig. 15.18** Thrust ball bearing on a Nemi's ship



**Fig. 15.19** Antifriction hinges

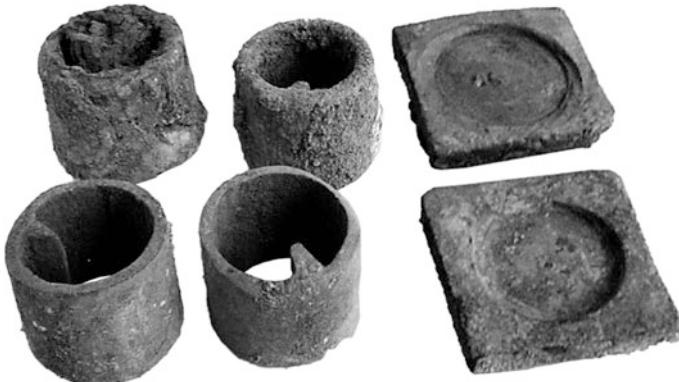


Nemi ship; in the upper part of the Figure a drawing of the find is shown and in the lower the reconstruction.

The set of bearings found in Herculaneum was much different. These were used for one of the water-wheel axles in the thermal baths, they were made of bronze and had a lenticular shape: the border of the circle rested in the incision of a large plate that was also made of bronze and was abundantly lubricated.

The thick bronze pivots used for main entry doors, similar to flanges, were also made of bronze and had to simultaneously support the weight of the door panels and facilitate movement. Made by a high precision lathe, they rotated on bronze tracks embedded in the thresholds.

In the following Figures some example of ancient bearings found at Herculaneum are reported: in Fig. 15.19 antifriction hinges made of bone, for furniture, and in Fig. 15.20 bearing hinges and rolling plates in bronze are shown.



**Fig. 15.20** Bearing hinges and rolling plates

## 15.6 Transport on Water

The idea of transporting people or things by using a floating tree trunk on a river is certainly prehistoric. From a floating tree trunk man discovered how to build pirogues first by hollowing out the trunks or by linking some of them together. Only much later the art of making hulls was discovered by assembling together some boards and naval architecture began; this happened at the dawn of the historical age.

In Chap. 8 the evolution of sails was presented, while in this paragraph we will present two examples of unusual ancient boats precursor of modern inventions.

### 15.6.1 Early Paddle Wheeled Boats

The idea of a wheeled boat, even prior to that of the floating mill, was innate to Vitruvius' design of a naval odometer, illustrated previously. Apart from its operation, we are also interested in its formal connotation: a hull with two paddle wheels along the sides that turn during navigation.

Though it may be self-evident to us that the wheels of a cart turn when it is moved, and that the cart moves when the wheels rotate, it was not so for the ancients. They were even less aware of the fact that if the motion of the water could rotate a wheel fixed to a still hull, if the wheel were made to turn in inert water, the hull would move! This very evident observation must have been confirmed experimentally: highly likely that millers turning a wheel in the still waters of a mill course using levers, might also manage to move the entire mill, even if slowly and only for a short distance.

In Fig. 15.21 is shown a bas-relief found at Mainz (Germany) near the river Rein representing a Roman ship that probably patrolled the Rein. The absence of the holes for the oars can be observed.

Whatever may have been the inventive stimulus, the first drawings of a wheeled boat must be placed at around the 3rd–4th century A.D.: of one we even have the



**Fig. 15.21** Bas-relief of a Roman ship at Mainz



**Fig. 15.22** Liburna with wheel propulsion

details, provided by a drawing and description by the anonymous author of *De Rebus Bellicis*. An even more important detail is that for the first time in the history of technology there appears a vehicle with the exact indication of an engine. This is the wheeled liburna, with three pairs of wheels rotated by three vertical shafts, each activated by a team of oxen. In Fig. 15.22 is reported an illustration from the ancient Roman code “*De rebus bellicis*”.

From a kinematic perspective this is unquestionably a derivation of the batteries of donkey-operated mills, such as those of the bakeries of Pompeii. The description reads:

The strength of the animals, supported by the action of a device, moves the warship easily, wherever necessary; this, because of its large size and inferior human strength, could not have been driven by the human hands of the crew. In its hold pairs of oxen tied to the machines turn the wheels tied to the sides of the ship; the movement of spokes protruding above the rim or convexity of the wheels, cleave the waters vigorously, like oars: they work wonderfully and ingeniously and their impetus produces movement.

This liburna, because of its grandeur and the machines it holds within, faces battle with such great strength as to easily destroy any enemy liburna that may approach.

We do not know if this project led to some tangible application, perhaps of a smaller size. Theoretically it appears to be feasible if for no other reason than the anomalous persistence of the idea, even though there is no mention in written and iconic sources. With the dissolution of the empire, the same concept emerged in the Middle Ages, reappearing systematically in the painstaking work of every technician. Thus we find side wheel boats in almost all drawings of medieval and renaissance engineers.

The horizontal axis wheel, powered from the top or the bottom, was paradoxically a technological step backward compared with the more archaic oblique paddle

wheel. But since it was the only machine of unquestionably simple construction that could provide a significant level of power, it continued to exist, arriving almost unchanged to the present day: one example is the Pelton turbine. The paddle wheel reached its peak in the Middle Ages, when it was used in all productive contexts.

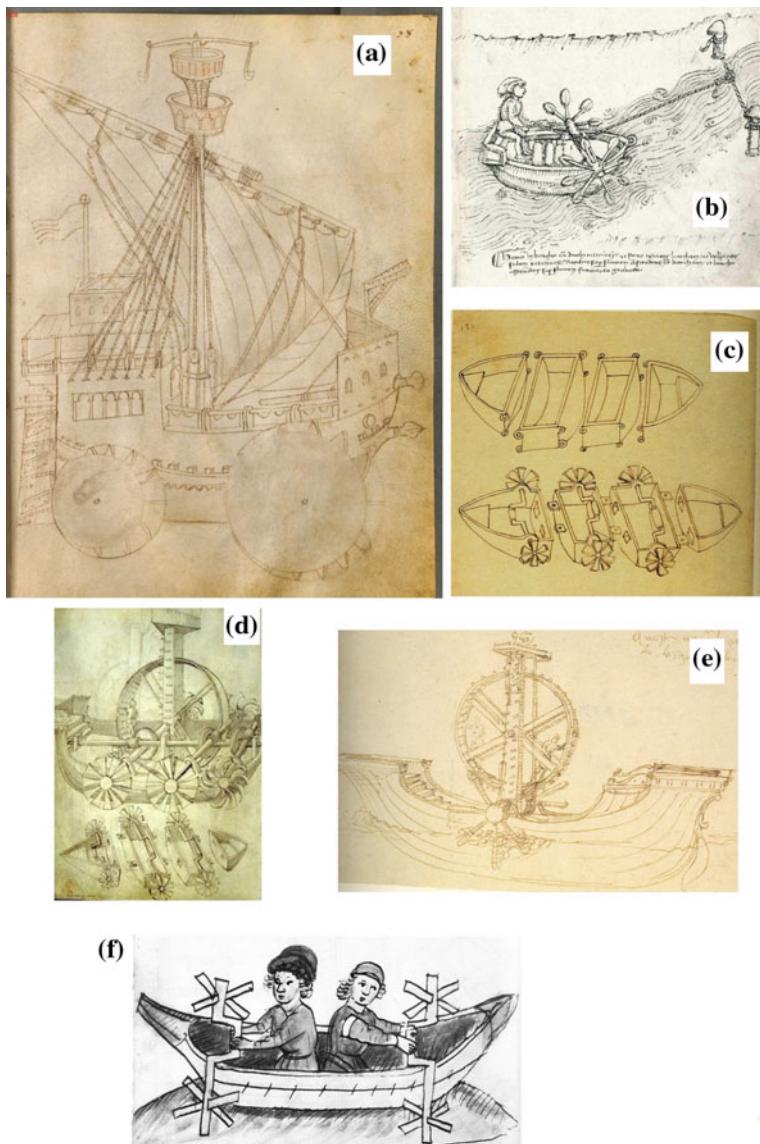
Paddle wheels or box wheels, activated the pumps that drained the mines, they pulled the large water-wheels to raise water, they activated the hoists for wells, moved the saws that cut the large blocks of stone, rhythmically lifted the hammers on the anvils. Yet other wheels moved great bellows to light crucibles: we have knowledge of such systems, called hydraulic bellows, existing around the 15th century, from the notes of many Italian engineers. And it was by virtue of their massive immission of compressed air, that furnaces led to an obvious improvement in metal products and to what is not incidentally defined as the iron age. In Fig. 15.23, some examples of later paddle ships are reported.

### 15.6.2 *Pneumatic Boats*

About 50 years ago, by involuntary and prophetic irony, a famous archaeologist and ethnologist (E. Salza Prini Ricotti) noted that no object was more useful than a pneumatic float, in effect a bag filled with air: "It can be used by the masses, be it for migration or for war, to cross bodies of water". Equating the disordered advance of miserable herds of refugees to the proud March of advancing armies may, only in appearance, appear to be a bit forced. But it is sufficient for both that a river impede their progress to prevent their reaching the opposite shore. And for many thousands of years, the simple bladder was the ultimate solution.

The military use of floats to cross rivers or small bodies of water has been documented since the II millennium B.C., and although this practice has been lost over time, never as in this case has its technological evolution changed so little. We may easily deduce that in the attempt to remove a dead body or carcass from the shore of the river, they observed its extraordinary capacity to float, incomparably superior to that of a live animal. It is also probable that the same conclusion may have been reached by noticing the difficulty in trying to immerse a swollen bag. In Fig. 15.24 Assyrian bas-reliefs showing the use of inflatable hides are reported (Contreau 1957).

It was a simple matter to view such resistance as an effective method to avoid drowning: a dual purpose container, to drink from when needed to live and not to drink to avoid dying. Full, it ensured survival on the ground, far from water, empty it allowed for survival on the water, far from land. In short, that dual purpose transformed the pack or sack into an essential piece of equipment for ancient armies. The equipment of all soldiers always included one that was emptied and blown up at a stream or river to be crossed, only to be quickly emptied and refilled with water upon arrival. To cross the water using carts they used rafts made of large tables and trunks, tied together and placed on top of such bags and barrels, the premise for pneumatic bridges made in the same manner.



**Fig. 15.23** Examples of later paddle ships: **a** Giovanni Fontana (f. 38 r.); **b** Mariano di Jacopo called “il Taccola” (1382–1453 circa); **c** Roberto Valturio (1405–1475) from ‘De re militari’; **d** Francesco di Giorgio Martini (1439–1501); **e** Antonio da Sangallo (1484–1546); **f** Hussite war Anonymous (Codex Latinus Monacensis 197, Part 1, f. 17v., second half of 15th century circa)

Xenophon, who lived between the V and the middle of the 4th century B.C., is perhaps the first to describe, in the *Anabasi*, the assembly of such a bridge to cross the Tigris. It was proposed to him by an unknown soldier, by these words:



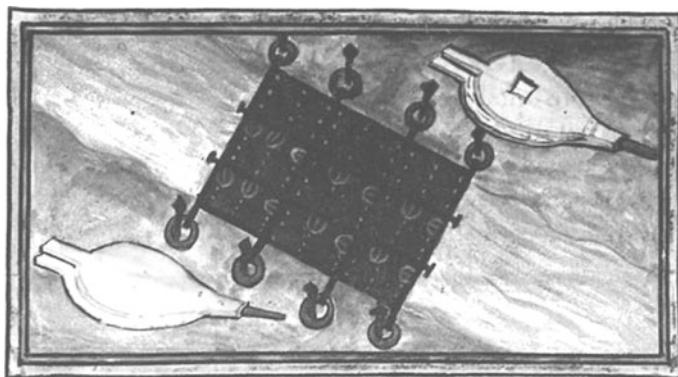
**Fig. 15.24** Assyrian bas-relief showing inflatable hides

O lords, I can help you to cross the river, four thousand hoplites at a time: but you must provide me with one talent as payment and two thousand bags; as there are many donkeys, oxen, sheep and goats here about it will be enough to kill them and remove their skin and then inflate the skins. The bags are to be tied together using the straps used for beasts of burden. Each will be anchored to the bottom using a rope with a stone as ballast. At this point I will anchor the row of bags on both shores and throw upon them a layer of branches and soil to form a path. You will not drown for each bag can support two men without sinking ....

The bag soon became part of the Roman military equipment, used as an individual float, as a raft and especially as support for attack decks. Svetonius, for example, states that the incredible speed of movement of Caesar's legions was due to the bags used to cross rivers. Caesar also notes that these bags were among the regulation equipment of the Lusitanians, Pliny confirmed their use by Arab warriors and Livy by the Spanish. In Fig. 15.25 is reported a picture from the "De rebus bellicis" showing a pneumatic bridge.

Around the 4th century of our era pneumatic bridges were also common, as confirmed by the anonymous author of *De rebus bellicis* in this phrase:

To prevent a river, as often occurs, from obstructing the road that the army must travel, the necessity that favours ingenuity excogitated a remedy that was highly economical and practical, prepared in this manner. Cow skins are to be tanned in the manner of the Arabs ...



**Fig. 15.25** Pneumatic bridge from “*De rebus bellicis*”

—for they use a very particular technique to treat the skins, using leather buckets to raise water from wells—with this type of skin ... bags measuring three and a half feet are to be sewn together so that when these bags ... are inflated, they have no protuberances; on the contrary their inflation must have a flat shape, expanding in a uniform manner; the bags are to be tied together by straps tied to the lower sides, while the upper sides are to have rings; in this manner all the elements are connected and take the form of a bridge. Thanks to the thrust of the current, this structure will extend easily towards the opposite shore, in a direction that is oblique to the river; once iron rods have been inserted into the ground on both sides and strong ropes extended in the central part, underneath the bags (to support the weight of those crossing the bridge) and on the sides (for stability), this structure will quickly provide the opportunity to cross a river ... On both shores there are to be manual ballista, to prevent an enemy attack from obstructing the work of those working on the bridge.

The illustration also shows large bellows connected with the bags. The concept is clear: continuous pumping was required to compensate for the inevitable losses caused by enemy arrows.

To the present day the inflatable bags shown in the Assyrian bas-reliefs are still used by some populations (see e.g. V. L. Grottanelli “*Etnologica l'uomo e le civiltà*” Labor, Milano, 1966).

## 15.7 Cableways

When two points were linked by a rope and to this last was hanged something like a pulley holding a load, the first cableway had been invented. The load could run downhill because of the gravity and could be pulled uphill by another rope, thinner than the main one that sustained the pulley and the load. The idea of linking two less accessible places by a rope, hence, is probably not very older than the invention of the ropes themselves. This clearly appears in the suspension bridges made by the



**Fig. 15.26** Chinese cableway of about 1250

Incas and in similar structures in Asia; in fact, this kind of bridges are called Tibetan bridges.

Because of the friction and the atmospheric agents, ropes made by vegetal fibres had a short life, hence it is very difficult to discover archaeological finds of them. Much more durable are the metallic ropes, especially those made by less oxidizable metals and alloys. The manufacture of wires made by copper, silver, gold and iron is found from around the 5th century B.C. and the manufacture of ropes made by metallic wires should have been started from the 3rd or the 2nd century B.C. The archaeological finds of very ancient metallic ropes are also very few; this probably because copper and its alloys were very expensive and were reclaimed as soon as possible, while the iron is quickly destroyed by corrosion. At Pompeii a copper lanyard was found made by three stands each of which was composed by 19 wires.

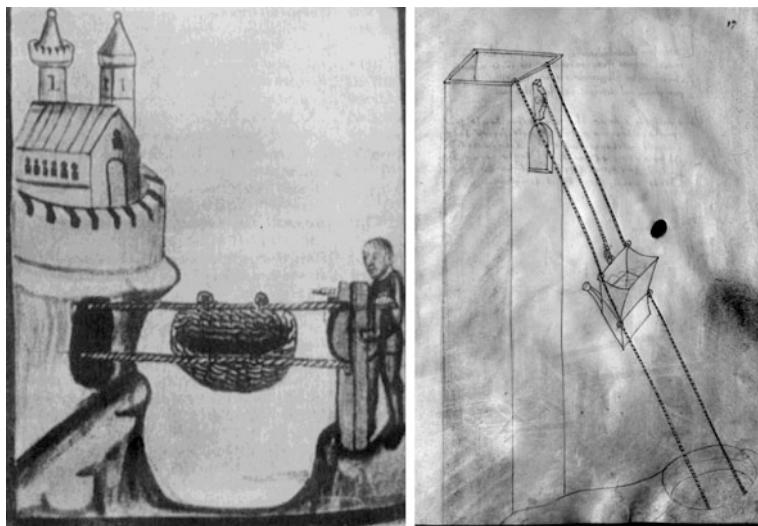
For the reasons reported above, the authors believe that cableways were used in very ancient times but they couldn't find any archaeological proof of it.

The first documented cableway is reported in Fig. 15.26 where a Chinese device of about 1250 is reported from H. Dieter Schmoll (*Weltseilbahngeschichte Band I: bis 1945*, Ottmar F. Steidl Verlag, Eugendorf/Salzburg, 2000).

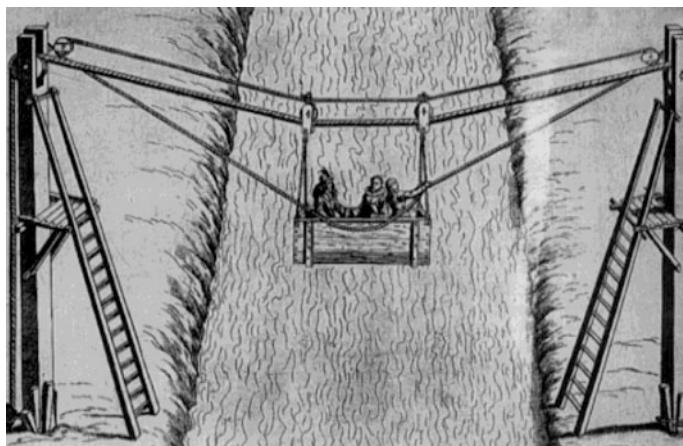
In Europe, at the end of the Middle Ages appear the cableways designed by Johannes Hartlieb (around 1400–1468); one of them is reported in Fig. 15.27.

In the same Figure is reported a device by Giovanni Fontana (1395– after 1454 A.D.), that will be wider cited in Chap. 15 about his automata; this last image is in the Fontana's treatise “*Bellicorum instrumentorum liber*” (Book on the war devices, 1420) that can be read on line on the Munchener Digitale Bibliotek.

In 1615 Fausto Veranzio (1551–1617), already cited in Chap. 6 for his wind motor and more widely in Chap. 7 for his water wheel, designed the “*Pons unius funis*” (Bridge [made by] an only rope) that is reported in Fig. 15.28.

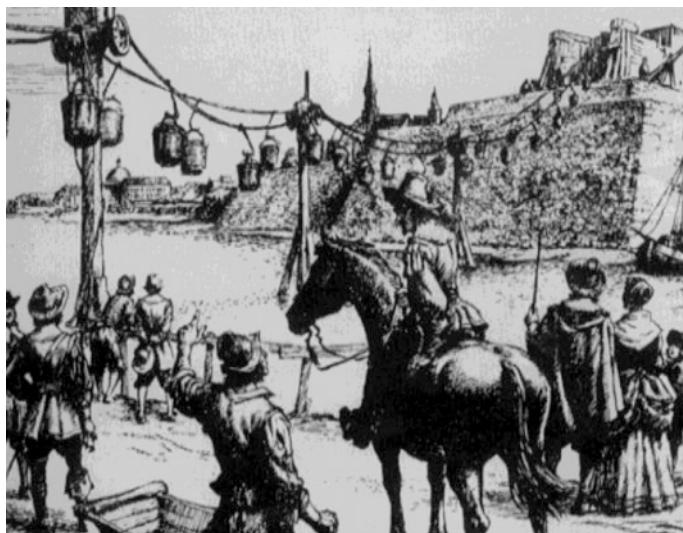


**Fig. 15.27** Cableway by Johannes Hartlieb (*left*) and a device by Giovanni Fontana; Bellicorum instrumentorum liber, folio 17 recto, Munchener Digitale Bibliotek (*right*)



**Fig. 15.28** The “Pons unius funis” by F. Veranzio; from H. Dieter Schmoll, op cit

Another interesting example of ancient cableway is reported in Fig. 15.29; it was designed by the Dutch engineer Adam Wybe (1584–1652) and was used to transport the building materials for the fortification “Bishofsberg” in Danzig.



**Fig. 15.29** Cableway by Adam Wybe

## 15.8 The Dawn of the Flight in the Antiquity

There is absolutely no doubt that the desire to fly has always, in every era, been one of the highest aspirations of humanity. Certainly in prehistoric times men must have envied birds their capacity to move through the third dimension for practical reasons: they could escape their predators and, from the skies, better scout the land in search of food.

Nevertheless it is difficult to think that it was only practical aspects that ignited this desire to fly. All mythologies in all civilizations and in every corner of the globe are peopled by winged beings as are all religions. But this desire to disengage from the earth is surely based also on other motivations, perhaps more profound ones, of the human spirit.

As all are aware, excluding the attempts made with aerostats and hot air balloons, the first mechanical flight crowned by success is believed to have taken place in Kitty Hawk, U.S.A. thanks to the efforts of brothers Wilbur and Orville Wright. But what about before?

Prior to the Wright Brothers there was an interminable list of artisans, engineers and inventors who attempted, sometimes successfully, to make objects heavier than air fly, sometimes even with a human crew.

We will consider the period of time that extends from ancient Egypt up to the Renaissance, dividing into historical periods.

## 15.8.1 *Legends and Tales*

### 15.8.1.1 Daedalus and Icarus: Legend or Reality?

Everyone is familiar with the legend of Daedalus and Icarus: Daedalus (to whom mythology also attributed the construction of robots) designed the Labyrinth in the palace of Minos, the legendary king of Crete, in Knossos. Once the palace was finished Minos imprisoned Daedalus and his son Icarus because he had helped Theseus and Ariadne to escape the Labyrinth. Daedalus therefore made wings of feathers and wax for himself and his son and together they escaped by flying away. But Icarus, overwhelmed by the thrill of flying, flew too high and the wax on his wings melted as he approached the sun, and he fell into the Aegean Sea. Daedalus instead landed happily in Sicily.

What seems to be an improbable legend is, instead a tale that, in essence, has a certain verisimilitude even in the technical-scientific context of the second millennium B.C.

If we view the palace of Knossos from the sky, we note that it is built on a north-facing slope on the Aegean Sea. By day, the exposure of the palace and the conformation of the ground can easily lead to creating ascensional thermal currents, ideal for hang-gliding.

### 15.8.1.2 Daedalus and Icarus in the Far East

A Japanese legend narrates that around 1100 A.D. a certain Minamoto Tametomo was exiled on an inhospitable island together with his son and that he managed to escape by building a giant kite made of reeds and paper. It is certainly surprising how this legend, belonging to a people who were almost at the other side of the world, is so similar to the Mediterranean one of Daedalus and Icarus.

Of course two legends are certainly not proof, however it is reasonable to view them as a sign. As we will see, in fact, there is evidence of a possible and perhaps even probable existence of experiments to do with gliding in ancient times.

What is certain is that there existed giant kites in China and Japan, capable of lifting one or two men, as early as the 4th–3rd century B.C. They were used as aerial observatories to observe enemy manoeuvres: basically like very high towers. As far as we can determine it was the Chinese, after the invention or the perfection of giant kites, who first became interested in their military application, adding rational modifications. They succeeded in increasing their lift capabilities to the point of using them in various circumstances for communications of crucial tactical importance and even to bring flying raiders inside cities under siege. The fore-runners of airborne troops.

To find reliable and detailed references to giant kites with crews on board, we must wait until 1285 and the ‘Million’ by Marco Polo. How these giants of the air were constructed may be easily deduced by similar ones that the fishermen of a



**Fig. 15.30** Japanese giant glider

Japanese village continued to build for centuries, using the same materials, bamboo and paper, up to 1914, fortunately still in time to leave unquestionable photographic evidence. In Fig. 15.30 a picture is reported, taken in 1914, of a Japanese giant glider. We cannot therefore exclude that news of their existence reached the west from the silk route.

### 15.8.2 Ancient Egypt

In 1898, in a tomb in Saqqara, they unearthed an object that resembled a bird, approximately 14 cm long, with a wing span of circa 18 cm. This was still 5 years prior to the Wright Brothers' experiment and the object was considered to be a stylized bird.

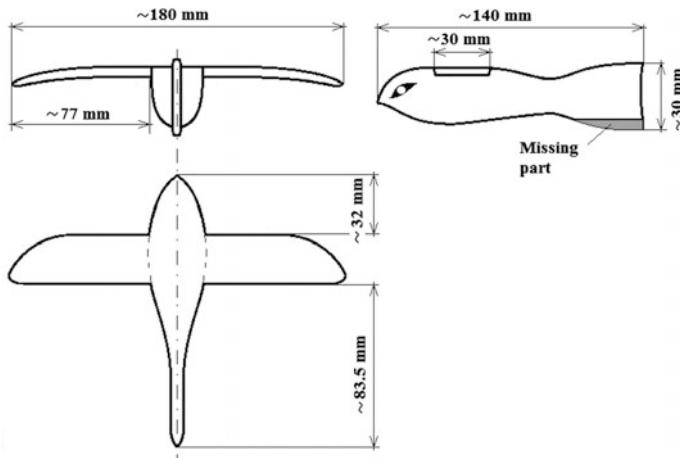
It wasn't until 1969 that dott. Khalil Messiha, observing the artefact in the Egyptian Museum in Cairo noted a similarity with a modern airplane.

In effect, its aspect had at least three anomalies indicated that it is not, in fact, a bird: the wings are straight, there is no trace of bird claws and the tail is vertical rather than horizontal. This last aspect is present only in flying objects built by man whereas birds have a horizontal tail.

In Fig. 15.31 a schematic 3 view drawing of the Saqqara bird is reported.

The relic was studied by experts in archeology and aeronautics who noted that the wings had a shape that was indispensable for stability in flight and who advanced the theory that the object might be the model for an airplane. Further studies led to the discovery of various other similar objects.

A technical commission was set up in 1971 by the Egyptian Ministry for Culture; a team of experts in aeronautics concluded that the artefact seemed to show that its designer had some complex aerodynamic knowledge and many people are



**Fig. 15.31** Schematic 3 view drawing of the Saqqara bird

convinced that the Saqqara bird is a proof that the ancient Egyptian had the capability to design gliders.

### 15.8.3 Ancient Greece and Hellenic Civilization

There are innumerable inventions in the field of engineering in Ancient Greece, especially during the Hellenic Era. A study of the technology of the Greco-Roman world has revealed the existence of machines whose designs were extremely advanced in concept in design criteria. Strangely, however, it was specifically during this era, as far as we know, that no actual flying machines were ever made, except for those conceived by Archytas of Tarentum who however lived in a relatively ancient era.

The Roman author and grammarian Aulus Gellius (ca. 125—after 180), in his work (*Noctes Atticae lib. X, c. 12*) writes that that the famous Archytas (428–347 B.C.), a philosopher, mathematician, astronomer, statesman, and strategist from Taranto, invented a mechanical dove powered by compressed air. According to other scholars, the dove could fly by beating its wings.

### 15.8.4 The Middle Ages

During the Middle Ages there are various references to flying machines, the oldest being of Arabic origin, followed by others made in Europe. We describe herein the

most important. There are numerous examples of rockets designed by Islamic engineers during the Middle Ages; some of them will be described in par. 14.10.6.

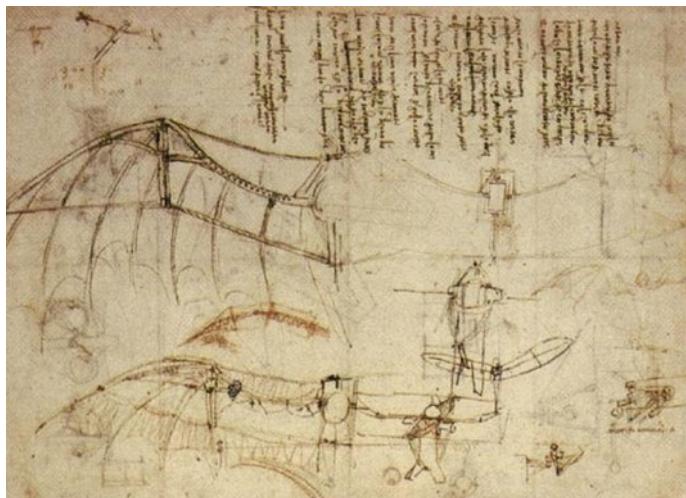
The first successful attempt at human flight was performed by Arab inventor Abbas Ibn Firnas (Cordoba, Spain 810—887 A.D.) who used adjustable wings covered with feathers. For this reason, a crater on the Moon was named in his honor. This Arab flying machine is particularly interesting because of the presence of hinged control surfaces at the trailing edge of the wing (ailerons), very similar to those of the modern aircrafts. Flying machines designed some centuries later were not provided with these control surfaces.

During the Middle Ages there are also several indications of more or less successful flight attempts; among these is the English Benedictine Monk Eilmer (Oliver) of Malmesbury. He lived between the 10th and the 11th Century and is reported to have flown for about 200 m with wings fastened to his arms and legs.

Concerning medieval flying machines we once again refer to Giovanni Fontana (Padova 1395, ~1455) and his treatise *Bellicorum Instrumentorum Liber* who describes building rocket-propelled flying doves. The devices by Fontana were essentially built to measure the height of buildings that could not otherwise be reached: they were loaded with an amount of propellant that was increased at each successive run, until the dove reached the required height of the walls. The amount of propellant used gave the height. In Fig. 15.32 one of these devices is shown.



**Fig. 15.32** Flying dove by Giovanni Fontana (f. 37 r.)



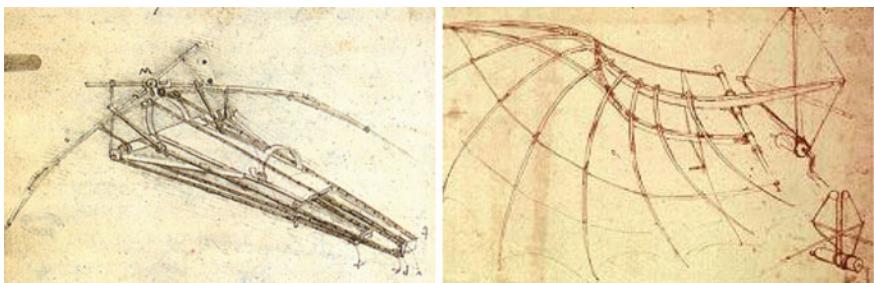
**Fig. 15.33** Ornitottero

### 15.8.5 *The Renaissance*

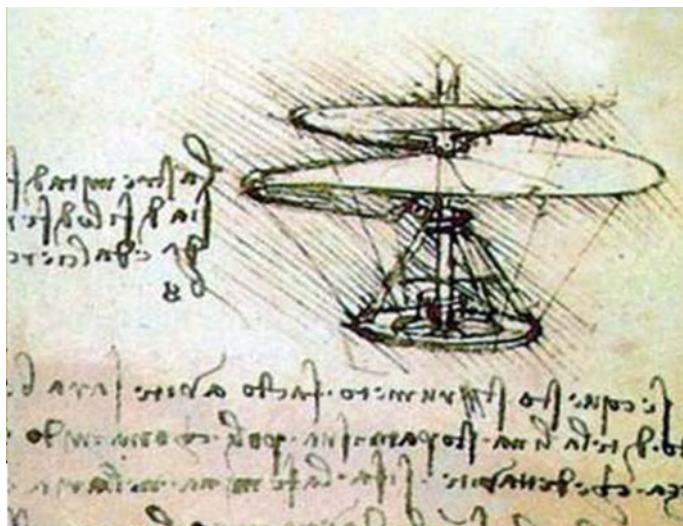
In 1505 Leonardo Da Vinci wrote the codex “Sul volo degli uccelli” (On the flight of birds); Fig. 15.33 is a drawing representing the flying machine “Ornitottero” (from the Greek Ornithos, bird and Ptérón, wing) by Leonardo.

The structure of the wing and the entire machine are illustrated in Fig. 15.34. This is an aircraft with a beating wing surface. Thus it is not a device conceived for gliding as are hang-gliders, but one that relies on a source of power (engine) inside the machine.

Another of Leonardo’s flying machine is the aerial screw, shown in Fig. 15.35, considered by some to be the precursor of the modern helicopter. As far as this point is concerned, it is interesting to note what Da Vinci himself write about the device:



**Fig. 15.34** Ornitottero and the wing structure



**Fig. 15.35** Aerial screw

“Trovo, se questo strumento a vite sarà ben fatto, cioè fatto di tela lina, stopata i suoi pori con amido, e svoltata con prestezza, che detta vite si fa la femmina nell’aria e monterà in alto” (Manoscritto B, foglio 83 v.).

“I find that, if this device is correctly built, that is to say made of linen, plugging its pores with starch, and quickly rotated, that screw will spiral in the air and rise”.

In Fig. 15.36, on the left, another of Da Vinci’s famous drawings: the parachute. On the right is the drawing by Mariano di Jacopo for comparison.

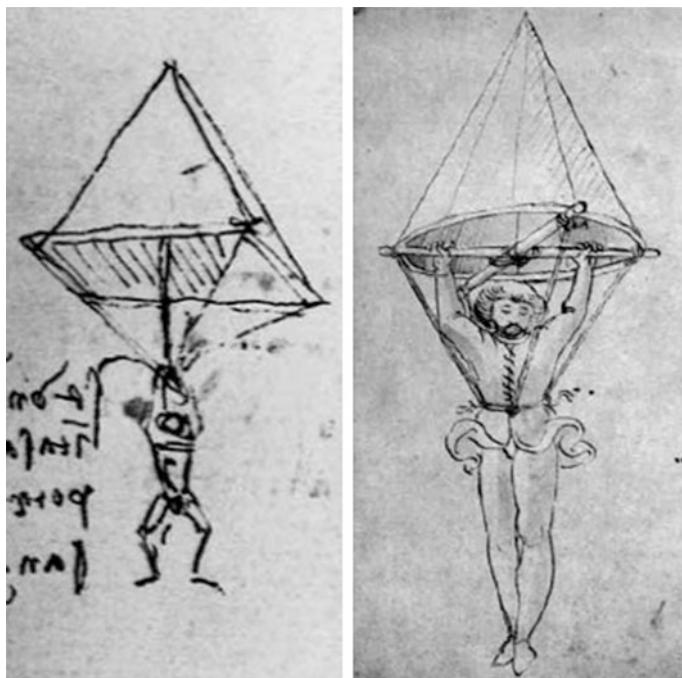
Much has been said and written of Leonardo’s flying machines, leading us to the following general considerations.

As many Authors have stated, none of Leonardo’s machines with an internal engine would ever have been able to fly because in that era there was no motor with a weight to power ratio that would permit human flight.

And we should add that, even if such a motor were to have been available, the aerial screw would never have been able to fly; in fact, if a torque was applied to the screw by any motor attached to the ‘fixed’ part, the ‘fixed’ part would also rotate, in a direction contrary to the screw, as soon as the machine lifted from the ground.

In addition, Leonardo Da Vinci was not familiar with the phenomenon of the propeller slip, which is the difference between the speed of the fluid before the propeller and after it. So, if the propeller had made the screw “spiral in the air” the slip would have been zero and, hence, the screw could give no pull.

And so it is natural to wonder why Leonardo would design a parachute in an era in which there were no flying machines. It must also be said that probably none of the machines designed by Leonardo, as they were conceived, could ever have flown.



**Fig. 15.36** Parachutes: Leonardo Da Vinci (Sx) and Mariano di Jacopo (Dx)

It is also interesting to mention that, during the Renaissance, several experiments were carried out regarding flight. The most interesting are probably the ones built by Conrad Haas and reported in next paragraph.

### 15.8.6 Ancient Rockets

Devices based on the action-reaction principles are very old; with reference to this we can consider the flying dove by Archytas, the rockets by Alaaddin Tayboga al-Omari al-Saki al-Meliki al-Nasir and by Giovanni Fontana mentioned in a previous paragraph and the aeolipile by Heron, a first example of reaction steam turbine, that is reported in Chap. 17.

Old examples of rocket constructions come from China and were described in Europe by the Venetian traveller Marco Polo in his “Il Milione” written at the end of the 8th century. Paradoxically the first Italian town that was bombed by rockets, in 1848 by the Austrians was Venezia (Venice). The Chinese used rockets either as fireworks or as weapons; the employment of rocketry in military application by the Chinese is dated 1232 A.D. in the battle of Kai-Fung-Fu against Mongol invaders. In the treatise Huolongjing or Huo Lung Ching (= fire dragon manual), written by



**Fig. 15.37** Rocket by Alaaddin Tayboga al-Omari al-Saki al-Meliki al-Nasir

the Chinese officers Jiao Yu and Liu Ji in the 14th century, they describe a large number of bombs and fire arms; among these also two stage rockets stabilized with fins. In the same treatise also different compositions for gunpowder and rocket propellant are reported.

During the Middle Ages, the Arabs carried out studies on rocketry. The oldest example of an Arab military treatise is a book on arms and military. The first section of this book dates around 775 and was written by an anonymous. The second section of the book, called “Kitab al-hiyal fi'l-hurub ve fath almada” in hifz al-durub, was copied in 1356 and was written by the Turkish commander Alaaddin Tayboga al-Omari al-Saki al-Meliki al-Nasir; in this second part, rocket bombs and burning arrows are described. Of these is the one reported in Fig. 15.37.

Another Arab inventor, the Syrian Hassan Al\_Rammah, around 1275, described a rocket powered torpedo having the shape of an egg, filled by gunpowder and stabilised on its course by a rudder.

Also Giovanni Fontana (already cited in par. 10.9 and wider mentioned in Chap. 16 for his automata) in his treatise (“*Bellorum instrumentorum liber*”) designed some rocket powered devices; on the folio 37 recto, it is possible to observe two rocket powered objects: an hare and a bird; the latter reminds us of the dove by Archytas and is used to measure vertical heights. This was obtained by adjusting the charge of power in the rocket: to a given power amount, corresponded a known height; on the same folio a device used to measure the amount of powder is also represented. On the folio 40 recto of the same work by Fontana is reported a rocket powered torpedo very similar to the one described by Hassan al-Rammah that had to be used against enemy vessels.

The most well-known examples of use of the rockets in Europe are the siege of Constantinople in 1453 where the Turks bombarded the city with rockets and in India against the British Army at the end of the 18th century. From this event, Sir William Congreve was inspired to design the rockets (named after him) that were used by the first time by the Wellington’s army at Waterloo.

Most of the rockets above mentioned were powered by black powder and essentially consisted in a hollow cylinder, closed at one of its ends, filled by gunpowder and ignited by a fuse; the combustion of the powder produced a large amount of gases that gave the propulsion. Rockets conceptually different from those mentioned before and showing a surprising modernity were invented during the renaissance.

In 1961 At Sibiu, a town in Rumania, in the local library a treatise was found (Sibiu public records *Varia II 374*) written between 1529 and 1556 by the Austrian engineer Conrad Haas. Haas was born in 1509 at Dornbach near Vienna. As *Zeugwart* (equipment manager) and arsenal master of the Austrian army under emperor Ferdinand I, he was sent to oversee the operation of the arsenal at Hermannstadt, now Sibiu Romania, that was in that part of Transylvania that in those days was a part of the Austrian Empire, where he died in 1576. In his treatise, Haas describes the technical details of rocket construction and explains the working principles of a rocket. Some of these are reported in Fig. 15.38.

The modernity of some of the Haas' rockets is very surprising: first of all he can be considered the inventor (almost in Europe) of the multi stage rockets, then he is very probably the first to use a liquid propellant. Another surprising modernity of Haas' knowledge is also represented by the bell-shaped nozzles; in addition he describes in great detail the composition of the propellant and its granulation in order to obtain different purposes and behaviour of the boosters. Moreover some of his rockets are stabilized by delta shaped fins.

A few decades later, at the end of the 16th century, the German firework maker Johann Schmidlap, attached smaller rockets to the tops of bigger rockets as they would reach higher altitudes.

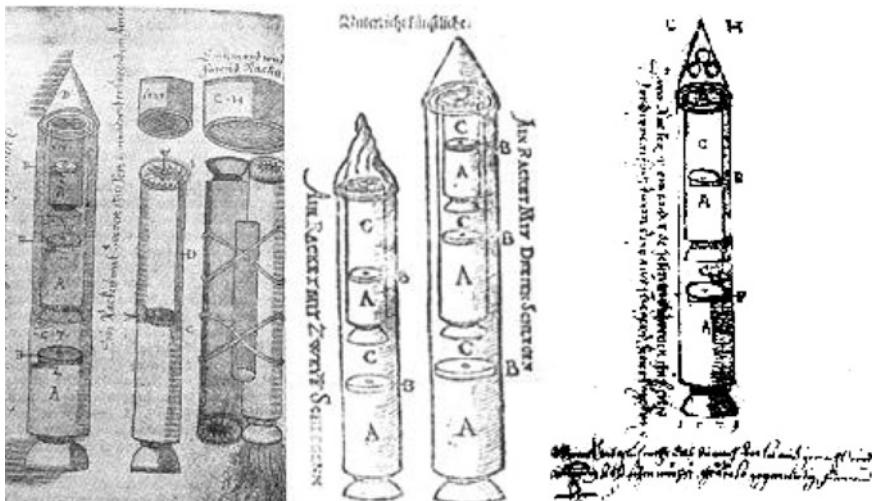


Fig. 15.38 Multi stage rockets by Conrad Haas

Before the treatise by Haas was discovered, the inventor of multi-stage rockets was considered Kazimierz Siemienowicz, a Polish general of artillery and military engineer, who in 1650, in his “*Artis Magnae Artilleriae, Pars prima*” (The Great Art of Artillery, first part), gave a description of a three stage rocket.

As for the word rocket, many Authors report that in 1379, an Italian artificier named Muratori used the word “rocchetto” (= little fuse) to describe gunpowder propelled arrows; from the Italian word came the English rocket and similar words in other languages.

### **Observations**

The Roman transport system and devices, the standardisation in the dimensions of wheels, hubs and chart’s gauge is the confirmation that in the 1st centuries after Christ a first industrial revolution took place, as narrated in the introduction of this book.

# Chapter 16

## Telecommunications

**Abstract** This chapter presents some ancient telecommunication devices, starting from the Greek-Roman Era till the 18th Century. Particularly interesting is the water telegraph that was based on a very modern concept and permitted to communicate fastly and efficiently in all the Roman Empire.

### Introduction

Within the animal kingdom, relations are often established by the characteristic and conventional sounds made by the different species. In man these slowly assumed the form of words, at first only a few then increasingly more and more numerous as required to describe what had happened and was happening to the senses or was elaborated by the brain. Communication thus was strictly limited by the range of perception of those sounds: by increasing the volume this range could be enlarged, but by very little and never, in the best of hypotheses, beyond the brief visual horizon. Recourse to sound instruments that could produce louder sounds soon began to be used, from the simplest to the most sophisticated: the common guiding principle was that they be able to vibrate the air or to produce noise and sounds that were more intense than those made by human beings.

When several ships sailed together it became necessary for them to communicate with each other and since it was not possible to send someone from one ship to another whenever required, a means was required to send messages. Various devices were invented, acoustic and optical, for short and long distances. Once these instruments were mastered, they also began to be used on land.

Successively more complex and effective media for communications were invented so that one of the indicators to “measure” the level of civilization and scientific knowledge of a civilization can be considered the communication systems.

In the following paragraphs the early systems will be presented; they will be divided depending, roughly, on their working principle.

## 16.1 Acoustic

In mythology, Miseno was the trumpeter on Aeneas' ships. He was not, however, a musician, and neither were musicians the many players of the horn, tuba and trumpets of the Roman legions. They were all signalmen, military tasked with communication between ships and later on the battlefield. This system was later adopted also within the civilian context.

As for acoustic communication systems, several methods were chosen, all of which could be differentiated into two categories: percussion instruments, in which the sound conveyed is the result of the beating of wood or metal elements, such as the gong, the drum or the tam-tam; aerophonic instruments in which vibration increases by the expansion of air in special cavities, such as horns, conches and metal tubes, ancestors of the horn and the trumpet.

Obviously an increase in range meant a decrease in intelligibility: a sound that could travel across kilometres could not be modulated like words. The rolling of drums, of tam tam or the echo of horns was basically uniform, thus the information to be transmitted had to be binary: affirmative if the sound was heard, negative if it was not: a very poor message. By regulating the emission and the pauses, additional meanings could be added to that restricted range. The maximum potential of acoustic transmission seems, and the conditional here is obligatory, to have been reached by Alexander the Macedonian, by the use of a singular horn whose sound could be heard from a distance of 20 km.

Perhaps a legend, perhaps the extraordinary result of favourable environmental conditions, difficult to ascertain, especially since we lack the same highly silent environmental context. It is totally impossible, on the other hand, to even attempt to understand the plan presented to him by an inhabitant of Sidon, to build a system of rapid communication that could connect his entire immense empire. Because of the great speed of signal transmission that he proposed, he was not believed and the matter ends there.

Acoustic signals did not disappear and continued to be used by armies, though to a lesser extent, since they were the only sounds that could be perceived by multitudes under any circumstance, either in the course of a battle or during the night when the soldiers were asleep. Consider the fact that even today we define a signal that draws our attention like an *alarm*, the call to arms that immediately followed the perception of the ancient acoustic signal. Even the mythical Lighthouse of Alexandria was equipped with a precursor of sirens activated by the wind, making it audible at sea even from a great distance.

The Roman army had specialists and a detailed code for the systematic use of acoustic signals issued by horns and trumpets. From these units we eventually developed the military bands that every military unit is proud to have.

In Fig. 16.1 are reported some examples of ancient acoustic communication systems: Carnyx players from Gundestrup silver cauldron, Denmark, 1st Century B.C., on the left; bas-reliefs showing horn and trumpet players of the Roman Imperial Era, on the right.



**Fig. 16.1** Ancient horn players

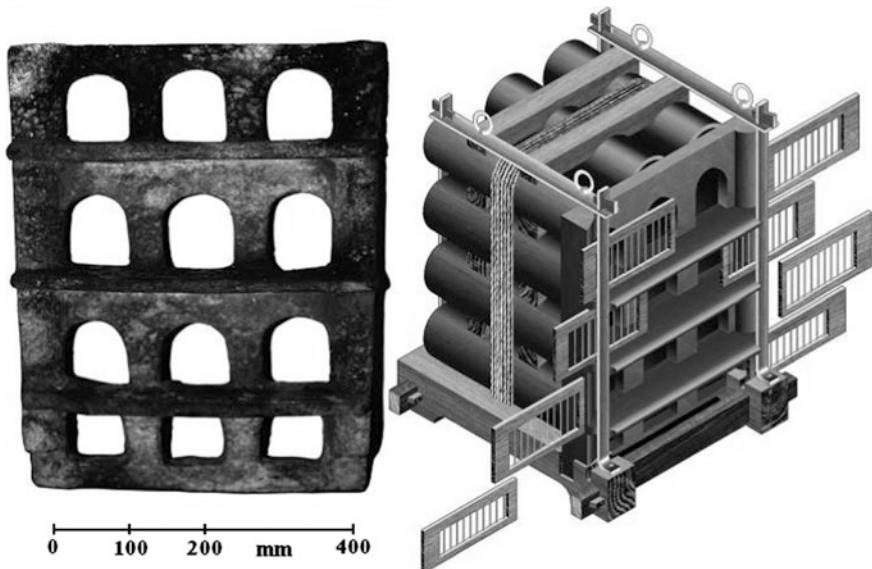
## 16.2 Carrier Pigeons

A few archaeological findings indicate the possible existence of mobile-fixed transmission systems, that is, signals between battleships in navigation and a fixed base. This was done by using pigeons kept in portable dovecotes, a method also used during the Second World War.

It is very surprising to note, once the shroud of silence is torn away, how such elementary means achieved the same results that today require such complex instruments. Cruising ships that communicated events daily with their base did so by simply freeing a few of the many pigeons they carried on board for such purpose. At an average speed of 60 km/h, this methodical bird can travel up to 1000 km in a single day, directing himself perfectly and easily returning to his own dovecote. A capability that was understood in the remotest of times and used for military operations.

Pompeian archaeology has restored a discrete number of massive frontal plates of terracotta used for portable dovecotes, perhaps for simplicity of construction and ease of cleanliness. On the other hand, it would not make any sense to imagine those remains to be of land use as the ones used on land were simply and economically made with four bricks.

That the principal naval bases of antiquity were systematically provided with dovecote towers is confirmed by the many ancient structures that still bear this name, such as the Torre Colombaia (Dovecote Tower) in Trapani, Italy. We must also note that carrier pigeons were used by the military even during the first and



**Fig. 16.2** Portable dovecote

second world war to such an extent that up to a few decades ago a special permit was required to raise pigeons!

In Fig. 16.2 are reported the remains of a portable dovecote found at Pompeii and its virtual reconstruction.

### 16.3 Optical Telecommunication Systems

Also very similar was the use of optical signals that probably derived conceptually from the acoustic ones. These were also used to transmit a simple uniform signal whose variability depended on whether it was seen or not. At night by fire and in the day by smoke: the scope was greater but its limitations basically identical, thus the need for an even crude codification. We know, for example, that it only took a few hours for Agamemnon to send a message by fire from Troy, relayed from thirteen intermediate posts, to notify his wife in Mycenae of his conquest and positive results within a few hours, triggering her ferocious revenge. Homer recounts the episode as does Aeschylus in his tragedy Agamemnon, giving the exact location of all the ancient repeaters.

Over time many expedients and various solutions were studied to increase the distance of those signals. The Romans reached such significant objectives that some scholars suppose that: "the military organization succeeded in realizing the most important communications network all ancient times by the use of signal towers.

Some scholars (AA.VV. *Le trasmissioni dell'esercito nel tempo*, 1995, Rivista Militare, Roma) concluded that, thanks to these towers, Rome could communicate with over 1200 cities and presidiums in the Italian peninsula, as many strategic centers in Gaul, 300 cities of the Iberian peninsula and with 500 in Asia through a network that extended over 60,000 km". The remains of these towers are still numerous and if nothing else prove the feasibility of this system.

Using the same criteria, let's examine some of the best solutions devised and used in the aerial communication system of the ancient world.

### 16.3.1 Systems Based on Image Modification

The rod telegraph was the most common communication system based on the image modification principle. Its appearance brings to mind the French Revolution, perhaps because of its description in the novel *The Count of Montecristo*. For this reason, it is difficult to imagine that something very similar was also used systematically by the Romans for long distance communication. The fact that this invention is connected with the Navy is confirmed by the numerous illustrations that depict the item sometimes astern, sometimes aft of the ship, obviously used to send detailed information to nearby units.

Much more reliable is the device mentioned by Publius Flavius Vegetius Renatus (end of 6th—first half of the 5th century B.C.), in his treatise (*Epitoma Rei Militari*) on the military art. He wrote:

Aliquanti in castellorum, aut urbium turribus appendunt trabes: quibus aliquando erectis, aliquando depositis indicant quae gerentur.

Some placed beams on the castles and towers of the city, and by holding them at times perpendicular and at times horizontally, notify what is happening.

According to Vegetius, at the top of some fortifications or on special isolated towers of the city, were two beams that rotated around a fulcrum. By placing them in either a vertical or a horizontal position, they could transmit what was happening. The idea cannot be considered a great novelty as it reproduced the system already used by warships, handed down to us in numerous illustrations, however, it became innovative when it was transformed into an earth based permanent system. Its effectiveness is demonstrated by the telegraph invented by Claude Chappe (1763–1805) and his brothers, also known as the rod telegraph, that began to connect all cities in France in 1792, initiating the era of communications.

Although we know little of Flavius Vegetius, we gather from some of his implicit references that he lived in the second half of the 4th century A.D. or perhaps in the first half of the V. What he expresses should be considered as an evocation of the past more than a description of the present. The army he describes is the army that existed at the peak of the empire and not the one on the decline. From this we conclude that the military technological solutions he mentioned refer to centuries prior, perhaps even before the founding of the Empire. Which would significantly

backdate the transmission device that played such a major role in the military and social events of Rome, as numerous implicit allusions would indicate.

The rods, described as beams, are visible from several kilometres, perhaps 5 to 10 under optimal visual conditions and against a homogenous background such as the surface of the ocean. The tube inserted into the masonry of the tower probably facilitated vision, without however increasing the scope. By cautiously manoeuvring the beams, most likely similar to standards 5–6 m long and changing the inclinations 45° at a time, they succeeded in having a letter of the alphabet correspond to every position. It is possible that in this manner they were able to send a brief message in a relatively short time. Unfortunately, the lack of binoculars compelled them to place the turrets on heights or coastal protuberances to improve visibility of the signal, which indicates that their use may have been primarily naval, perhaps even between ships. Considering that each station required two or three men, a line 200 km long would have required hundreds, a not exaggerated number if it was intended to connect Rome with its naval bases. Even Tiberius' villa in Capri may have been connected with Miseno so that the emperor could receive daily bulletins from Rome during his 10 years' residence on the island. In Fig. 16.3 a virtual reconstruction of a rod telegraph is reported.

Roman iconography avoided portraying any machine or device especially when it was for military use: by a singular exception, however, something of the sort has been found, in addition to the aforementioned naval images, and since it cannot be interpreted in any other manner it must by exclusion refer to an optical telegraph system. A marginal panel of the Trajan column depicts a circular tower, at the top of



**Fig. 16.3** Authors' virtual reconstruction of a Roman rod telegraph

which are two parallel vertical rods of some length. They are not the risers of a ladder, as the location would be absurd, nor frames for trellises or wood shields, useless due to the narrowness of the tower, nor are they scaffolding for the ceiling as they are too high.

The only convincing explanation is that the tower was the base for an optical telegraph and the two rods the famous beams mentioned by Vegetius to send dispatches. Its close formal and functional affinity with the rod telegraph of the Chappe brothers is obvious when we compare the bas-relief with some 19th century prints of cylindrical towers used to support the optical telegraph or built especially for the French network. In Fig. 16.4 are reported a particular of the Trajan column in which a probable pole telegraph device has been highlighted and three prints showing Chappe telegraphs.

From a conceptual point of view this communication system is still adopted in the train bracket semaphore and also in the semaphore flag signaling system used by several Navies; the latter is based on the waving of a pair of hand-held flags in a particular pattern on the ships. In Fig. 16.5 are reported a bracket semaphore for trains and some examples of the flag signaling system.

### ***16.3.2 Systems Based on Brilliancy Modification***

In his work on the shape and the size of the earth, Pliny also describes the relativity of time. In other words, he anticipates the concept of time differences and demonstrates it by using the long line of semaphore turrets, *turris Hannibal*, that functioned along the Iberian coast. He observed that a brief dispatch launched from these turrets towards the west along a parallel axis reached the end in significantly less time than was required to do the same but in the opposite direction! It being understood that the message was sent at an equal speed over an equal distance, the only explanation implied a difference in the local time, caused by the apparent rotation of the sun. and since this difference was approximately 12 h, whatever time may have been required to re-launch the message from each turret, the line must have been of significant extension, which is strange for a simple coastal defence system.

The words “*turris Hannibal*” do not refer to the inventor of the system, of little repute for the Roman mentality, but to the user, or the authority who had decided to install it or use it, in this case the Carthaginian commander. Since the Romans defined any structure that was prevalently vertical, whether of military or civilian use, as *turris* we cannot determine the main features of these towers with any degree of certainty. However, as the guiding principle was similar to the one adopted along the limes of the Danube, it is likely that the turrets were similar to those etched on the Trajan column, from which archaeologists have determined the measurements of the base, approximately  $5 \times 5$  m, and interaxes, between 600 and 1000 m. If such were the case, we could also understand how they transmitted their messages, as several panels of the column implicitly explain the function of these turrets. From

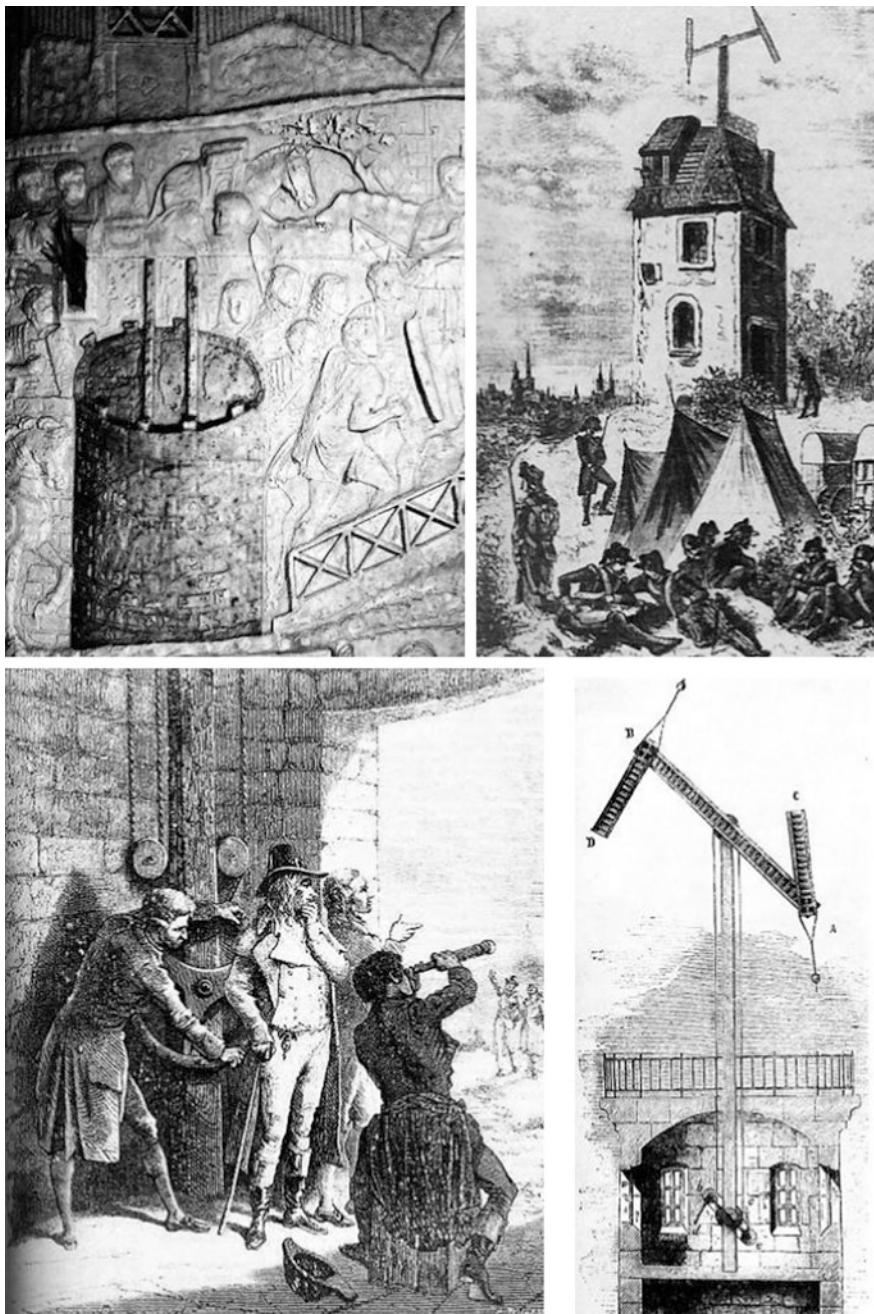
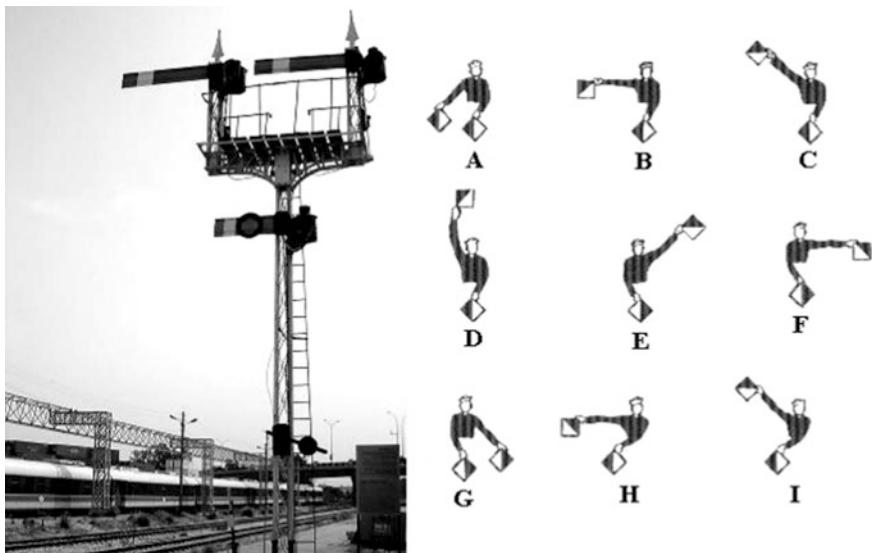


Fig. 16.4 A particular of the Trajan Column and pole telegraphs



**Fig. 16.5** Modern bracket semaphore and flag signaling examples

an operational perspective, a stern-walk along three sides of the first floor of the tower, accessible from a single room opening towards the interior of the limes, suggests their use. The torch that is systematically represented in front of this room, can be moved along the balcony to the right or to left of the tower. However, when the structure intercedes, on the left it cannot be seen from the right and on the right it cannot be seen from the left. In effect, the torch that at rest was visible from both directions, suddenly disappeared from one of these directions, thus notifying the beginning of transmission in the opposite direction.

In other words, the signal from a tower could travel in a precise direction, for a limited number of towers up to the end tower, the final receiver of the signal and directly connected with the attack forces. This explains why they used the first floor rather than an upper terrace, since it was higher and more visible.

In Fig. 16.6 are reported from top to bottom and from left to right a detail of the Trajan Column showing semaphore turrets along the Danube, 2nd century B.C., a modern reconstruction of it, an autors' virtual reconstruction, an enlarged detail of the Trajan Column.

The polarization of the signal, and the fact that it functioned by day and by night, confirmed by bales of hay for smoke and piles of wood for fire, is proof of the existence of a military telegraph network of vast extension and complexity, in spite of the rudimentary nature of the signal. There were also other systems of transmission, perhaps used together with the above, and we have a description and allusive image of at least one of these systems.

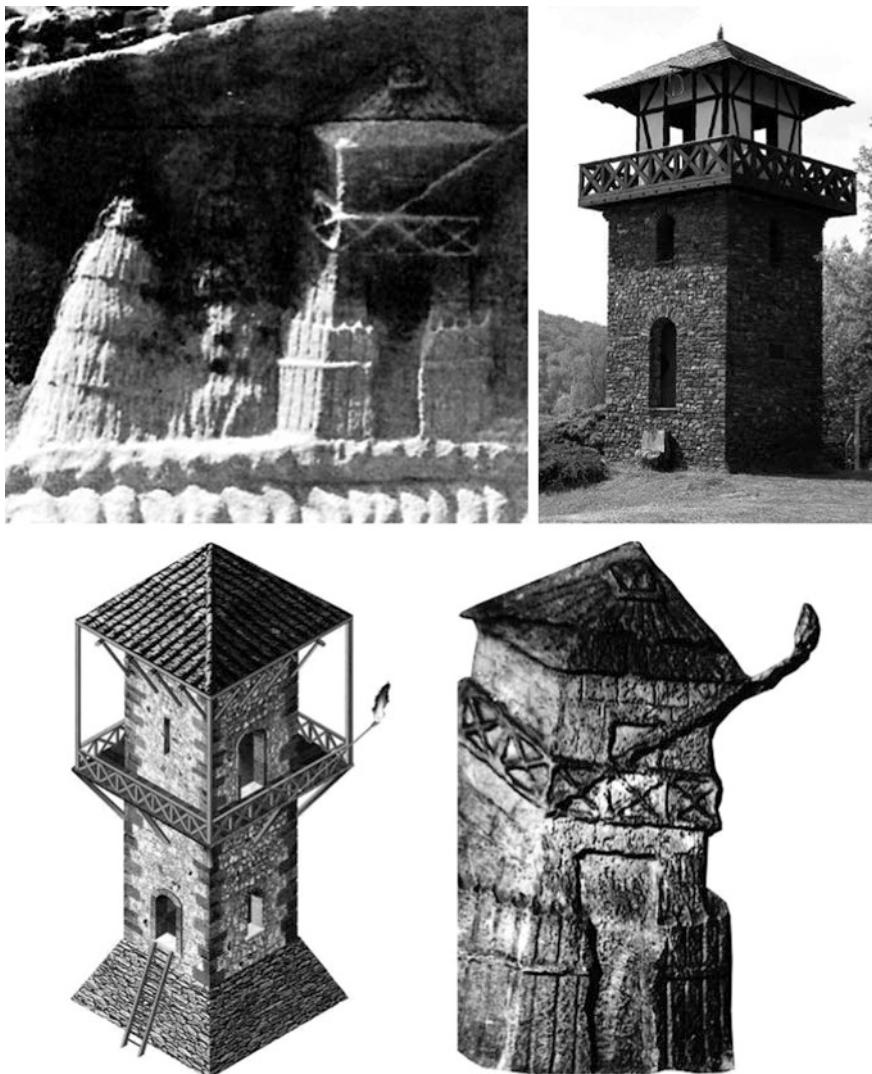
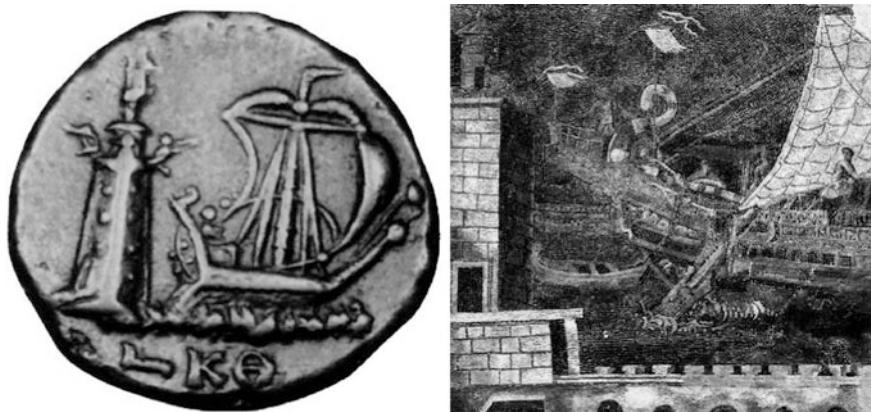


Fig. 16.6 Semaphore turrets

#### 16.4 Lighthouses

Like many other inventions, the lighthouse was not a Roman idea: the very first was built in Alexandria by Ptolemy and was considered one of the seven wonders of ancient times. But the Romans did know how to make use of this invention for ships that were continuously navigating the Mediterranean, to the extent that it



**Fig. 16.7** Lighthouse of Alexandria

became essential for all ships. Though lighthouses are still in existence and still function, their original purpose was very different.

In Fig. 16.7 are reported some reproductions of the lighthouse of Alexandria: on a coin, and on a mosaic.

As far as can be determined, there were still about 400 Roman lighthouses in operation along the coasts of the Empire by the end of the 4th century A.D. Most were based on the legendary tower erected on the islet of Pharos, off the coast of Alexandria, one of the seven marvels of the ancient world, and the lighthouse par excellence. Even while this great construction was being designed by Sostratus of Cnidus, begun by Ptolemy Soter and finished by his son Ptolemy Philadelphus around the end of the 3rd century B.C., it had a dual purpose: to locate the port for ships but also, and especially, to display the splendour of the dynasty. It was intended to be an emblem of the knowledge springing from the underlying and just as mythical library.

Architecturally, the Lighthouse of Alexandria had three sections of decreasing size located on a large square stone base, with lesser towers at the top. The base section resembles a square pyramid about 60 m tall and 30 per side. The interior was an octagonal body that surpassed the first section by more than half. Between the two was a double helical ramp, used perhaps to carry the wood to be burnt. Above the octagonal structure was a cylindrical drum about 10 m high, along its border were columns that supported the conical top, surmounted by the statue of Neptune, inside of which was the large brazier for the lantern.

The enormous flame burned between the columns and came out amplified and agitated by the wind, making it visible for up to 60 km. According to some sources, rotating mirrors were placed around the brazier to direct the light of the flames, like in modern lighthouses. But is the comparison between these two similar constructions the correct one? Can the respective tasks be equated when night navigation at the time was insignificant?

Merchant ships coasted without ever losing sight of land, anchoring in the first inlet as night fell, to leave again the following morning. Certainly such a powerful lighthouse like the one in Alexandria was useful to ships entering the Mediterranean, directed towards the city. But in the III sec. B.C. these ships were so few, even in the summer, so the colossal work and even more its burdensome management, whether it be using wood, oil or naphtha was not justified.

This has always been known by the numerous scholars who have studied its operation: but no one has ever inquired into the underlying logic. On the contrary, since similar though smaller structures continued to be built in the following centuries, the obvious nature of its purpose seemed to silence any reservation. There was no doubt that once the Romans began to navigate the seas, they also began to build lighthouses in all major ports. And yet even their merchant ships very rarely sailed at night far from ports because of the excessive risks caused by the scarce visibility. Why would they need lighthouses and for whom? Certainly not for fishermen who, though they went out at night, were even less likely to sail far from land?

What is most surprising is that the mosaics, the frescoes, bas-reliefs and coins representing Roman lighthouses always show them in daylight, as can be deduced from the fervour of work in loading and unloading ships, the movement of people on the decks and wharfs, the light background of the images so clearly different from night images.

In Fig. 16.8 is reported a mosaic found at Ostia representing a Roman lighthouse and a virtual reconstruction of the lighthouse of Miseno.



**Fig. 16.8** Roman lighthouses: mosaic and virtual reconstruction

Over all these activities are the vivid flames of the lighthouses: a systematic error of the artists or is it our own systematic error in wishing to equate them to modern lighthouses?

The Roman lighthouse was not very useful and almost superfluous at night, but was however very useful and almost indispensable by day, especially for ships sailing the high seas who lost sight of land. In a certain sense we might say that it was not navigation on the high seas that required the lighthouses but rather the presence of the lighthouses that encouraged navigation. The solution of this paradox is in the different type of visibility provided by lighthouses, not by flame but by the smoke that it released. Since the function of a lighthouse was to indicate land when it could no longer be seen from the ship, and not the port that would be easy to find once the coast was visible, it was logical to build them not at the entrance to the port, but on the nearest heights. The black column of smoke rising for thousands of meters could be seen at a distance of not tens but hundreds of kilometers.

And due to the drift of smoke, even navigators sailing the famous transversal routes never lost sight of that slim trace on land, virtually prolonging coasting even where, for obvious reasons, it would not have been possible. The function of the lighthouse, over time, became what it has remained to our day, acquiring a symbolic value. The lighthouse indicating the road to safety in the shadows of the storm, became the symbol of faith! With unquestionable coherence the churches of the civilisations that traded with the near east and all along the coast of Amalfi, began to build bell towers that were the miniature reproduction of the Lighthouse of Alexandria, still firmly standing. Those modest descendants of lighthouses still exist, contrary to its mythical archetype, the Lighthouse of Alexandria, that collapsed in 1323. In 1480 the Sultan Quaitbay of Egypt constructed a fortress on its ruins, using the same stones of this celebrated symbol of antiquity.

## 16.5 The Water Telegraph

Roman lighthouses powered by combustible liquids were easy to use as it was sufficient to provide them with rotating sheets of metal to act as reflectors. Since their flame was vertical, by rotating the reflector they could deviate the strip of light in any direction. The system was sufficiently functional but still could not be used to transmit anything more than simple binary signals. However, it did serve as the basis for the fixed dispatch transmitter or water telegraph, more properly defined as a synchronous telewriter, something that had been invented several centuries prior by Greek technicians and described by Eneas the Tactician.

The device was very simple, with no distinction between the transmitter and the receiver, so that the same device could perform both functions. It also served as an intermediate repeater, allowing for longer range transmission than was possible with heliographs or individual lighthouses. In very general terms, it consisted of a cylindrical container with a faucet at the base and a graduated float within. In this manner a simple sequence of four dispatches could be sent. These were:

- I Nulla quaestio = No questions
- II Auxilia Navalia = Naval aids
- III Milites deficiunt = We need soldiers
- IV Non habemus panem = We have no bread

Each notch was identified by a precise number corresponding to a different, pre-set message. Meticulously identical in volume and type of faucet, they were installed in each station, filled with water up to the top, awaiting use. To begin transmission a metal mirror was used to send a flash of light to the receiver. Once receipt was confirmed by a return flash, a third flash ordered the temporary opening of the faucets. Water began to flow from the containers, causing a simultaneous synchronous descent of the graduated float in both, notch by notch. When the numbered notch in the transmitter touched the upper border of the cylinder, a final flash ordered the closing of the faucets, allowing the receiver to read the same number as the one transmitted, that is, the message.

To illustrate the operating sequence, imagine a container 30 cm in diameter, approximately 1 m high, divided into 10 notches, one every 10 cm. If equipped with a 10 l/s faucet, the rotation of every notch requires approximately 80 s, or almost 12 min to transmit the final notch. Thus, to send the message III-Milites deficiunt, that is we need soldiers, only 4 min pass between the second and the third flash!

From a strictly technical viewpoint this system was a precursor of synchronous transmission, conceptually similar to today's telefax. The dispatch was not transmitted by analogic variation, but reconstructed by the contemporaneity of intervention between the sending and the receiving station. Since only the commands for the opening and closing of a specific device were transmitted, even if they were intercepted, the message would not be understood. In Fig. 16.9 are reported a panel depicting operations of the telegraph (Athens, Museum of telecommunications), a pictorial reconstruction and two authors' virtual reconstructions.

The above described equipment was shown to be reliable and simple to build and to use. It is likely that with some slight modification of the float, perhaps transforming it into a graduated cylinder slightly smaller than the container, a sort of giant syringe, they were able to achieve a device that could also operate on unstable surfaces, such as ships. Its maximum range, as we have said, depended upon the heliograph, that is, on the visibility of its luminous signal. If for example, this signal had been launched from the lighthouse of Alexandria the range of transmission could have reached 60 km, about forty for the lighthouse of Miseno. However, we presume that normally this range did not exceed thirty km, as repeaters or other communication systems examined further on would have been required for greater ranges.

### **Observations**

One sector of Roman technology that is almost completely ignored is the sector of communications: since for us this is almost synonymous with radio transmissions by means of high frequency electromagnetic oscillations, it seems logical to conclude that since these had yet to be discovered, this particular sector of technology



**Fig. 16.9** The water telegraph

was absent. But in fact, in an empire that extended, even if partially, over three continents, with armies deployed along frontiers thousands of kilometres long, constantly awaiting orders and instructions, and with numerous fleets sailing the Mediterranean, the Baltic, the Red Sea and the Atlantic and Indian oceans, such was not the case.

Moreover, it must be considered that, mostly during the Roman Empire, the need to communicate with distant military units was very strong; in addition, many Roman emperors spent a considerable amount of time in Capri (that is an island) or in other places a long way from Rome where they had their luxurious mansions. Since the political affairs were not very quiet in most of that age, the emperors could spend time away from Rome only if a very fast and reliable system of communications was available. As it was shown, such communication system did exist in those ages.

Since very ancient times, optical signals using fire at night and smoke during the day in some manner permitted if not the transmission of messages, at least communication of agreed upon events. A mirror in the sun, properly called heliograph, could send coded flashes for dozens of kilometres in accordance with pre-arranged codes, sent in particular contexts and times.

Since there were some problems related to the angle of the mirrors relative to the position of the sun, the transmission and response could only take place according to specific directives and in specific hours of the day. This still left the unresolved problem of the minuscule quantity of information that could be sent. It is probable that after several attempts they succeeded in building nocturnal heliographs, similar to lighthouses and that actual lighthouses may have been used as nocturnal heliographs.

# **Chapter 17**

## **Medicine and Health**

**Abstract** In this chapter some examples of the ancient medical knowledge are briefly exposed. The topics are: the medical assistance provided to the Roman legionnaires, the reconstructive plastic surgery, the early Penicillin and the beginning of the biological warfare.

### **Introduction**

Activities aiming to restore health are as old as the Homo Sapiens, or perhaps even older. In less ancient times, Egyptians and Sumerians certainly had medical knowledge more advanced than is commonly assumed. However these activities and this knowledge in the medical field were not linked to inventions in the sense that we give to this term today. Probably the first examples of the invention of an extensive health care system and of devolved infrastructure for this purpose, on a large scale, are in the Roman army.

### **17.1 Medical Assistance Provided to Legionaries**

Although the medical treatments provided to legionnaires during the Imperial Era included caring for both the injured and the ill, greater attention was focused on the former, carried out in two stages. The first stage took place on the battle field and immediately behind the front lines, and was reserved for the less injured, that is those they thought could be saved by simple medication. Some of their most common tasks was to treat fractures, extract arrowheads, suture wounds and stop hemorrhages. For this purpose the legion doctors had an effective surgical case, the *capsa*, provided with appropriate instruments and irons as well as bandages and ointments. Their professional skills, which given the perpetual state of war they were able to perfect in just a few years, allowed them to save a great number of men although it was understood that in that violent context the great majority of the wounded did not survive. Nevertheless, to find a similar number of injured men saved on the battlefield we must wait until the First World War. The second stage of the treatment process concerned the more seriously injured, those who required

hospitalization, extensive therapy and rehabilitation that could only be provided inside the *valetudinari*.

## 17.2 Reconstructive Plastic Surgery

The first reconstructive surgery took place on October 23, 1814, two centuries ago, in the operating Room of the Duke of York Hospital, London, a structure more similar to the Roman *valetudinaria* than our modern hospitals. Joseph Carpue, professor of surgery at that hospital reconstructed the nose of Captain Williamson, 30th Regiment of the British Army, a nose that an ineffective therapy using mercury had destroyed. Carpue had read an unusual article published in 1794 in *The Gentleman's Magazine* (1794 vol. 76 pp. 890 and foll.), providing a detailed description of the reconstruction of the nose of a tank driver in the British Army stationed in India. The unfortunate soldier, called Cowasjee, had been taken prisoner by Sultan Tipu in 1792 who in addition to cutting off his hand had also cut off his nose. A nose that was restored to him 12 months later thanks to an operation that had become rather common in the region.

At the time nose reconstruction was a practice that was three thousand years old in India, as there is mention of the practice even in the sacred texts of Veda, the majority of which were composed around the end of the second millennium B.C. This was preceded by a legend dating to 1500 B.C. describing the amputation of a nose, inflicted by Prince Lakshmana on Princess Surpunakha, and its reconstruction ordered by the court physicians of King Ravana. By the beginning of the I millennium B.C. nasal reconstruction was considered a routine operation in India, a fact confirmed in the surgical treatise *Sushruta Samhita*, edited by Sushuruta, who lived in the city of Varanasi around the year 600 and is reputed to be one of the greatest Indian physicians.

With the coming of the Middle Ages any notion of reconstructive surgery disappeared, and we must wait until the Renaissance to once again find a family of empirical surgeons, the Branca family of Catania, around the middle of the 1400 s. C. The two members of that family who truly stand out are Gustavo and Antonio Branca, respectively father and son, both of whom appear to have practiced nasal reconstruction, the first by removing a flap of skin from the face and the other from inside the patient's forearm. They used the same technique to reconstruct ears and lips, leading to defining their method as the 'Italian method', as opposed to the heretofore described Indian method. They were followed by Gaspare Tagliacozzi, born in Bologna in 1545, who used mostly the technique of Antonio Branca for his reconstructive surgery, describing it in his treatise *De Curtorum Chirurgia per Insitione*, not published until after his death in 1599: a table shows the procedure used to reconstruct a nose using a layer of skin taken from the arm instead of the forearm, which he considered too distant and unstable.

Captain Williamson's nose reconstruction succeeded perfectly and was immediately replicated, especially in the military context.

### 17.3 Early Penicillin

In 1895, Doctor Vincenzo Tiberio, born in 1869 in Sepino, a small town in the province of Campobasso, was a man of great skill who worked as a medical officer in the Italia Navy Medical Corps. Before joining the navy Tiberio had been an assistant professor, with a renewable annual appointment, at the Institute of Medical Pathology, Faculty of Medicine, University of Naples.

Tiberio published an important study titled *Sugli estratti di alcune muffe*, on the bacterial effects produced by a mold found near the well of a house he owned in Arzano. He wrote that he had personally observed: «the action of the aqueous extracts of mucor mucedo, penicillium glaucum and aspergillus flavescens on some pathogenic schzomycetes and saprophytes as they have, especially the aspergillus, notable antibacterial power. The aqueous extracts have moderate leukocytic power, especially aspergillus extract. In experimental infections with the typhus bacillus and the vibrio cholerae, only the latter demonstrated a certain immunizing and therapeutic result. The author attributes this action partly to the anti-microbe power of the principles contained in molds, and partly to the leukocytosis they produce.» Subsequent modification of the molecule led to the discovery of phenoxymethylpenicillin, also known as penicillin V, an antibiotic of the penicillin family, in turn belonging to the  $\beta$ -lactam class of antibiotics. If there had been additional studies actual penicillin, discovered by Fleming in 1928, would have been available 35 years before, saving an enormous number of lives: unfortunately, first the war and then the premature death of the senior officer in 1915 put a brusque end to his promising researches, fundamental in improving reconstructive surgery.

### 17.4 The Beginning of Biological Warfare

Biological warfare is believed to have started in the Genoese colony of Caffa, on the Black Sea, under siege by the Tartars of Gani Bek in 1347, and the point of departure for the propagation of the Black Plague. In the following 2 years this epidemic, admirably recounted by Boccaccio, spread to all of Europe, with over 25 million victims. The only ones exempt, or only slightly involved, were the regions that had been conquered by the Mongols, such as Hungary and Poland.

As in all other human war tragedies, in this one also a device played a fatal role. In this particular case the “trebuchet” (see Chap. 18), a vector that turned out to be ideal for biological warfare as it took down targets using a projectile with an almost vertical drop angle. Batteries of trebuchets battered the city of Caffa for months by a continuous launching of plague victim cadavers. Although the cadavers were handled without any precautions, almost as if they were launching innocuous fertilizer, none of the Tartars tasked with the operation suffered any consequences. Not so the inhabitants of Caffa, soon contaminated, and all the others who came into

contact with the crews of the ships fleeing its port, from Messina to Marseilles, from Pisa to Genoa, transformed into so many sources of contamination.

Almost all sources available agree regarding the strange and constant diet followed by the Mongols, which did not include bread, vegetables, legumes and only a very small quantity of meat. Their sustenance consisted mostly of milk, generally from horses, millet flour and many of its derivatives. The milk was used to make butter, kumiz—a highly caloric and alcoholic drink-, yogurt, airan—a sort of high energy condensed milk obtained by drying and pulverization—and lactose, also very nutritious. As for vitamins, starches and mineral salts were obtained from four bulbs that were abundant in wild state in the plains of central Asia: onion, garlic, carrot and turnip. All foods that were much healthier than the Mediterranean diet of the time and that provided the Tartars with considerable immunity from many infectious diseases, including, according to some scholars, the plague or pathological forms considered as such.

# Chapter 18

## Secondary Motors

**Abstract** In this chapter the ancient secondary motors are presented before the conventions of the thermal engines and of the electric motors. The secondary motors were essentially based on devices in which the weight was the moving force or motors in which the elastic energy was stored. Examples of the first are the cranes, the thread wheel and probably the siege towers; while elastic motors, instead were represented by almost all the ancient throwing machines. As for the latter, virtual reconstructions and mathematical models of the machines are presented, permitting to compute their kinematics, dynamics and performances. A ballista powered by air springs is also presented. Finally, some studies on a possible steam cannon, invented by Archimedes, and its behaviour are presented.

### Introduction

Most of the ancient secondary motors, before the invention of thermal engines and electric motors, were spring motors since they were based on the principle that mechanical energy could be “stored” by the deformation of a flexible element.

For the Greeks any device that caused another object to move was a motor; this same criteria was used later by the Romans without any alteration. The first motor was the wind as it drove the sails and the water that dragged and pulled tree trunks in its wake as reported in Chap. 8. Later, counterweights were devised using the same system as that used to raise sails and that was later applied to theatrical curtains as it was reported about gravity driven motors in Chap. 11. The observation of the movement of tow ropes and of sails as they were pulled taught led to other motors powered by the potential elastic energy of flexion and torsion.

Regarding the spring motor, from a chronological perspective, its invention is indeed very old, as even the oldest type of trap implies the use of a spring, often a bent branch that naturally bounced back to its natural configuration. At that time no one actually understood the reasons for this phenomenon, but they quickly learned how to use it. They also realised, just as quickly, that after a few uses most of the branches no longer returned to their original erect position. Very few maintained that property of flexibility for an extended period while others were not at all suitable and would soon break off.

**Fig. 18.1** Bows

Physics defines the first as elastic and the second as inelastic or plastic motion. In actual fact, all bodies tend to eventually lose their elasticity, thus this characteristic more directly indicates its persistence, a basic feature of weapons that function by cycles of deformation and recovery. A bow is a perfect example: when subjected to stress, it bends, acting as an accumulator that stores the energy expended to deform it; when it is straightened, it performs like a motor that gives back the stored energy in the form of function. Without getting into the reasons for this action, it must be said that natural elastic properties were soon well understood and were used perhaps as early as 40–30,000 years ago. This resulted not only in more sophisticated traps and more powerful bows, but a much vaster range of application. Experience led to other elastic manifestations, even more beneficial for reversible motor systems. But thousands of years would pass before these were actually put to use. In Fig. 18.1 are represented, on the left a simple bow, in the middle a composite bow and on the right some details of its internal structure that consisted of sinew, wood and horn all closely bound.

The elastic deformation of a solid is manifested in four distinct ways, the result of four types of solicitation. The first is flexion, associated with rather long objects, like the axis of a diving board. The second is compression, occurring when an object is between two opposing forces that tend to crush it, typical of the upholstery on our couches. The third is traction, when an object is pulled between two equal and opposing forces, a very common example would be braces or suspenders. The fourth is torsion, the result of the opposing rotation of the two extremities of one object, for example, when we wring out wet clothes.

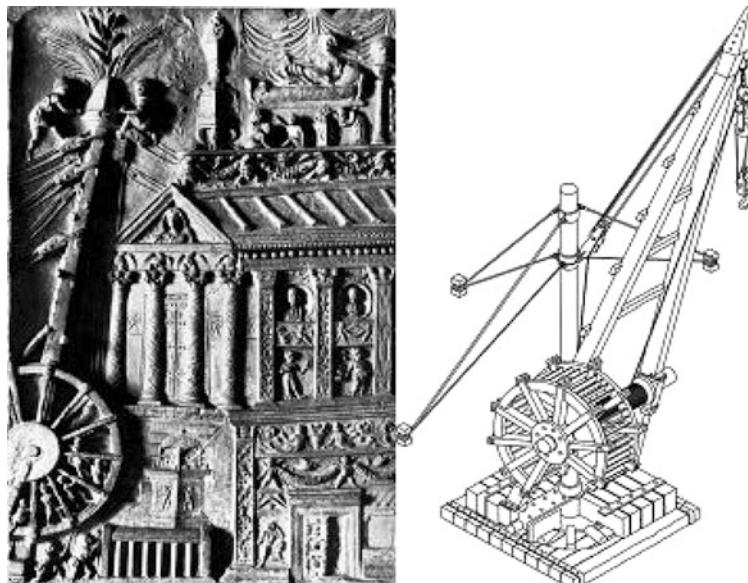
In ancient times also compressed air and steam were used to build motors; a first example of steam turbine is the famous aeolipile by Heron.

Finally, among the secondary motors the counterweight motors are also to be considered. Among the latter, those devices that were employed in some theaters, like the Colosseum, in elevators and also to lift the curtains can be considered and also the devices to operate the large cranes and to move the siege towers.

## 18.1 Cranes and Tackle

As proven by numerous bas-reliefs and even more numerous grandiose constructions, the Romans were familiar with and used a great number of cranes. These were activated by simple muscular strength multiplied in various ways and had gear wheels and pulleys. Larger and more powerful cranes used a large ramming wheel or capstan.

The wheel that resembled a giant squirrel cage was turned by slaves who continuously clambered upward inside the wheel. As its diameter increased, so did its boom and the number of slaves required and, consequently its mass: even if they didn't know how to calculate the torque, it was simple to determine the proportions required for the intended use. However, as demonstrated by the survival of this machine up to the beginning of the 20th century, though called *stone quarry wheel*, only a maximum of five men could be used to activate it, at least the traditional models. The wheel allowed for a faster and more rational use of human muscle power, but could not provide the power of a capstan. A capstan was basically a winch with a vertical axle that could support longer and more shafts than a horizontal one and could be rotated by as many as thirty men at a time. In Fig. 18.2 is



**Fig. 18.2** Large crane

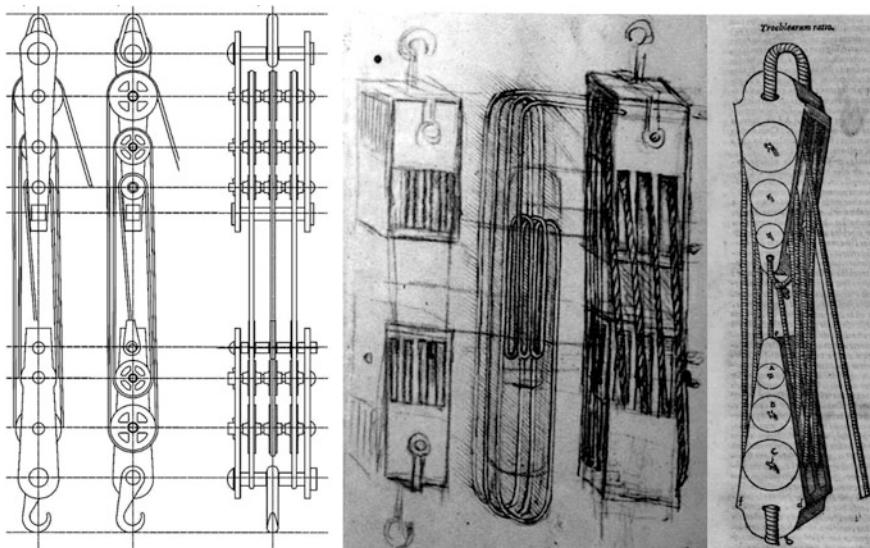
reported a funeral bas relief from the tomb of Hanerii showing a large crane with a ramming wheel and an axonometric reconstruction of it.

As a result, it was much more powerful than the horizontal axle winch and even stronger than the ramming wheel. But whether the motor was a wheel or a capstan, the structure of the crane did not differ greatly from what we now call a derrick. Its anchorages also allowed the operators to incline the boom and the traverse.

The first cranes described by Vitruvius were used for public construction and in ports for loading and unloading operations, as illustrated by numerous and often extremely detailed bas-reliefs. A third type of crane was much simpler and consisted of a vertical post anchored by four braces and a flexible boom. Actually this was even more similar to a derrick, though in miniature, and was used by the military to move large launching machines and for naval armaments.

Accepting the fact that Roman cranes basically differed only in size and motor systems, the one element that was common to all was a pulley hoist. Vitruvius describes two of these machines, one with five pulleys and one with three. Each in turn had versions with pulleys that were either lined up or installed side by side. The five-pulley hoist is known as the *pentaspaston* and had three fixed pulleys and movable pulleys, while the *trispaston* hoist had only three, two upper fixed pulleys and one lower movable one. In Fig. 18.3 are reported a reconstruction of the pentaspaston as described by Vitruvius, as drawn by Leonardo da Vinci and as reconstructed by Daniele Barbaro in his translation of the “de Architectura” by Vitruvius.

Today, the uses of hoists with either aligned or side by side pulleys are not only extremely vast but also very diversified. From the colossal cranes used in ports or for emergency vehicles to the small ones for domestic use but that are nevertheless



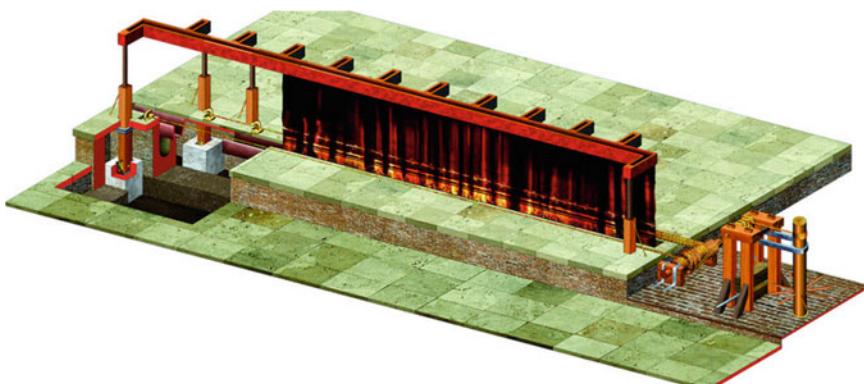
**Fig. 18.3** Pentaspaston

capable of lifting tons. They also have some rather curious and unexpected uses, such as the high voltage aerial cables for high speed trains that are maintained taught by a counterweight electronically activated by a *pentaspaston*.

## 18.2 Gravity Driven Elevators

Gravity driven motors were used in ancient times for a number of devices, one of them is the Heron's programmable moving robot described in Chap. 21. Among those motors activated by the force of gravity there was one that was very widely used, especially to raise and lower curtains. In Roman theatres the curtains did not open from the sides nor could they descend downward as the stage did not have any upper horizontal structure. Consequently, the curtain was raised by a special longitudinal housing located immediately in front of the stage, remaining folded during the performance. The same housing also contained telescopic elements at regular intervals used to lift the curtain. These were made entirely of wood and consisted of an external rod and an interior plank: when the ropes were pulled, these elements were lifted, much as a modern day antenna.

The lifting was accomplished by a complex machine that can very simplistically be compared to a hoist and a counterweight of lead blocks. Since the curtain and its horizontal support beams weighed over ten tons, the counterweight had to weigh even more. Very ingeniously it was divided into two parts, which individually weighed less than the curtain: but when the two sections were joined and thus became heavier than the curtains, as they were lowered the curtains were lifted. The motion occurred always in a very precise and uniform manner and the servants simply used the pulley to lift half of the counterweight. In Fig. 18.4 a virtual reconstruction of a device to move the curtains is represented.



**Fig. 18.4** Virtual reconstruction of the device to lift the curtains

### 18.3 Siege Towers

For Biton it was Posidonius the Macedonian, who, while working for Alexander, built a mobile tower, elepoli, (=taker of cities) approximately 15 m high, equipping it with a mechanism that could make it self-moving. Historians, however, believe the self-moving tower was conceived by Epimacus the Athenian, engineer of Demetrios Poliorketes (poliorketes means: besieger of cities), who was in turn the nephew of Alexander, during the siege of Rhodes. This tower was 40 m tall and weighed more than 100 tons.

In Fig. 18.5 is reported an author's virtual reconstruction of the elepoli of Posidonius.

In Fig. 18.6 is reported a virtual reconstruction of the great elepoli of Demetrios Poliorketes.

For the reconstructions, we started from several classics; among them it seems interesting to report a piece from the "Epitoma Rei Militari", written the end of the 4th century and the first half of the 5th century A.D:

Liber IV, par. XVII—Turres autem dicuntur machinamenta ad aedificiorum speciem ex trabibus tabulatisque compacta et, ne tantum opus hostili concremetur incendio, diligenter ex crudis coris uel centonibus communita, quibus pro modo altitudinis additur

**Fig. 18.5** Virtual reconstruction of the elepoli of Posidonius



**Fig. 18.6** Reconstruction of the elepoli of demetrios poliorchetes



latitudo. Nam interdum tricenos pedes per quadrum interdum quadragesimos uel quinquagenos latae sunt. Proceritas autem ipsarum tanta fit, ut non solum muros sed etiam turres lapideas altitudine superent. His plures rotae mechanica arte subduntur, quarum lapsu uolubili magnitudo tam ampla moueat. Praesens autem periculum ciuitatis est, si ad murum fuerit turris admota. Plures enim accipit scalas et diuerso genere conatur inrumpere. Nam in inferioribus habet arietem, cuius impetu destruit muros, circa medium uero partem accipit pontem, factum de duabus trabibus saeptumque de uimine, quem subito prolatum inter turrem murumque constituant et per eum egredientes de machina bellatores in ciuitatem transeunt et occupant muros. In superioribus autem turris illius partibus contati et sagittarii collocantur, qui defensores urbis ex alto contis missilibus saxisque prosternant. Quo facto ciuitas capitur sine mora. Quid enim auxili superest, cum hi, qui de murorum altitudine sperabant repente supra se aspiciant altioreum hostium murum?

Towers are also called the machines similar to buildings firmly hold by crossbeams and having well sewed shelves and not tanned leathers or pads so that a so big building can't be destroyed by the enemy fire, their high is equal to the breadth. In fact sometimes are  $30 \times 30$  feet (8.88 m), sometimes  $40 \times 40$  or  $50 \times 50$ . Their size is so big that they are taller than the walls and also than the towers (of the town). Under them thanks to mechanics some wheels are installed so that, by their rotation, such a big object can be moved. So, a terrible danger for a town occurs when a (siege) tower is drawn near the walls. In facts it contains many stairs and (the enemies) try to burst in (the town) in different ways. In fact in

the lower part (the siege tower) has a ram, by means of its knock it breaks down the walls, and at the middle it has a bridge, made by two cantilevers and weaved wicker, that the soldiers quickly push out and put between the tower and the walls and over it they come out the machine, get into the town and conquer the walls. In the upper parts of this tower, instead, are located spearmen and bowmen that strike from above the town defenders with spears, darts and stones. In this way the town was conquered. In fact, what kind of help remains to those that relied on (their) walls highness when they suddenly see a higher wall over themselves?

We have little information regarding the mechanisms conceived to move those giants. Flavius Vegetius in his “Epitoma rei militari” = the art of the war (4th century B.C.) writes that: “using a sophisticated mechanism, many wheels were applied (to the siege towers), and the motion of these wheels were able to move such a large machine”. It could be interesting to remember that the famous Latin motto “si vis pacem, para bellum” = If you want peace be prepared for war, from which the word “parabellum” used for some light weapons of the 20th century, is by Flavius Vegezio.

What seems to be clear is that these towers were powered by internal motors. To this end, we can consider the following pieces from the De Bello Gallico (liber II, par. XXX and XXXI), in which Caesar describes the siege at a town of the Gauls Atuatuci:

XXX—...Ubi vineis actis aggere exstructo turrim procul constitui viderunt, primum inridere ex muro atque increpitare vocibus, quod tanta machinatio a tanto spatio instrueretur: quibusnam manibus aut quibus viribus praesertim homines tantulae statuerae—nam plerumque omnibus Gallis prae magnitudine corporum suorum brevitas nostra contemptui est—tanti oneris turrim in muro posse conlocare confidenter?

XXXI—Ubi vero moveri et adpropinquare moenibus viderunt, nova atque inusitata specie commoti legatos ad Caesarem de pace miserunt, qui ad hunc modum locuti: non se existimare Romanos sine ope divina bellum gerere, qui tantae altitudinis machinationes tanta celeritate promovere et ex propinquitate pugnare possent, se suaque omnia eorum potestati permittere dixerunt.

XXX—... As soon as (the Gauls) saw that, having we pushed on the vinea (mobile roofs) and built an embankment, we started to built a tower, at first they derided and insulted us because a so big device was built so far (the walls): on what hands and on what force could ever the Romans rely, small as they were, in order to bring near the walls a so heavy tower? All the Gauls, in fact, scorn our height if compared with their large bodies.

XXXI—As they saw that the tower was moved and was approaching their walls, frightened by the unusual sight, (the Gauls) sent ambassadors to Caesar to negotiate the peace; they said that they think the Roman make war with the help of the goods since they can move such big machines so fast, (hence) the put themselves all their wealth under the power of Caesar.

### **18.3.1 Possible Internal Motors**

In this paragraph some possible internal motors are proposed. In the observation some computing are reposted.

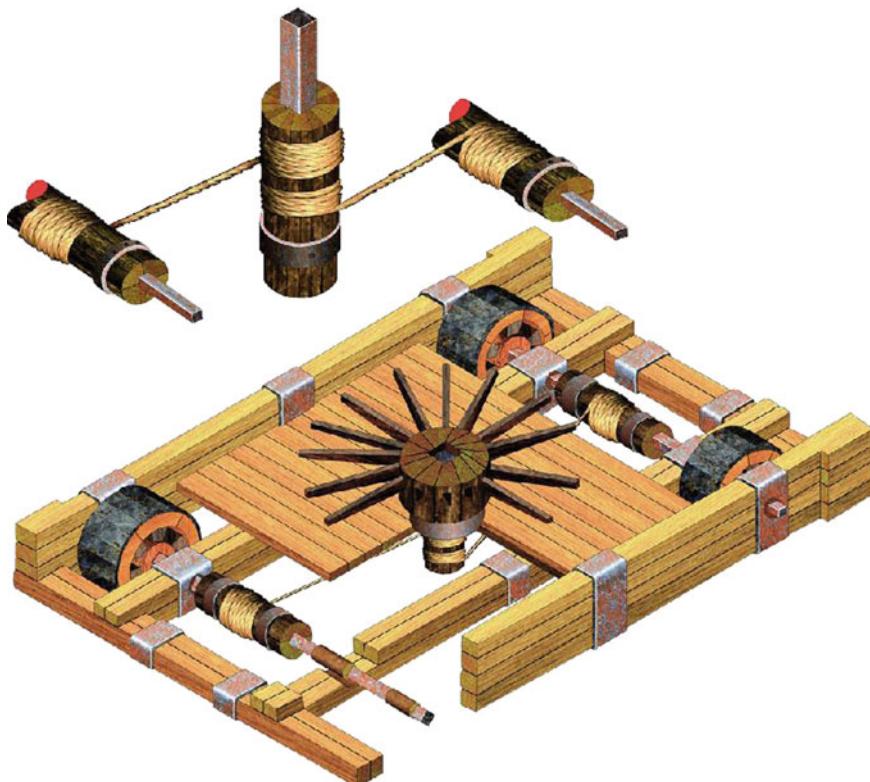
### 18.3.1.1 Capstan

We can presume that they made use of a capstan a device that was well known during that era. Manoeuvring required many men divided among its numerous and massive beams. As for the transmission of movement itself, which we presume to be integral, the most elementary system consisted of a pair of large ropes twisted around each axis with one extremity connected to the shaft of the capstan. When the shaft turned, the ropes twisted around it and caused the rotation of the wheels as they unwound from the axes.

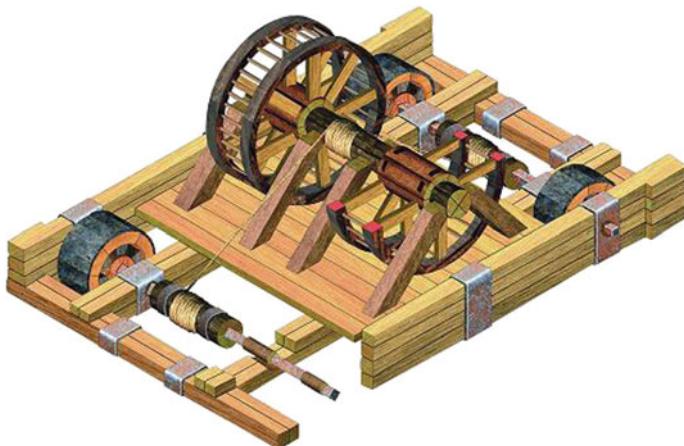
In Fig. 18.7 virtual reconstructions of capstan motorization systems for the elepoli is reported.

### 18.3.1.2 Threadwheel

Another possible motor consisted in the thread wheel, a device largely used in the large cranes, see Fig. 18.2.



**Fig. 18.7** Virtual reconstruction of a double ramming capstan motor



**Fig. 18.8** Virtual reconstruction of a capstan with rope transmission

In Fig. 18.8 is showed an authors' pictorial reconstruction of a double thread wheel motor with rope transmission on two axles and in Figure a capstan with rope transmission and a detail of it.

### 18.3.1.3 Counterweight Motor

It is well-known that Heron of Alexandria, in the 1st century A.D., used counterweight motors to move figurines representing animals in a sort of theatre in which the actors were automata moved by this kind of motor; this will be described more in details in the Chap. 21 on automation.

Anyway, it is possible to suppose that such motors were used to move those towers also. In the observations some computing demonstrating the suitability of such a motor are reported.

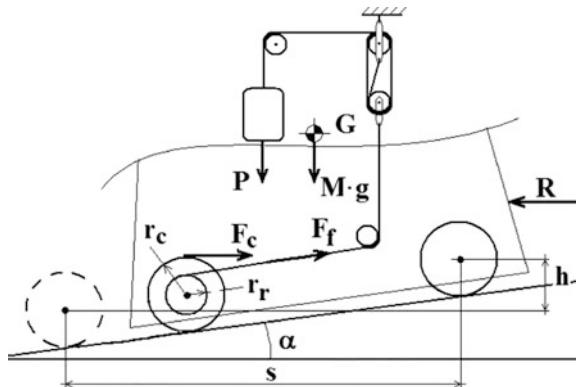
In Fig. 18.9 a scheme of the working principle is shown.

A counterweight having 1000 kg mass is linked to a block and tackle with 5 pulleys (pentaspaston, see Fig. 18.3). The mobile group of pulleys is linked to a rope that is rolled on the wheel axle, like it was made in the previous reconstructions. We can imagine that the counterweight consisted in a tank filled by water that was emptied when it reached the bottom, lifted empty and then filled by a pump or a chain of buckles.

The presence of water tanks is suggested by this piece (XX, 851) by Diodorus Siculus:

... Demetrios, afraid of the fire that could spread and destroy the whole machine, was forced to operate and acted to extinguish the fire by using the water reserves that were located at the various levels of the helepolis. Finally, by the trumpet call, recalled the men that operated the machine which moved the (helepolis) back out of the reach of the darts.

**Fig. 18.9** Working principle of the helepolis counterweight motor



### 18.3.2 The Motion of the Tower

In order to evaluate the force required for the traction of an helepolis (see Fig. 18.9), we considered a machine of average dimensions having the following technical characteristics:

- helepolis height: 30 m;
- full helepolis' mass: 40,000 kg;
- radius of the wheel rim:  $r_c = 1.5$  m;
- radius of the drum connected to the wheel axle on which the rope is rolled:  $r_r = 0.8$  m;
- ground slope:  $\alpha = 2\%$ ;
- coefficient of friction between helepolis and ground:  $f = 0.02$ .

For the data reported above, the following must be pointed out:

- the slope value was fixed to represent an almost level ground with some local bottomlands;
- as for the coefficient of friction wooden wheels on hard ground were considered; it is evident that, if we had considered a track made of wooden boards, the friction would be rather lower.

With the above reported data it is easy to compute the force required to move the helepolis; it is given by sum of the rolling friction force and the force required to climb the height difference.

$$R = M \times g \times (f + h/s) = 40,000 \times 9.81 \times (0.02 + 0.02) \approx 16,000 \text{ N} \quad (18.1)$$

This force, naturally, is the force that must be exerted on the wheel rim to move the helepolis at a constant speed; hence, on the drum it is necessary to exert a force:

$$F_c = R \times r_c / r_r = 16,000 \times 1.5 / 0.8 = 30,000 \text{ N} \quad (18.2)$$

A good rope made by hemp having 48 mm diameter made nowadays has a tensile strength higher than 150,000 N (British Standard), that is to say 5 times higher. Obviously an high safety factor must be considered because one must take onto account both the rope wear and that, 2000 years ago, the ropes were not manufactured as well as today. The latter aspect plays a less important role than expected: the British Standards of the middle of the 20th century for naval ropes, cited before, give the same tensile strength for ropes made by stationary stranding-machine and for ropes made on the rope work train; the latter manufacturing technique is very similar to the one used from the Egyptian age for medium and large ropes.

So, it seems reasonable to assume that, on the drum, a rope having a 50 mm diameter was rolled. The force required to unroll the rope on a pulley can be computed by means of the following empirical equation:

$$F_{av} = 0.02 F d^2 / D \quad (18.3)$$

If we consider a rope diameter  $d = 50$  mm and a drum diameter  $D = 2 r_r = 1600$  mm, by using the units of Eq. (18.3), we obtain:

$$F_{av} = 0.02 \times 30,000 \times (50^2 / 1600) = 937.5 \text{ N} \quad (18.4)$$

The unroll force can thus be neglected since, for our purposes, the computing can be rather rough. Hence, it will be assumed that the force that must be exerted on the drum is the one given by Eq. (18.2).

In the following paragraphs the possible mechanical systems to exert this traction on the rope rolled on the drum will be presented.

### **Capstan motor**

The capstan is such a simple and well-known machine that it is not necessary to report any historical reference on it. The working principle is shown in Fig. 7.2.

If we assume that the length of the capstan bars is  $b_1 = 1.5$  m, the radius of the capstan drum is  $b_2 = 0.3$  m and if we neglect the force  $F_2$  on the unloaded of the rope, the force that is necessary to apply to the bars, in order to obtain the traction force  $F_c$  on the rope, given from Eq. (18.2) is:

$$F_1 = F_c \times b_2 / b_1 = 30,000 \times 0.3 / 1.5 = 6000 \text{ N}$$

Considering that a man can exert on the bar a continuous force of 200 N average, we obtain that almost 30 men were required; this means that, for instance, we must suppose the presence of 2 capstan with 8 bars each and 2 men on each bar, that is to say 32 men. Since in the analysis we did not consider neither the force to unroll the rope nor the friction on the winch drum, the average force exerted by

each one of the 32 men should be higher; this was possible but it does not seem so easy.

### Treadwheel

The treadwheel and its working principle was shown in Fig. 4.2. In order to compute, roughly, the tensile force on the rope that can be exerted, let us assume the following data:

mass of a man (in those ages):  $m = 65 \text{ kg}$ , hence:  $F_1 \approx 650 \text{ N}$ ;  
mean radius of the rolling of the rope:  $r_1 = 0.3 \text{ m}$ ;  
mean radius of the tread wheel:  $r_2 = 3 \text{ m}$ ;  
mean level at which a man acts from the bottom:  $h = 0.5 \text{ m}$ .

From Fig. 18.9 it follows:

$$b = \sqrt{r_2^2 - (r_2 - h)^2} = 1.66 \text{ m.}$$

Hence:

$$F_2 = F_1 b / r_1 \approx 3600 \text{ N}$$

Obviously  $F_2$  represents the force exerted on the rope by each of the men in the wheel. Hence, in order to obtain the tensile force, computed by Eq. (18.2),  $30,000/3600 \approx 8$  men were necessary. So, it is possible to suppose the presence of 2 tread wheels, each one with 4 men, as disposed in our pictorial reconstruction in Fig. 18.7. This reconstruction seems more realistic than the previous one.

### Counterweight

In order to verify, conceptually, the possibility that a counterweight motor could move an helepolis, we assumed the following data:

- counterweight mass = 1000 kg;
- radius of the helepolis' wheels:  $r_c = 1.5 \text{ m}$ ;
- radius of the drum that is the axle shaft:  $r_r = 0.8 \text{ m}$ ;
- block and tackle with 5 pulleys (Pentaspaston, described by Vitruvius in 1st century B.C.).

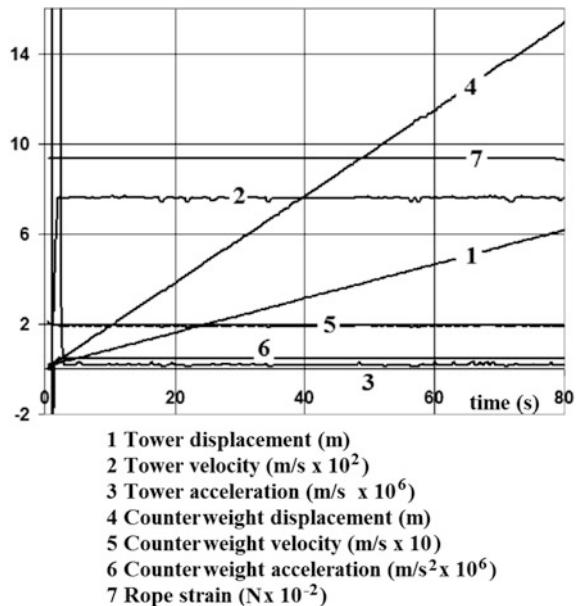
With the data above, it is easy to compute that if the counterweight goes down 20 m, the helepolis will go ahead:

$$(20/5) \cdot (1.5/0.8) = 7.5 \text{ m}$$

This amount seems reasonable with respect to the speed of a siege machine.

It can also be supposed that the force  $F_c$  that must be exerted on the wheels' ring, to move the helepolis at a constant speed, is the one computed by Eq. (18.1) and that the force  $F_f$  that must be exerted on the drum is the one given by Eq. (18.2).

**Fig. 18.10** Simulation results of the tower behavior



Since the block and tackle has 5 pulleys, and also two more pulleys are present as a transfer case, if we suppose that the manufacturing of pulleys and shaft was not very accurate, we can compute an efficiency  $h \approx 0.7$ .

So, if the counterweight weighs about 10{,}000 N, the force that will pull (through the block and tackle) the rope rolled on the drum will be:

$$F = 1000 \cdot 9.807 \cdot 5 \cdot 0.7 = 34,335 \text{ N} > F_f$$

Therefore, conceptually, such a motor will be able to move an helepolis whose mass is 40,000 kg.

A model by WM2D™ of the considered helepolis was made in order to simulate its motion. In Fig. 18.10 diagrams are reported, computed by setting the control in order to obtain a constant counterweight speed of 0.25 m/s. How it is possible to observe, the simulation results show that the counterweight motor seems to be suitable and effective for the helepolis propulsion.

## 18.4 The Trebuchet

Another application of gravity driven motor is represented by the trebuchet. According to confirmed sources, the trebuchet appeared in Asia between the 5th and the 3rd century B.C., during the Zhou dynasty. It was made to function by the

**Fig. 18.11** Virtual reconstruction of a trebuchet



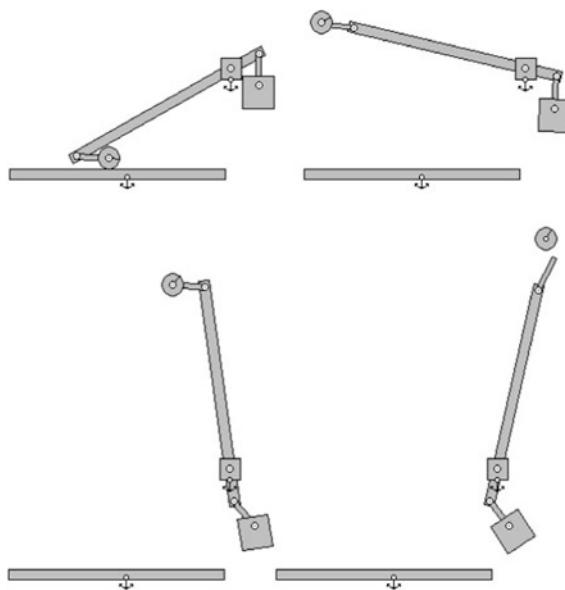
simultaneous pulling of ropes by numerous servants: when pulled the arm rotated forcefully, launching a heavy projectile. The weapon reached the Mediterranean when the western Roman empire was almost completely dispelled but was studied by the Byzantines, especially for its military applications.

From the mechanical aspect, its construction appears to be extremely simple, basically consisting of a rotating beam inserted into a post that divided it into two arms, one longer than the other. The longer section ended in a harness while the short one ended in a number of traction ropes, later replaced by a counterweight. To extend the length of the longer section, they also attached a sling for the projectile. The trebuchet, on the other hand, became popular in Western Europe much later and after the Crusades it dominated the siege scenarios for almost 3 centuries.

A virtual reconstruction of a trebuchet is reported in Fig. 18.11.

In order to show the working principle of the trebuchet, in Fig. 18.12 four frames of a simulation by WM2D™ are reported.

**Fig. 18.12** WM2D™ model of a trebuchet



## 18.5 Flexion Elastic Motors

According to numerous hieroglyphics, the four types mentioned above were already used in weapons during the second millennium B.C. It is also plausible that, starting from the 5th–4th century B.C., the experience accrued was put to use in building powerful launch weapons. Although all elastic deformations were potentially suitable to this use, only flexion and torsion could be used immediately. Compression and traction motors were studied in a later period, generating several archetypes for less ephemeral purposes. The passage from flexion motors to torsion motors and to sheet metal flexion testifies to their need for reliable and constant performance.

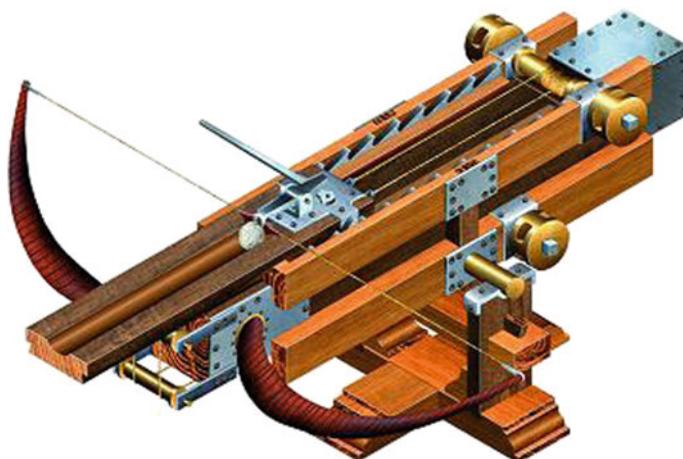
Examples of ancient flexion motors are the war machines used to throw balls or arrows. In Fig. 18.13 is reported a reconstruction of a “gastrafetes”.

The name gastrafetes ( $\gamma\alpha\sigma\tau\rho\phi\epsilon\tau\epsilon\varsigma$ ) comes from the ancient Greek word “gaster” that means belly since its rear end was put on the belly. This weapon, that was similar to a cross bow, was ordered by Dionysius the older, the tyrant of Syracuse, in the early 4th century B.C. and. According to E.W. Marsden, the range of its arrows was about 25 % longer than that of a bow reaching 180–230 m ca.

In Fig. 18.14 is reported a reconstruction of a large ballista the design of which is attributed to Isidoro of Abidus and is described by Biton (3rd century B.C.) in his treatise on war machines construction.



**Fig. 18.13** Reconstruction of a gastrafetes



**Fig. 18.14** Reconstruction of the ballista by Isidoro di Abidus

### 18.5.1 Metal Spring Flexion Elastic Motors

Beginning in the 2nd century B.C., the focus was on conceiving a spring that was no longer a combination of wood, horns and sinews, but a thin sheet of forged and tempered metal, capable of reacting to any deformation, an ideal motor of little bulk but great power and longevity. From this it was only a short step to the carriage spring in steel or bronze.

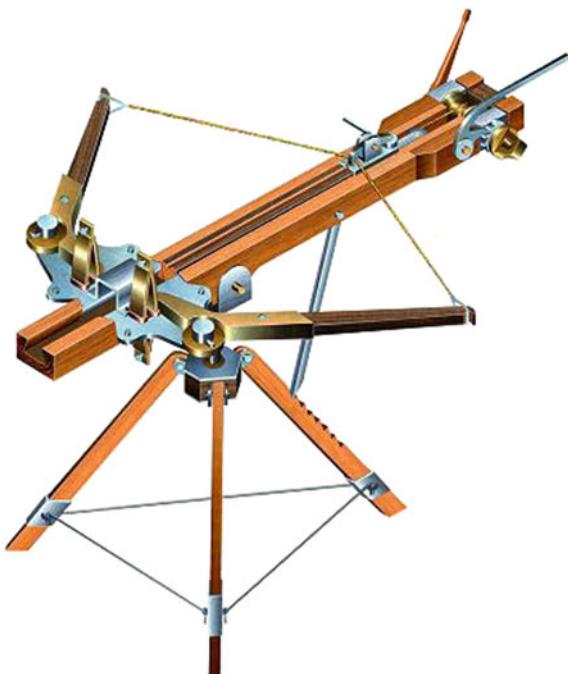
From a mechanical perspective, the spring in general and the crossbow spring in particular have very little technological value, then as now. But reality is quite different as this was the first metal object to use reverse elasticity.

As for the terms ballista or ballistra and catapult it has to be pointed out what follows: during the Classic Ages the first term indicated a stone or balls throwing machine since it comes from the Greek word ballein ( $\beta\alpha\lambda\lambda\epsilon\imath\nu$ ) = to hurl a stone; catapult ( $\kappa\alpha\tau\alpha\pi\epsilon\lambda\tau\eta\zeta$ ) generally indicated an arrow throwing machine. During the Middle Ages the terms were used with the opposite meaning. The term ballista was, possibly, invented by Ctesibius. Since we have a detailed description from Philon of Byzantium, we know that the construction of this weapon began with the forming of bronze leaves or folios (foils), which he called scales.

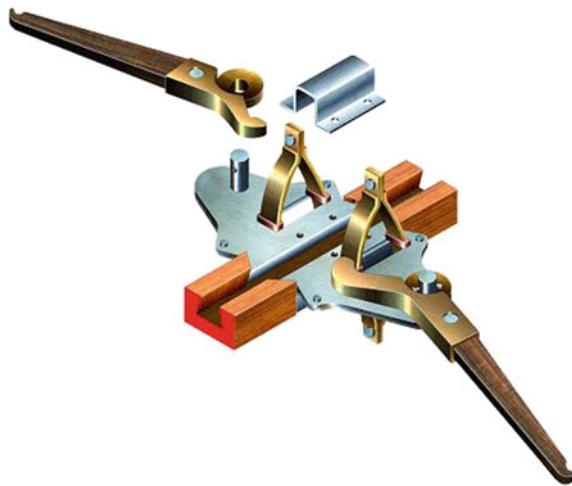
Numerous allusions indicate that Ctesibius' bronze springs only had two layers. The first secured to the opposing symmetrical layer by means of two pins, the second secured to the extrados of both, leaving the ends free. Size and curvature were the same for all, as was thickness, approximately 10 mm per leaf. The result was two superimposed leaves for each of the opposing arches: reminiscent of the elliptical springs on carts or railroad wagons, currently defined as composite leaf springs, or more simply springs. In Fig. 18.15 is reported a virtual reconstruction of Ctesibius' catapult with bronze springs according with his description;

Since steel was not yet available the leaves were made of a special bronze alloy, composed of 97 parts copper and 3 parts tin, the same alloy used today to make bronze springs. A minimum deviation in the quantities of the two metals, the smallest impurity, and there would be no elasticity. For catapults Ctesibius used two iron supports in the shape of ivy leaves, or two lobated plates, inserting a leaf spring

**Fig. 18.15** Virtual reconstruction of catapult with bronze springs



**Fig. 18.16** Detail of the spring mechanism



into each. One of the pins acted as a fulcrum for the arms, each of which had a cord attached. A solution very similar to our modern day bottle openers with mobile arms. In Fig. 18.16 is reported a detail of the spring mechanism.

When the device was ready, a pull on the embrasure cord would rotate the arms which in turn would push against the springs through the cam. The springs would flatten and compress a catch located adjacent to the frame. At that point the weapon was loaded and a resilient wheel with retrograde arrest hooks acted as a safety catch, similar to all other artillery pieces. When the trigger released the catch, the springs returned to their original curvature, providing a violent thrust to the arms which transmitted the same motion to the dart or arrow, like the medieval steel crossbows used 15 centuries later.

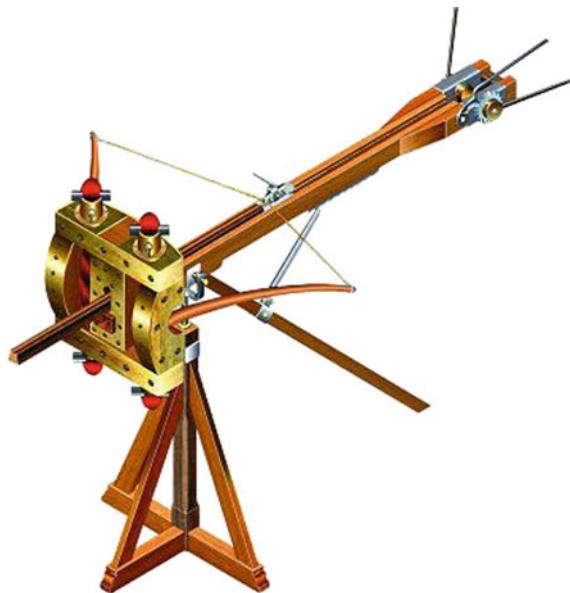
Ctesibius' catapult may not have been a particularly effective weapon, but the spring that was its motor had an extremely prevalent use two millenniums later since this small item is used in a large number of our devices today.

## 18.6 Torsion Elastic Motors

The ideal motor for a launching machine would have had to be small and powerful: according to sources something of the sort appeared around the middle of the 4th century B.C. It may have been suggested by the torsion press, used in Egypt for thousands of years to press vegetable essences, or the more recent frame-saw with a rope and rod tightener. Difficult to determine now: what we do know is that this was the period in which the first torsion artillery appeared on the scene and that would replaced flexion artillery in just a few decades.

From a construction aspect, a torsion motor consisted of a strong square wooden frame, reinforced by iron straps, divided into three separate sections. The central

**Fig. 18.17** Virtual reconstruction of a Roman catapult with torsion motor



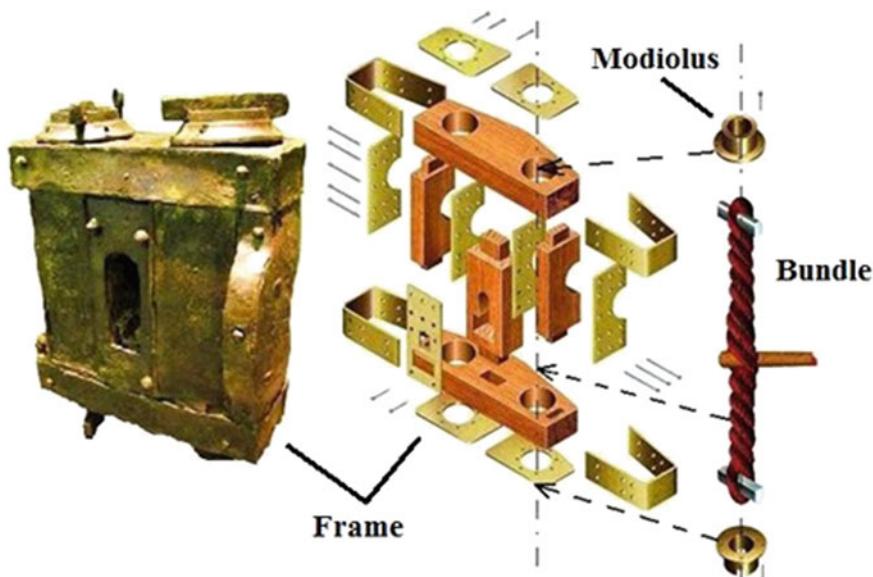
section was used to insert the shaft of the weapons, while the sides were for the two bundles of twisted yarns. Inside were the arms to which the bundle was affixed, like the ends of an archery bow. In Fig. 18.17 is reported an authors' virtual reconstruction of a Roman catapult with torsion motor, according to data provided by Vitruvius.

In Fig. 18.18 is reported a propulsor of a Roman catapult found in Xantem, Germany and an authors' exploded view of it with one of its coils.

The torsion motor essentially consisted in a bundle of yarns made by horse hairs or (most frequently) woman's hairs. The yarns were coiled from an upper iron bar to a lower one in order to make a bundle; the later were passed in an upper *modiolus* (=module) and in a lower one, so that its section was circular, and the two *modioli* were located on the machine head through two plates. After the hairs coil was located, it was possible to turn the modioli in order to give an initial charge to the hairs, then the modioli were blocked. In the middle of the bundle was located a lever: turning the latter, the bundle was torqued and the yarns were lengthened so that the bundle stored some elastic energy. In the balistae this elastic energy was then given to the projectile by means of a rope, linked to ends of the two levers and having in its middle the projectile.

In the following pieces from the classics, are reported two examples of descriptions of those throwing machines in classic age by Vitruvius, De Architectura liber X, caput XI:

Nam quae fiunt in capitibus foramina, per quorum spatia contenduntur capillo maxime muliebri vel nervo funes, magnitudine ponderis lapidis, quem debet ea ballista mittere, ex ratione gravitatis proportione sumuntur, quemadmodum catapultis de longitudinibus sagitarum.



**Fig. 18.18** Virtual reconstruction of the propulsor of a Roman catapult

In fact, holes are made in the mainframe and through them are brought the cords, made mostly of woman's hair or of sinews, which are proportioned to the weight of the stone that the ballista must throw and a ratio between weights and lengths is taken in the same manner in which (it is done) with the catapults for the length of the arrows.

And also by Appianus Alexandrinus (Greek: Αππιανός ~95–~165), Wars against Carthage, liber VIII, caput XCIII.

Efficientbantque singulis diebus clypeus centum, trecentos gladios; tela quae ex catapultis mittuntur, mille; tragulas et lanceas quigentas; catapultas, quotot poterant: quas ut tendere possent, raserunt feminas, quem aliorum pilorum esset inopia.

Each day they made 100 shields, 300 swords, 1,000 missiles for catapults, 500 darts and javelins, and as many catapults as they could. For strings to bend them the women cut off their hair for want of other fibers.

## 18.7 Throwing Machines Operated by Torsion Motors

In the next sections the main throwing machines that were operated by torsion motors are presented. These represent the artillery of the Greek and Roman armies and significantly contributed to the successful campaigns of the Roman Legions.

### 18.7.1 The Ballista

This machine was essentially a direct fire artillery piece designed to throw lead balls or, more frequently, store balls. It was built with the arms disposed in two different kinds of arrangements: the euthytone and the palintone.

The differences among the two types are shown in Fig. 18.19.

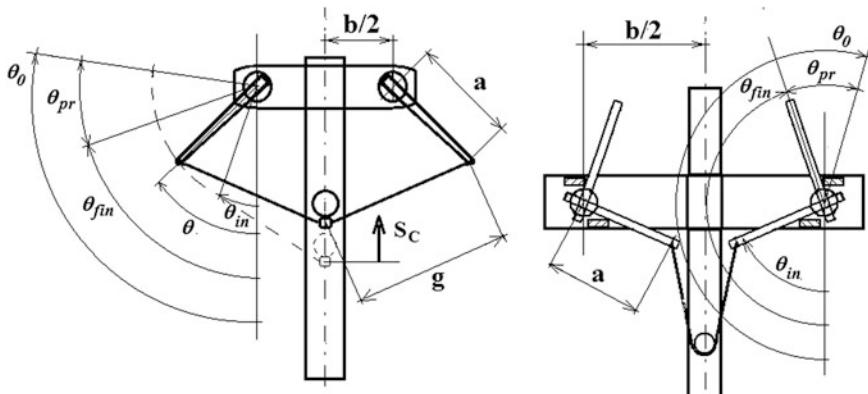
#### 18.7.1.1 The Euthytone Ballista

This kind of ballista was accurately described by Viruvius. The machine is very similar to the one shown in Fig. 18.17.

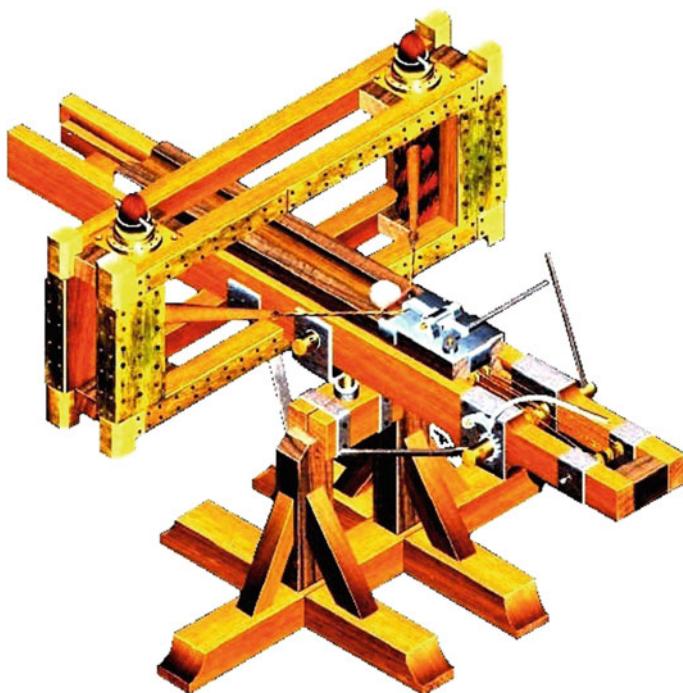
#### 18.7.1.2 The Palintone Ballista

In Fig. 18.20 an authors' pictorial reconstruction of the great ballista, the remains of which were found in Hatra (actually al-Hadr in Iraq) is represented.

This kind of ballista appeared about in the 1st century A.D. and, according to some authors (see e.g. Hart and Lewis 2009) was somehow considered as a sort of “secret weapon”. This is probably why few or nothing can be found in the classics about this machine. Fortunately relicts of this machine and several bas reliefs depicting it were found. The machine is designed as a palintone as essentially consists in a ballista whose arms are inside the frames. This solutions permitted to obtain some advantages (see e.g. Pagano and Rossi 2013) since the arms could rotate of a larger angle than the one of the euthytone.



**Fig. 18.19** Different types of balistae: euthytone (*left*) and palintone (*right*)



**Fig. 18.20** Pictorial reconstruction of the great ballista of Hatra

The one found at Hatra was a gigantic machine designed to throw heavy projectiles (up to 33 kg for some relics) and its arms had a wider rotation. Moreover, from the relics, it was found that the bundle casings were designed for bundles having an approximate L/D ratio of 9.

### 18.7.2 *The Catapult*

From a mechanical point of view, there were very little or negligible differences among the ballista and the catapult. The latter was in fact almost identical machine but designed to throw rather big darts or javelins instead of stones. Small catapults, used as light field artillery pieces, were called by the Romans “scorpio”, literally scorpion, probably because its arrows acted as the stinger of that animal.

It must be observed that during the Middle Age, the terms ballista and catapult were used in the opposite meaning: ballista for a javelin throwing machine and catapult for a stone throwing machine.

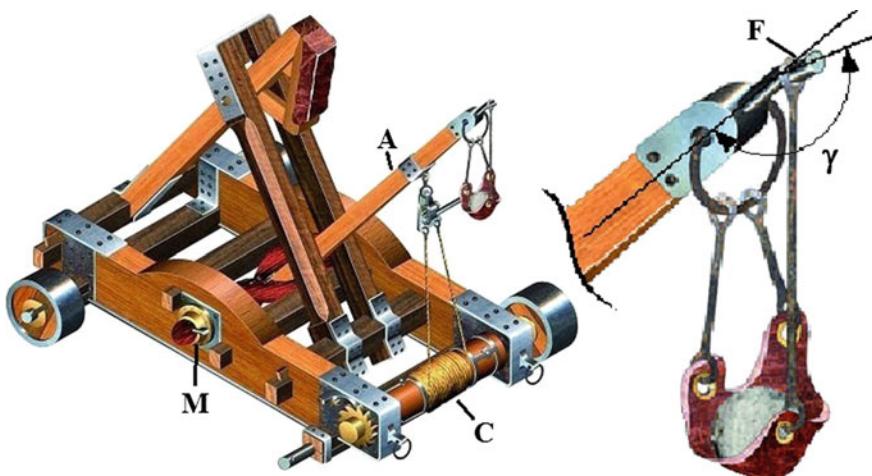
### 18.7.3 The Onager

The onager was a rather mysterious ancient war machine, indeed. In fact, very few information are available in ancient literature about this war machines; even Viruvius does not give us any new about it. Some news about a “*monoanchon*” can be found in the 5th book, named “*Belopoeica*” of the treatise on the mechanics Mechanike syntaxis (Compendium of Mechanics) by Philo of Byzantium (ca. 280 BC–ca. 220 BC); it is described as a throwing machine having an only big arm instead of two little arms. No more news can be found in ancient literature till the 4th Century A.D. when Ammianus Marcellinus (325/330–after 391) describes it rather in details and names it “*onagrum*”. This terms literally comes from the latin “*onagrus*” that means donkey; this was probably because it’s working was similar to the kick of a donkey.

It is interesting to remember that inside the city of Pompeii, for instance, several stone balls were found that were larger than the holes on the walls that were made by the impact of the projectiles thrown by the ballistae. Those big balls had been thrown by the onagers of Silla and had jumped over the walls of Pompeii during the siege in 89 B.C.

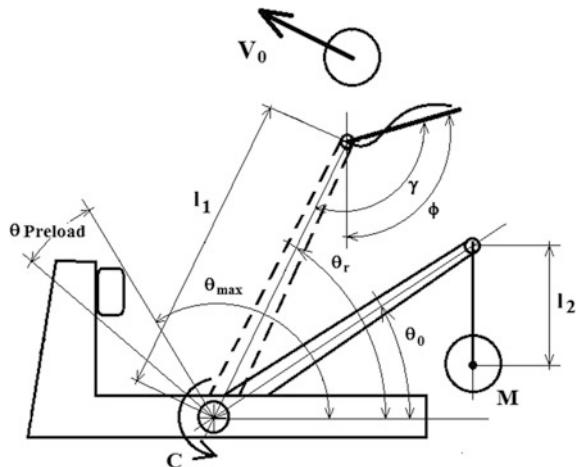
What is certain is that this artillery piece was built to attack position that were protected by walls or similar shields thanks to the parabolic trajectory of the projectiles.

A pictorial reconstruction of the onager is reported in Fig. 18.21. A working principle of the machine is reported in Fig. 18.22.



**Fig. 18.21** Pictorial reconstruction of the onager and particular of the linkage of the sling

**Fig. 18.22** Working principle of the onager



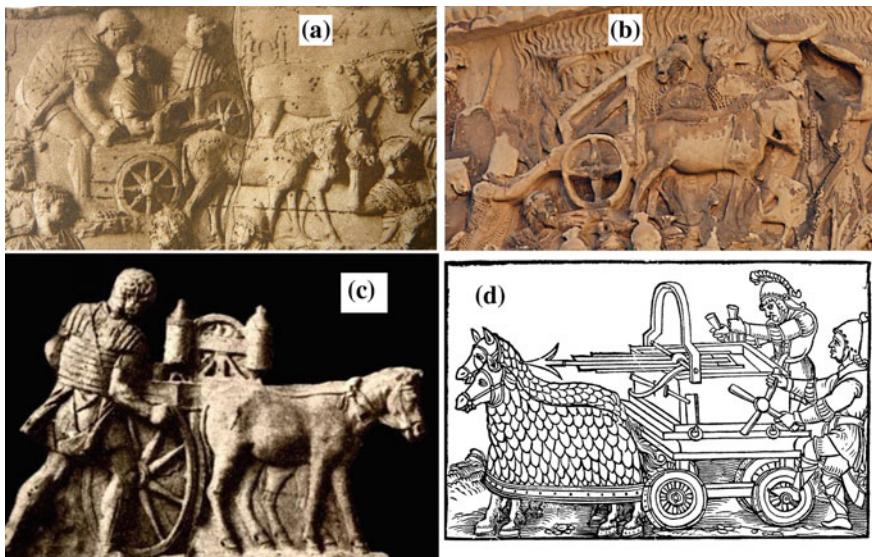
From Figs. 18.21 and 18.22 the machine and its working principle can be understood. Essentially the machine was composed by a single arm (a in Fig. 18.21) that is inserted in a bundle made by yarns obtained by woman hairs. This bundle represents the torsion motor of the machine and gives an elastic couple (c in Fig. 18.21) to the arm. The bundle can be preloaded by means of the *modioli* M (Fig. 18.21). On the other end of the arm, a sling is linked (which kinematic length is indicated with  $l_2$  in Fig. 18.22) that holds the projectile. One of the sling ropes is fixed to the arm while the other rope is linked by means of a ring that is put on a pin (F in the particular of Fig. 18.21); the axis of this pin can be set with a desired angle  $\gamma$  respect to the axis of the arm. Finally, a capstan rotates the arm to charge the torsion spring and, hence, the machine.

When the trigger is pushed, the arm is released and it will rotate because of the couple given by the torsion motor. The projectile will be released by the sling when its ropes will be approximately aligned with the pin axis since in this condition the ring of the sling will climb over the pin. In this way, by changing the angle  $\gamma$ , the initial throwing angle of the projectile and its initial velocity can both be set.

#### 18.7.4 The Cheiroballistra

The Roman cheirobalistra or manubalista (Iriarte 2000; Russo 2004) is a small scorpion developed to give the Roman legion a lightweight support weapon.

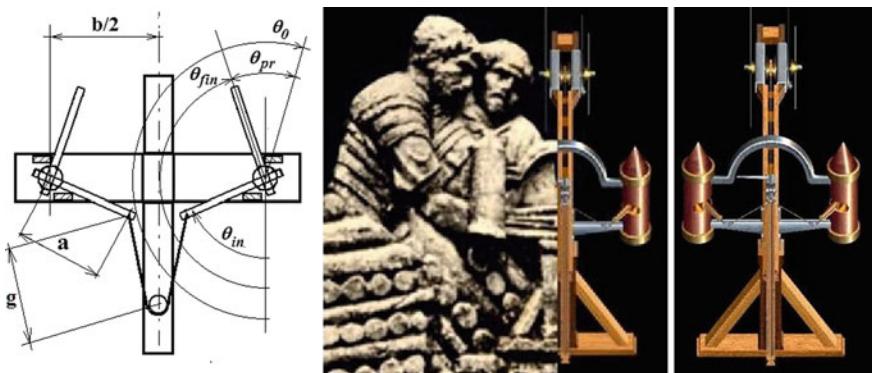
An interesting example of cheiroballistra is the imperial carrobalista that was developed in the 1st century A.D. and represents the first example of mobile artillery. It was mounted on a chart in order to provide a quick deployment of artillery piece to obtain a close support to the infantrymen. In this sense it represents the first example of infantry support gun (or battalion gun) that was then developed



**Fig. 18.23** **a, c** Trajan column; **b** Aurelian column; **d** De Rebus Bellicis (Trad. XVI Sec.)

in modern (18th–20th century) warfare. In Fig. 18.23 examples of the imperial carroballista are shown.

Based on some authors' previous studies and on several investigations by other Authors, the authors supposed that this ballista (see Fig. 18.24) was based on an palintone design. Several studies, some by the authors also, demonstrated that the palintone is more efficient because the arms rotation angle is wider than that one of an euthytone. So it is reasonable to suppose such a design for a machine that should develop enough power in small dimensions.



**Fig. 18.24** Bas relief and scheme of the machine

## 18.8 Mechanics of the Throwing Machines

In this paragraph models of previously described machines are presented in order to compute their mechanical behavior and their performances.

### 18.8.1 The Torsion Motor

It must be told that the design of the Greek-Roman throwing machines was based on a module; the latter was the diameter of the modiolus shown in Fig. 18.18.

Probably the first ancient scientist who stated the relationship between the weight of the projectile and the modulus diameter was Archimedes of Syracuse. From Philon of Byzantium to Vitruvius, all the throwing machines designer and theoreticians say that this relationship is:

$$D = 1.1 \cdot \sqrt[3]{100 \cdot m} \quad (18.5)$$

where

$D$  is the diameter of the modiolus (hence of the hair bundle) in digits (1 digit  $\approx 19.5$  mm)

$m$  is the mass of the projectile in mine (1 mina  $\approx 431$  grams)

Once the diameter of the modiolus was stated as described, all the other main dimensions of the machine were taken on this dimension. In Fig. 18.25 a scheme of a ballista and a particular of the frame with the modiolus are shown.

As for the design of this machine, Vitruvius is very meticulous in giving the ratios between the diameter of the modiolus and all the other main dimensions of the machine:

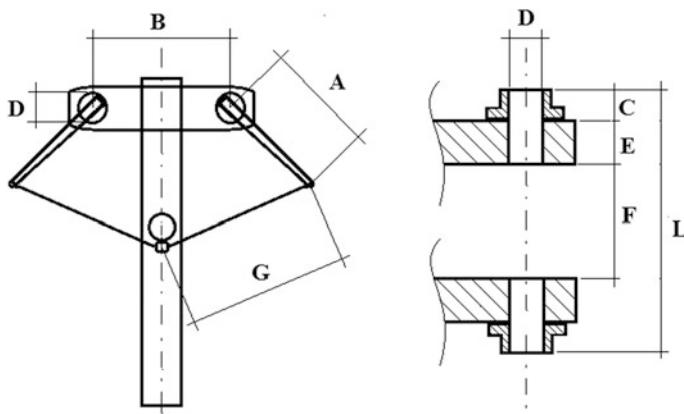


Fig. 18.25 Scheme of a balista

$$A = 7 D$$

$$B = 3 + \frac{1}{4} D$$

$C \sim 0.5 D$  (this datum is desumed by some relicts)

$$E = 1 D$$

$$F = 4 D$$

$d_1 = 9/16 D$ , diameter of the arm near the bundle

$d_2 = 7/16 D$ , diameter of the arm near the rope

As for the catapult, according to Philo of Byzantium and to Vitruvius, the diameter of the modiolus was computed by starting from the length of the arrow. If the latter is indicated with S, the diameter of the modiolus is:

$$D = S/9 \quad (18.6)$$

From the data above, we can deduce that the bundle length L was 7 times its diameter D. If we consider that about  $\frac{1}{4} D$  of the hair bundles are reasonably blocked in the modioli, we can consider that the coil of fibers that really were twisted by the arm A had a ratio:

$$\frac{L}{D} = 6.5$$

The half of the rope length G can be deduced by considering that it was straight when the arms A were at the end of their run; that is to say, the rope was a straight line when the arms made an angle of about 20 degrees before the horizontal in Fig. 18.26. Hence we have:

$$G = 1/2 B + A \cdot \cos 20^\circ = 8.2D$$

In order to evaluate the torsional energy of the bundle the following model is proposed.

Since the modioli are blocked in the machine frame, the external sections of the fibers bundle can neither rotate nor translate, so the structure is statically indeterminate. In Fig. 18.26 is shown a scheme of half of the bundle, from the modiolus (blocked in the frame) to the lever; so the length indicated with  $l_0$  is one half of the bundle length.

In the same Figure also a cross section of the bundle is reported.

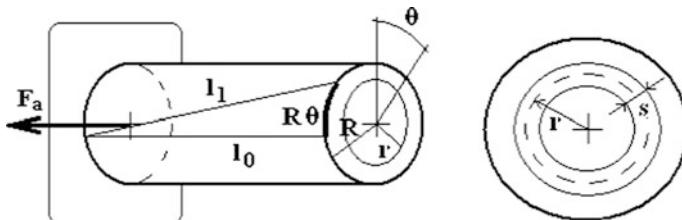


Fig. 18.26 Model of the bundle

If we consider a rotation  $\theta$  of the arm (i.e. of the section in the middle of the bundle), the elongation  $\Delta l$  of each fiber is:

$$\Delta l = l_1 - l_0 = \sqrt{r^2\theta^2 + l_0^2} - l_0 \quad (18.7)$$

So, each fiber will be stressed by a force  $F_f$ :

$$F_f = E A_f \Delta l / l_0 \quad (18.8)$$

where  $E$  is the Young's modulus of the hair yarns.

Now, the ratio  $L/D$  between the length and the diameter of the bundle normally was between 6 and 9.5 and, according to Vitruvius, this ratio, was 6.5; moreover, in the palintonon balistae, the arms rotation was no more than 1 radiant. So if we consider those fibers that are located on the surface of the bundle, the maximum value of the fibers inclination (if the arm rotation is 1 radiant) is:

$$\beta = \arctan(r\theta/l_0) = \arctan(1/6.5) \cong 8.75^\circ$$

So, if we consider that we the force given from Eq. (18.3) as axial, the error is negligible.

The force exerted by the fibers on an annulus having mean radius  $r_i$  and infinitesimal thickness  $s$  is:

$$\begin{aligned} F_i &= E A_i \Delta l_i / l_0 = E 2 \pi r_i s \frac{\sqrt{r_i^2\theta^2 + l_0^2} - l_0}{l_0} \\ &= E 2 \pi r_i s \left( \sqrt{\frac{r_i^2\theta^2}{l_0^2} + 1} - 1 \right) \end{aligned} \quad (18.9)$$

The axial force that the half bundle exerts is:

$$\begin{aligned} F &= E 2 \pi \int_0^R r \left( \sqrt{\frac{r^2\theta^2}{l_0^2} + 1} - 1 \right) dr \\ &= \frac{2 E \pi l_0^2}{3 \theta^2} \left[ \sqrt{\left( \frac{R^2\theta^2}{l_0^2} + 1 \right)^3} - 1 \right] - E \pi R^2 \end{aligned} \quad (18.9')$$

It must be remarked that the force given by Eq. (18.9') is one half of the force exerted by each of the bundles because, as before said, the length  $l_0$  represents one half of the bundle length.

### 18.8.1.1 The Elastic Energy

If we suppose that the fiber are stressed under the proportionality limit, the elastic energy  $L_i$  in the generic  $i$ -th fiber is:

$$\begin{aligned} L_i &= F_i(l_i - l_0)/2 = \frac{F_i l_0}{2} \sqrt{\frac{r_i^2 \theta^2}{l_0^2} + 1} - 1 \\ &= E \pi r_i s l_0 \left( \sqrt{\frac{r_i^2 \theta^2}{l_0^2} + 1} - 1 \right)^2 \end{aligned} \quad (18.10)$$

Hence the elastic energy of half bundle is:

$$\begin{aligned} L &= \int_0^R L_i = E \pi l_0 \int_0^R \left( \sqrt{\frac{r^2 \theta^2}{l_0^2} + 1} - 1 \right)^2 r dr \\ &= E \pi l_0 \left\{ \frac{R^4 \theta^2}{4 l_0^2} + R^2 - \frac{2 l_0^2}{3 \theta^2} \left( \frac{R^2 \theta^2}{l_0^2} + 1 \right)^{\frac{3}{2}} + \frac{2 l_0^2}{3 \theta^2} \right\} \end{aligned} \quad (18.11)$$

In the next paragraphs, we will indicate the quantity in curly brackets as  $f_1(\theta)$ , so from Eq. (18.11), the elastic energy in the whole bundle will be simply written as follows:

$$L = 2E \pi l_0 \cdot f_1(\theta) \quad (18.12)$$

Now, the more a bundle of yarns are twisted, the less is its strength; in addition, if we consider the tensile behaviour of the hair (i.e. tensile strength and modulus of Young), we can desume that an hard twisting was not suitable. So, it seems more realistic to suppose that the coil was made up by almost parallel yarns; this agrees, also, with some of the reconstructions drawn by Marsden.

In the next paragraph, some aspect on the stress of the fibers and the L/D ratio of the fibers

### 18.8.1.2 The Stress in the Hairs

It is well-known that the stress  $\sigma$  is given by:

$$\sigma = E \frac{\Delta l}{l_0}$$

So, the stress in the hairs on the external surface if the bundle is:

$$\sigma = E \frac{\sqrt{R^2\theta^2 + l_0} - l_0}{l_0} = E \sqrt{\left(\frac{R}{l_0}\right)^2 \theta^2 + 1} - 1 \quad (18.13)$$

Hence:

$$\frac{\left(\frac{\sigma}{E} + 1\right)^2 - 1}{\theta^2} = \left(\frac{R}{l_0}\right)^2 = \left(\frac{L}{D}\right)^2 \quad (18.13')$$

The numerator of the first term of Eq. (18.13) only depends on the tensile features of the hairs. If the latter are known, it is possible to compute the value of the twist  $\theta_e$  imposed to the bungle over which the hairs are stressed over the proportionality limit  $\sigma_e$ , as a function of the ratio L/D.

Qiang Xiao et al. found that Caucasian women aged 20 hairs have the following tensile features:

$$E = 5.41 \text{ GPa}$$

$$\sigma_e = 93.33 \text{ MPa}$$

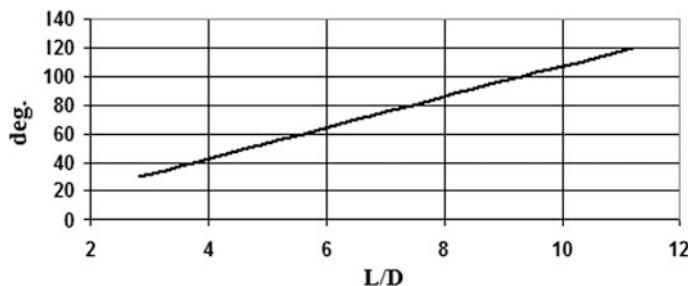
Now, it must be considered that the hairs are not parallel but spinned in yarns and the latter are coiled into a bundle; so we must assume that the “equivalent” modulus of Young of the bundle is lower than the one of a single hair. From [Tonelli, Bertoli, Manna] and from experiences of the author (when he was technical manager of a rope factory) it seems reasonable to assume that the “equivalent” modulus of Young for the hair bundle is  $0.8 \cdot E$ , hence the following value of the “equivalent” modulus of Young can be taken:

$$E' \cong 4.35 \text{ GPa}$$

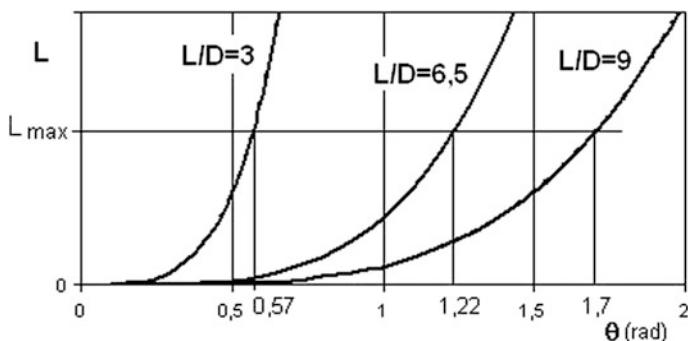
From Eq. (18.13) we have:

$$L/D = \sqrt{\frac{\theta^2}{\left(\frac{\sigma_e}{E'} + 1\right)^2 - 1}} \cong \sqrt{\frac{\theta^2}{0.035}} \Rightarrow \theta_{\max} \cong 10.7 \cdot L/D (\circ) \quad (18.14)$$

In Fig. 18.27 is shown the twist of the hair bundle that corresponds to stressing the hairs on the surface of the bundle at their proportionality limit  $\sigma_e$ ; over this rotation, the hairs will be quickly stressed over their yield point. It is evident that, for an L/D ratio of 6.5 (according to Vitruvius), the maximum rotation is about 70 degrees. It must be remarked that this maximum rotation is made by the arm rotation and the initial rotation of the bundle that represents the spring preload.



**Fig. 18.27** Maximum bundle torsion versus L/D



**Fig. 18.28** Elastic energy versus rotation

This seems to agree with an arm rotation of 50 degrees, that was typical for those machines, and a 20 degrees initial rotation of the moduli to give the preload.

In Fig. 18.28 are reported the elastic energy of the bundle as a function of the torsion of the bundle itself, for some L/D ratios. All the graphs were obtained considering the same bundle volume, i.e. bundles in which it was possible to store the same energy. From the Figure, indeed, it can be observed that the maximum stored energy is constant: the horizontal line marked with “ $L_{max}$ ”, in fact, represents the elastic energy that corresponds, for each of the bundles, to a rotation over which the external hairs stress is over the proportionality limit  $\sigma_e$ . The intersection of this line with the curves indicates the maximum torsion angle for each L/D ratio, as it can be deduced from Eq. (18.14) and from Fig. 18.27.

From Fig. 18.26 it is evident that the higher is the L/D ratio, the wider must be the arms rotation in order to store in the bundle the maximum possible elastic energy. From the latter Figure it can be observed, also, that the lower is the L/D ratio, the higher is the slope of the curve. As far as this aspect is concerned we can observe that, to higher slopes, will corresponds a faster release of energy during the throwing of the projectile. The last aspect seems similar to what happens in firearms where, with heavy projectiles, slow burning powders are used while quick burning

powders are used with light projectiles. This suggests that high L/D ratios for the bundle could have been used for machines that heavier projectiles.

Finally, it must be observed that the shape of the curves in Fig. 18.28 are similar to the theoretical and experimental plots of the spring (representing the bundle) torque versus the arm rotation by Hart and Lewis 1986, 2009), that have already proposed models for ancient throwing machines.

## 18.8.2 The Models and the Performances of the Machines

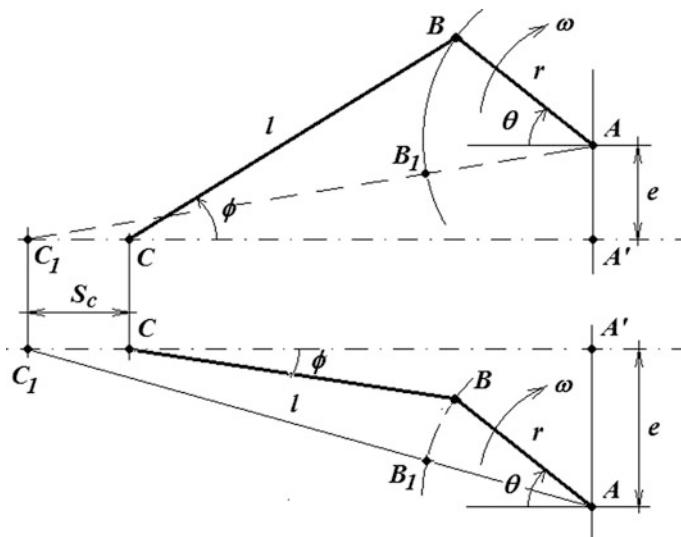
### 18.8.2.1 The Ballista and the Catapult

As already told, ballista and catapult were almost identical from a mechanical point of view. There were two types of arrangements: the euthytone and the palintone. In Fig. 18.29 the kinematic scheme of both the types of ballistae are shown.

By the scheme reported in Fig. 18.29, it is easy to obtain the projectile displacement, as a function of the arm position.

Palintone:

$$S_{C,\text{eut}} = a \cdot \left[ \sqrt{(\mu + 1)^2 - \varepsilon^2} - \cos \theta - \sqrt{\mu^2 - (\sin \theta + \varepsilon)^2} \right] = a \cdot f_{2,\text{eut}}(\theta) \quad (18.15e)$$



**Fig. 18.29** Kinematic scheme of the palintone (up) and euthytone (down) ballista

Euthytone:

$$S_{C,pal} = a \cdot \left[ \sqrt{(\mu + 1)^2 - \varepsilon^2} - \cos \theta - \sqrt{\mu^2 - (\varepsilon - \sin \theta)^2} \right] = a \cdot f_{2,pal}(\theta) \quad (18.15p)$$

where

$\theta_{in}$  the initial angular position of the arm when the machine is loaded,

$\theta$  the generic arm position,

$\theta_{fin}$  the final position of the arm when the projectile leaves the ballista,

$\theta_0$  the ideal position of the arm in which the bundle is not preloaded

Moreover, according to the Figure, we indicated with:

$$\mu = \frac{g}{a}, \text{ and } \varepsilon = \frac{b/2}{a}$$

By differentiating the equations above the projectile velocity as a function of the arm position  $\theta$  and of the arm velocity  $\dot{\theta}$ .

Euthytone:

$$V_{C,eut} = a \cdot \dot{\theta} \cdot \left[ \sin \theta + \frac{\sin 2\theta + 2 \cdot \varepsilon \cdot \cos \theta}{2\sqrt{\mu^2 - (\sin \theta + \varepsilon)^2}} \right] = a \cdot \dot{\theta} \cdot f_{3,eut}(\theta) \quad (18.16e)$$

Palintone:

$$V_{C,pal} = a \cdot \dot{\theta} \cdot \left[ \sin \theta + \frac{\sin 2\theta - 2 \cdot \varepsilon \cdot \cos \theta}{2\sqrt{\mu^2 - (\varepsilon - \sin \theta)^2}} \right] = a \cdot \dot{\theta} \cdot f_{3,pal}(\theta) \quad (18.16p)$$

Hence:

$$\left( \frac{\dot{\theta}}{V_c} \right)^2 = \frac{1}{[a \cdot f_3(\theta)]^2}$$

From the energy balance, it follows:

$$E_{cin} = L - L_{attr} \quad (18.17)$$

where

$E_{cin}$  is the kinetic energy of the moving components of the machine,

$L$  is the elastic energy of the bundle, calculated using Eq. (18.11),

$L_{attr}$  is the energy lost due to the friction between the projectile and its guide  
Indicating with:

$m$  the projectile mass,

$I_b$  the mass moment of inertia for each arm,

$f$  the coefficient of friction between the projectile and the guide,

in a generic configuration defined by the arm rotation  $\theta$ , the terms of Eq. (18.17) are:

$$\begin{aligned} E_{cin} &= 1/2(m \cdot V_C^2 + 2 \cdot I_b \dot{\theta}^2) = 1/2V_C^2 \left[ m + 2 \cdot I_b \left( \frac{\dot{\theta}}{V_C} \right)^2 \right] \\ &= 1/2V_C^2 \left( m + \frac{2 \cdot I_b}{[a \cdot f_3(\theta)]^2} \right) \end{aligned}$$

$$L = 4 \cdot E \pi l_0 \cdot [f_1(\theta_0 - \theta_{in}) - f_1(\theta - \theta_{in})]$$

$$L_{attr} = m \cdot g \cdot f \cdot S_C = m \cdot g \cdot f \cdot a \cdot [f_2(\theta) - f_2(\theta_{in})]$$

So:

$$\begin{aligned} 1/2V_C^2 \left( m + \frac{2 \cdot I_b}{[a \cdot f_3(\theta)]^2} \right) &= \\ = 4 \cdot E \pi l_0 \cdot [f_1(\theta_0 - \theta_{in}) - f_1(\theta - \theta_{in})] - m \cdot g \cdot f \cdot a \cdot [f_2(\theta) - f_2(\theta_{in})] & \end{aligned}$$

Hence:

$$V_C = \sqrt{2 \cdot \frac{4E \pi l_0 [f_1(\theta_{in} - \theta_0) - f_1(\theta - \theta_{in})] - mgfa [f_2(\theta) - f_2(\theta_{in})]}{\left( m + \frac{2I_b}{[af_3(\theta)]^2} \right)}} \quad (18.18)$$

Equation (18.18) allows to calculate the projectile velocity for a given arm angle  $\theta$ . Naturally, the quantities  $f_1$ ,  $f_2$  and  $f_3$  are computed for the eutitonon or for the palintonon, depending on which machine is considered.

In order to show examples of the performances of an eutitonon and a palintonon, the following machines were studied, both throwing a 10 minae (= 4.31 kg) stone:

### Euthytone

According to Vitruvius the main dimensions of this machine were:

$$D = 11 \text{ digits} \approx 214.5 \text{ mm}$$

$$a = 7D \approx 1500 \text{ mm}$$

The following arm rotations were considered:

$$\theta_{in} = 20^\circ$$

$$\theta_{fin} = 65^\circ$$

$$\theta_0 = 90^\circ$$

It must be observed that, with the values above, the maximum torsion of bundle (arm rotation plus preload) is  $70^\circ$  that correspond to stressing the hair on the surface of the bundle at their proportionality limit  $\sigma_e$ , as shown in Fig. 18.16.

In order to evaluate the rope length, we assumed that the latter was straight when the arms were at their final position; hence, from Fig. 18.18 we have:

$$g = \frac{b}{2} + a \cos(\pi/2 - \theta_{in})$$

And hence:

$$\mu = \frac{g}{a} = \frac{13}{56} \cos(\pi/2 - \theta_{in}) \approx 1.14$$

$$\varepsilon = \frac{b/2}{a} \approx 0.23$$

It must be observed that the parameter  $\mu$  (that depends on the length of the rope) plays an rather important role.

The mass moment of inertia of each arm, was determined as that of a cylinder having a mean diameter  $d = 1/2 D$  in beech wood, which density is  $730 \text{ kg/m}^3$ .

$$I_b = 7.1 \text{ kg m}^2$$

The coefficient of friction between the projectile and the guide was assumed:

$$f = 0.5.$$

Using the data above, the projectile velocity was calculated as a function of the arm position  $\theta$  and reported in Fig. 18.30.

Figure 18.31 reports the force of inertia of the projectile as a function of the arm rotation.

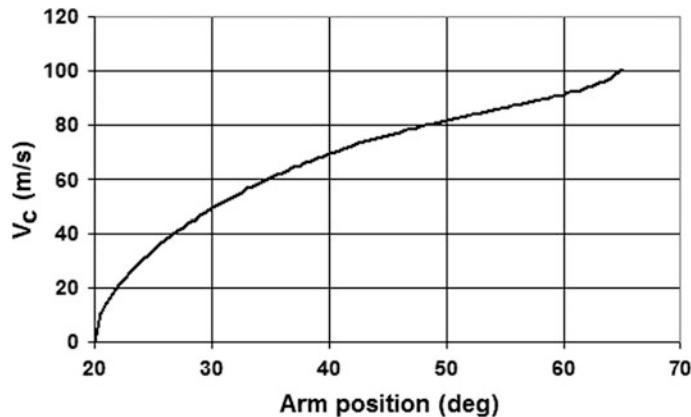


Fig. 18.30 Projectile velocity versus arm position

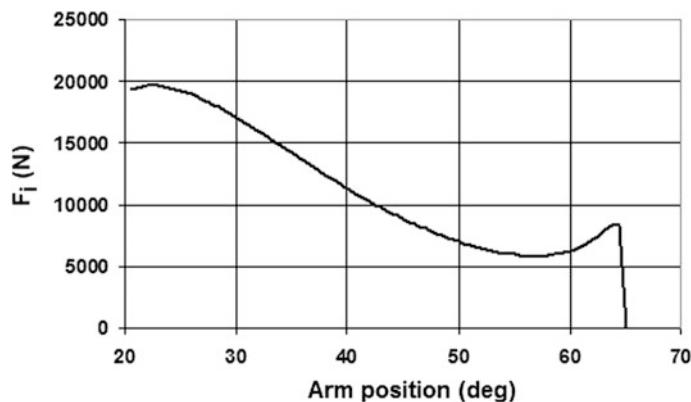


Fig. 18.31 Force of inertia on the projectile versus arm rotation

### Palintone

A projectile having the same mass (4.31 kg) was considered for a palintone machine. It was supposed that the latter had the same modioli diameter and the same arm length.

For the palintone, the following arm rotations were considered:

$$\theta_{\text{in}} = 55^\circ$$

$$\theta_{\text{fin}} = 140^\circ$$

$$\theta_0 = 165^\circ$$

Since the maximum torsional spring (hair bundle) rotation is  $110^\circ$ , from Fig. 18.27 it comes that  $L/D$  must be 10.25.

The distance  $b$  was assumed, according to some reconstructions and archaeological finds, as

$$b = 1,15 \cdot 2 \cdot a$$

The rope length was evaluated assuming that the latter was straight when the arms were at their final position, as it was done for the euthytone; from Fig. 18.18 it follows:

$$g = \frac{b}{2} - a \cos(\vartheta_{\text{fin}} - \pi/2)$$

So, it was assumed:

$$\begin{aligned}\mu &= \frac{g}{a} = \frac{b/2}{a} - \cos(\vartheta_{\text{fin}} - \pi/2) = 1.15 \cos(\vartheta_{\text{fin}} - \pi/2) = 0.507 \\ \varepsilon &= \frac{b/2}{a} = 1.15\end{aligned}$$

In Fig. 18.32 the projectile velocity versus arm position is reported and in Fig. 18.33 the force of inertia on the projectile versus arm rotation is reported.

The projectile trajectories can be computed by using a simple model for the air drag force  $R$ :

$$\mathbf{R} = -\frac{1}{2} C_d \rho V^2 A \mathbf{v} \quad (18.19)$$

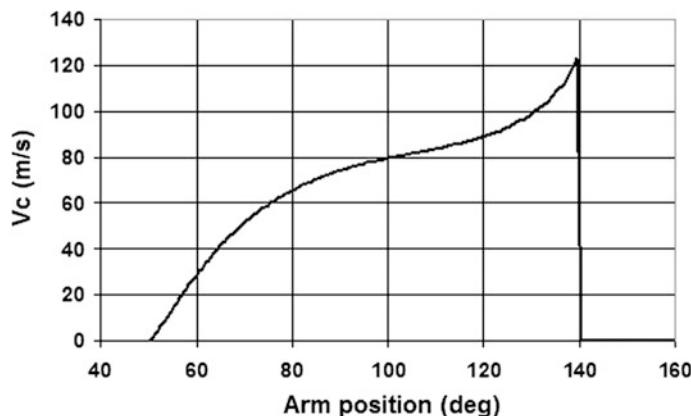
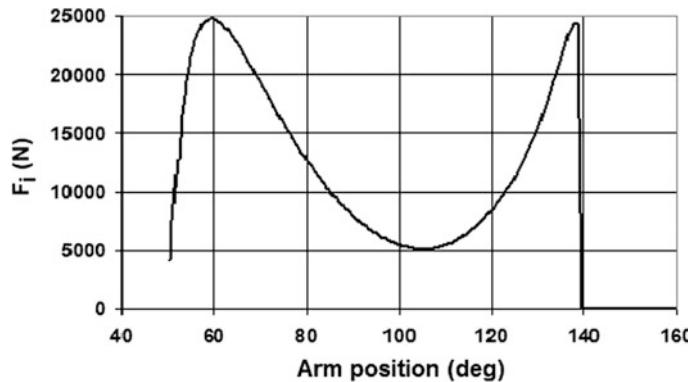


Fig. 18.32 Projectile velocity versus arm position

**Fig. 18.33** Force of inertia on the projectile versus arm rotation

where

$C_v$  is the drag coefficient for a rough sphere  $\approx 0.5$

$\rho$  is the mass density of the air  $= 1,225 \text{ kg/m}^3$ ,

$V$  is the speed (module with its unit vector  $v$ ) of the projectile,

$A$  is the area of the projectile's cross section.

The differential equations governing the motion can be obtained by projecting along the classical horizontal rightward,  $x(t)$ , and vertical upward direction,  $y(t)$ , the following vector equation:

$$m \mathbf{a}(P) + \frac{1}{2} C_v \rho V A \mathbf{V}(P) - m \mathbf{g} = \mathbf{0} \quad (18.20)$$

where  $P$  is the vector configuring the position of the projectile for any instant of time. Equation (18.20) was numerically solved.

All the above, permitted to compute the following examples:

If an euthytone ballista is considered, throwing a 4.31 kg mass stone ball with an initial velocity of 95 m/s, the following performances can be computed.

In Table 18.1, examples of range Figures are shown; in the table are reported:

The angle of elevation  $\theta$ ,

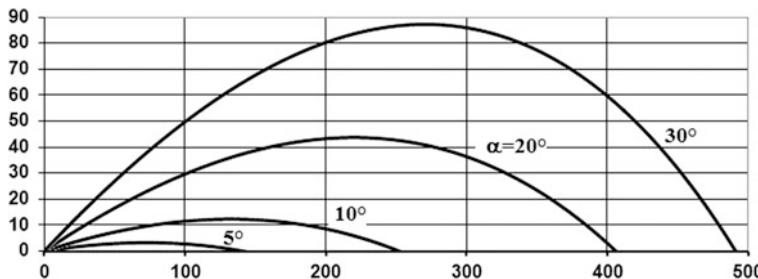
the range in meters,

the maximum height reached by the projectile

the velocity at the impact  $V_f$ ,

**Table 18.1** Euthytone ballista range Figures;  
projectile mass = 4.31 kg,  
initial velocity 95 m/s

$\theta$ (deg)	Range (m)	$h_{\max}$ (m)	$V_f$ (m/s)	$\beta$ (deg)	$T_f$ (s)
5	141.6	3.3	79.8	5.6	1.6
10	252	12.3	70	12.3	3
20	406.2	43.7	59.7	27.1	6
30	491	87.3	56.9	41.3	6.4



**Fig. 18.34** Trajectories for the euthytone

the angle at the impact  $\beta$ ,  
the time of flight  $T_f$ .

for elevation angle  $\theta$  of  $5^\circ$ ,  $10^\circ$ ,  $20^\circ$  and  $30^\circ$ . In Fig. 18.34 the trajectories for the same conditions are shown

If a large palintone is considered, throwing a  $40 \text{ minae} = 21.55 \text{ kg}$  projectile consisting of an almost spherical stone having about 254 mm diameter, with an initial velocity of 118 m/s, the following performances can be computed.

In Table 18.2 and in Fig. 18.35, range Figures and trajectories are reported.

As for the terminal effect of those projectiles, it can be interesting to observe the holes produced by stone balls thrown against the walls of the city of Pompeii during the Lucius Cornelius Silla's siege in 89 A.C.; one of them is shown in Fig. 18.36. In the Figure, each ruler mark is 10 cm, so the holes have a diameter of almost 150 mm that is the projectile that was considered for the example of Table 18.1 and Fig. 18.25.

### 18.8.2.2 The Catapult

An example for a small scorpio like the repeating catapult shown in the Chap. 21 on the automatic device is here presented.

In Fig. 11.37 are reported the projectile velocity versus the arm position, considering arrows weights of 100, 150 and 200 grams, having the cross section of a circle of 32 mm diameter. As for the air drag coefficient, in Eq. (18.2) it was assumed  $C_v = 0.35$  (Fig. 18.37).

**Table 18.2** Palintone ballista range Figures; projectile mass = 21.55 kg, initial velocity 118 m/s

$\theta$ (deg)	Range (m)	$h_{\max}$ (m)	$V_f$ (m/s)	$\beta$ (deg)	$T_f$
5	221	5.1	110.7	5.5	2
10	396.5	19.2	89.1	12	4
20	645.1	68.7	76.6	26.5	7.5
30	785.5	137.6	73	40.5	10.6

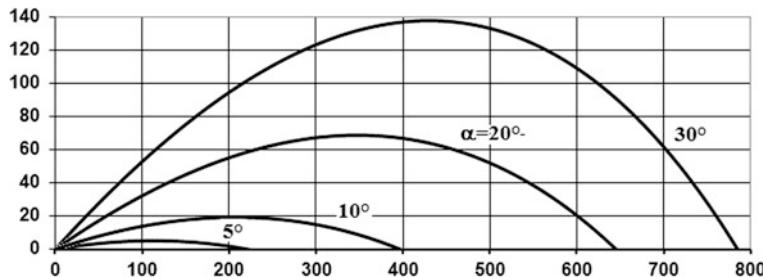


Fig. 18.35 Trajectories for the large palintone



Fig. 18.36 Holes caused by the impact of ballistae projectiles

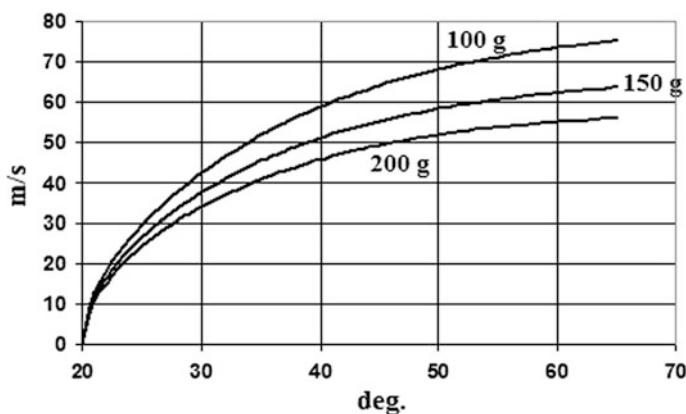
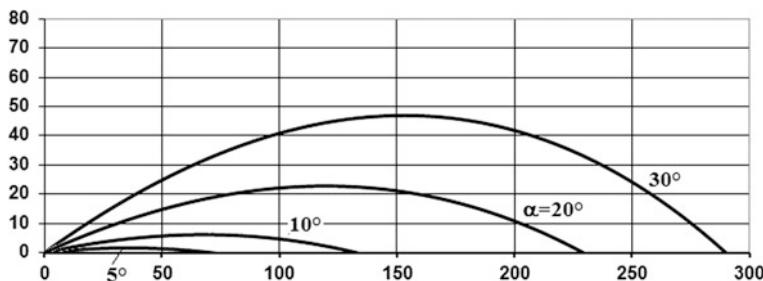


Fig. 18.37 Projectile velocity as a function of the arm position

**Table 18.3** Repeating catapult range Figures; projectile mass = 150 g, initial velocity 65 m/s

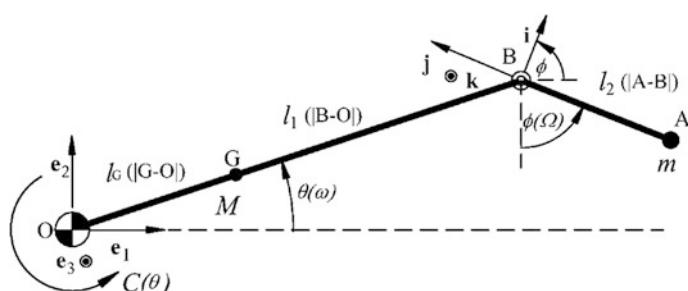
$\theta$ (deg)	Range (m)	$h_{\max}$ (m)	$V_f$ (m/s)	$\beta$ (deg)	$T_f$ (s)
5	70.6	1.6	60	5.2	1.1
10	132.5	6.1	56	11	2.2
20	229.1	22.8	50.8	23.5	4.3
30	289.8	46.9	48.8	36	6.2

**Fig. 18.38** Trajectories for repeating catapult (small scorpio)

In Table 18.3 and in Fig. 18.38 range Figures and trajectories of such a small scorpio are reported.

### 18.8.2.3 The Onager

Figure 18.39 shows a generic configuration of an onager. The onager is modelled as a two degrees of freedom machine ( $\theta, \phi$ ) and, in spite of the flexibility of the sling (A-B), the machine is modelled as it were made up of two rigid bodies (i.e. the arm (or lever), OB, and the sling, AB); this latter assumption is not evidently fulfilled by a geometrical point of view but it becomes a reasonable choice when we consider its extreme points, constrained at a fixed distance through the arising forces.

**Fig. 18.39** Nomenclature used to describe the generic configuration of the onager

The inertial load associated with the sling is neglected whilst the kinetic and potential energies of the machine are written as follows:

$$\begin{cases} T = \frac{1}{2}M\mathbf{V}(G) \circ \mathbf{V}(G) + \frac{1}{2}I_G \dot{\theta}^2 + \frac{1}{2}m\mathbf{V}(A) \circ \mathbf{V}(A) \\ U = Mg[l_G + l_G \sin(\theta)] + mg[l_1 + l_2 + l_1 \sin(\theta) - l_2 \cos(\phi)] \end{cases} \quad (18.21)$$

where ‘◦’ represents the dot product. Based on Eq. (18.21), the pure governing differential of the motion can be obtained by resorting to analytical mechanics and, specifically, to Lagrange’s equations:

$$\begin{cases} \frac{d}{dt} \left( \frac{\partial L}{\partial(\dot{\theta}, \dot{\phi})} \right) - \frac{\partial L}{\partial(\theta, \phi)} = Q_{(\theta, \phi)} \\ L = T - U \end{cases} \quad (18.22)$$

where the generalized forces ( $Q_{(\theta, \phi)}$ ) acting over the virtual generalized displacements ( $\delta\theta, \delta\phi$ ) consist of the torque  $C(\theta)$  in one of the two differential equations of motion.

For the torque  $C(\theta)$ , Eq. (18.12) is taken into account. Equation (18.21) clarifies the action employed for activating the onager. In particular, when the onager starts to fire its projectile, and thus move from its initial conditions (herein assumed to be  $\theta(t=0) = \theta_0 = 35^\circ, \phi(t=0) = 0^\circ, \omega(t=0) = \Omega(t=0) = 0$  rpm), the lever is subjected to the maximum torque but this falls away as  $\theta$  increases.

$$C(\theta) = -2E\pi l_o \left[ \frac{R^4(\theta - \theta_{and} - \theta_0)}{2l_o^2} - \frac{4l_o^2}{3(\theta - \theta_{and} - \theta_0)^3} \right. \\ \left. + \frac{4l_o^2 \left( \frac{R^2(\theta - \theta_{and} - \theta_0)^2}{l_o^2} + 1 \right)^{3/2}}{3(\theta - \theta_{and} - \theta_0)^3} \right. \\ \left. - \frac{2R^2 \sqrt{\frac{R^2(\theta - \theta_{and} - \theta_0)^2}{l_o^2} + 1}}{(\theta - \theta_{and} - \theta_0)} \right] \quad (18.23)$$

In Eq. (18.23)  $\theta_{and}$  represents the span that brings the lever from that point where the spring (bundle) is not deformed to its initial condition,  $\theta_0$ ; from Fig. 18.11, this is:

$$\theta_{and} = \theta_{max} + \theta_{preload} - \theta_0 \quad (18.24)$$

Thus,  $\theta_{and}$  constitutes the entire preload of the spring providing the maximum torque in the initial condition ( $t = 0$ ).

To apply Eq. (18.22), the velocity of points G and A (Fig. 18.29) must be explicated. To this end, the following equations, based on rigid body kinematics, are taken into account:

$$\begin{aligned}\mathbf{V}(G) &= \boldsymbol{\omega} \times (G - O) = -\dot{\theta} l_G \sin(\theta) \mathbf{e}_1 + \dot{\theta} l_G \cos(\theta) \mathbf{e}_2 \\ \mathbf{V}(A) &= \mathbf{V}(B) + \boldsymbol{\Omega} \times (A - B) = \\ &= [-\dot{\theta} l_1 \sin(\theta) + \dot{\phi} l_2 \cos(\phi)] \mathbf{e}_1 + [\dot{\theta} l_1 \cos(\theta) + \dot{\phi} l_2 \sin(\phi)] \mathbf{e}_2\end{aligned}\quad (18.25)$$

Of course, these velocities could also be expressed in the mobile reference ( $\mathbf{i}$ ,  $\mathbf{j}$ ,  $\mathbf{k}$ ), but this choice does not immediately provide any technical interest with respect to the kinematic parameters used to measure the performance of the onager. Such a reference could be adopted to immediately derive the tension in the ropes through the equilibrium condition of the projectile placed in A.

Once Eq. (18.25) is introduced in (18.21), Eq. (18.22) can be applied and the following governing differential equations are obtained:

$$\begin{cases} g \sin(\phi) - l_1 \dot{\theta}^2 \cos(\theta - \phi) - l_1 \ddot{\theta} \sin(\theta - \phi) + l_2 \dot{\phi} = 0 \\ g(ml_1 + Ml_G) \cos(\theta) + ml_1 l_2 \dot{\phi}^2 \cos(\theta - \phi) + (I_o + ml_1^2) \ddot{\theta} + \\ - ml_1 l_2 \ddot{\phi} \sin(\theta - \phi) - C(\theta) = 0 \end{cases}\quad (18.26)$$

In order to evaluate the performance of an onager, a machine having the following dimensions was considered:

Length of the arm: 2.2 m

Length of the sling: 1 m

Weight of the projectile: 17.44 kg (=40 Roman minae), consisting in a stone sphere having approximately 237 mm diameter

By solving the differential equations the dynamical behavior of the machine itself was computed. This permitted to compute the projectile initial velocity in several working conditions. Finally, the range Figures were computed by means of Eqs. (18.19) and (18.20).

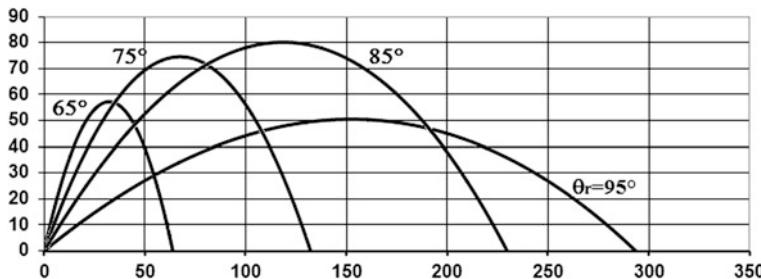
The range of this throwing machine could be adjusted both by changing the angle  $\gamma$  and by changing the bundle torque, that is to say by releasing the arm from a different starting position. So, in the following, two examples are reported:

(A) Ranges by varying the releasing angle  $\gamma$

The results in Table 18.4 and Fig. 18.40 are referred to the same bundle torsion ( $\theta_{\text{and}} = 110^\circ$ ), and different  $\theta_r$  (i.e. by assuming a different releasing angle  $\gamma$  between the finger and the arm).

**Table 18.4** Onager range Figures;  $\theta_{\text{and}} = 110^\circ$

$\theta_r$ ( $^\circ$ )	$V_0$ (m/s)	$\alpha$ ( $^\circ$ )	Range (m)	$h_{\max}$ (m)	$V_f$ (m/s)	$\beta$ ( $^\circ$ )
65	35.72	73.99	63.8	57.3	33.9	74
75	43.66	65.1	132.2	74.6	40.2	67
85	52.3	52.5	229.7	80.1	45.7	55.5
95	61.4	32.46	293.5	50.5	50.6	36.7



**Fig. 18.40** Onager: trajectories for  $\theta_{\text{and}} = 110^\circ$

In the range Figure tables, in addition to the range, the following data are reported:

$\theta_r$  arm angular position when the projectile is released;

$V_0$  projectile initial velocity

$\alpha$  projectile initial direction

$h_{\max}$  maximum height reached by the projectile

$V_f$  projectile velocity at the impact

$\beta$  angle of the projectile at the impact

#### (B) Ranges by varying the bundle torsion

The results in Table 18.5 and Fig. 18.41 are referred to almost the same angle  $\gamma$  between the finger and the arm but adjusting the range by changing the bundle torsion ( $\theta_{\text{and}}$ ). From the previous tables and Figures, it is possible to observe that this war machine was capable of valuable performance permitting to throw a considerable projectile with a remarkable energy jumping over the walls.

Moreover, it is interesting to note that, generally, the range could be adjusted by changing the angle  $\gamma$ ; on the other side, the range can be also adjusted by changing the bundle torque obtaining more “flat” trajectories than the previous ones.

If a comparison with modern howitzers can be made, we could conclude that the ways to adjust the range essentially corresponds to both a variation of the gun barrel elevation and of the weight of the firing charge.

**Table 18.5** Onager: range figures;  $\theta_r = 95^\circ$

$\theta_r$ (°)	$V_0$ (m/s)	$\alpha$ (°)	Range (m)	$h_{\max}$ (m)	$V_f$ (m/s)	$\beta$ (°)
75	29.1	29.69	71.4	10.4	27.7	30.6
85	37.67	30.64	118.7	18.1	34.8	32.3
95	46.78	31.5	179.5	28.9	41.5	34
105	56.41	32.18	252.8	42.3	47.7	35.8
115	66.57	32.71	337.2	59.3	53.4	37.6

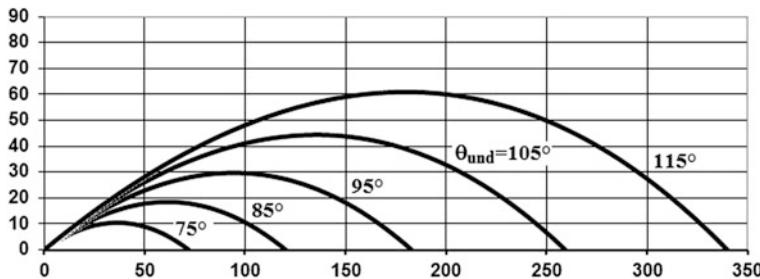


Fig. 18.41 Onager trajectories for  $\theta_r = 95^\circ$

#### 18.8.2.4 The Cheiroballista

According to several authors, the main dimensions of the machine are reported in Fig. 18.42; moreover, the most probable torsion motor of these machines was made by a helical torsion spring, shown in Fig. 18.42. This kind of motor, in fact, was compatible with the technology of those ages and was small and powerful enough.

For such a machine, an initial velocity of 104 m/s was computed with a projectile having 200 g of mass.

In order to evaluate the projectile range we considered two possible projectiles:

- A lead ball having 32 mm diameter and a mass of about 200 grams,
- A bolt having about the same mass and cross section.

In Fig. 18.43 the trajectories for the bolt are reported, considering an initial velocity of 104 m/s. As it is possible to observe, the trajectories are rather flat; this means a rather high possibility to hit the target even for little errors in estimating the real distance of the target itself.

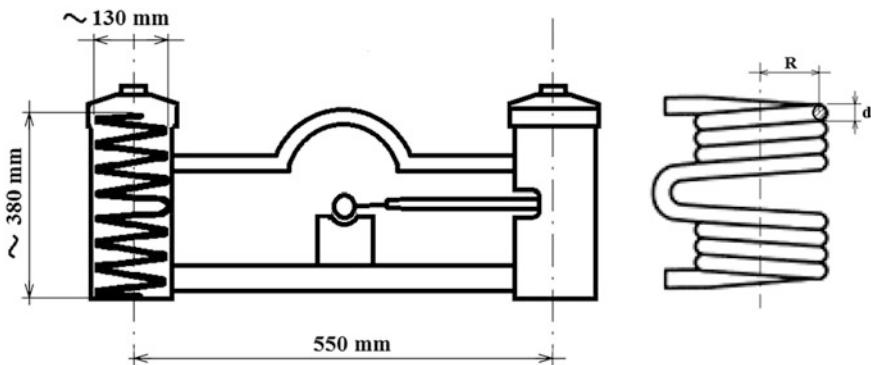


Fig. 18.42 Scheme of the Cheiroballista

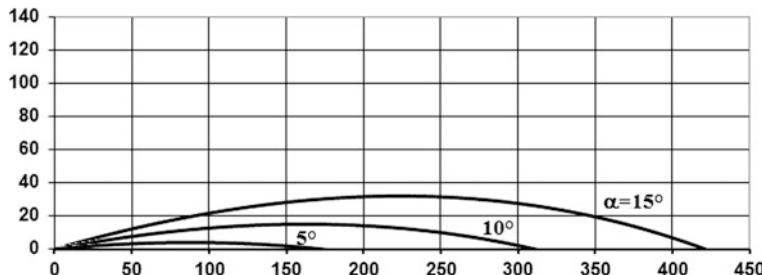


Fig. 18.43 Bolt trajectory

**Table 18.6** Range figures for lead ball

Elevation (deg.)	Range (m)	V <sub>f</sub> (m/s)	Impact energy (J)
5	165	84.4	712
10	290	72.5	526
15	385	65.3	426

**Table 18.7** Range figures for bolt

Elevation (deg.)	Range (m)	V <sub>f</sub> (m/s)	Impact energy (J)
5	172	89.3	797
10	310.6	79.4	630
15	421	72.7	529

In Tables 18.6 and 18.7 the range Figures are reported for a lead sphere and a bolt, respectively.

For comparison, 650 J is the energy of a 3.6 g bullet fired by a NATO 5.56 × 45 cal. ordnance rifle at 300 meters from the muzzle, while 500 J is the energy of a 8 g bullet at the muzzle fired by 9 × 19 cal. NATO ordnance pistol. Obviously, since those modern bullets are much lighter than the ballista projectile, their translational momentum, hence the shock at the impact, is much lower than the projectiles thrown by the carroballista.

## 18.9 Pneumatic Motors

The most common examples of ancient pneumatic motors are represented by pneumatically powered weapons.

As absurd as it may seem, the most remote ballistic method used to hurl projectiles implied the use of compressed air. Even before the rotating sling, the simple flexible arch and perhaps even before the spear, the human species learned how to

strike a close target with a jet of saliva or a small kernel, by expelling it using a forceful gust of air from the lips.

An essentially simple principle, but one that is extremely complex to exploit effectively, that is, to transform into a weapon or a tool. In an indefinable historical context some ethnic groups succeeded, making a propulsor, highly sophisticated in its apparent ingenuity, and perfectly appropriate to its intended use. This was the blowpipe, a slim cane that emitted a very small arrow by a strong puff of air. Its complexity is in the linearity of the cane, about 4 meters long, the perfect grip of the dart or arrow, achieved by slim rings and, the immediate lethal effect of its curare. With the exception of this last fact, a blowpipe meets all the criteria of a firearm: a gas that expands instantaneously in a cane, a projectile with an accelerating core, and an aiming device to strike the target. Since the expansion was not the result of instantaneous combustion, as is the case with gunpowder, it cannot be considered an actual firearm but a compressed air weapon.

Ethnologically, the blowpipe is the most recent individual launching device but it is not a launching weapon, as the lethal nature of its projectile, that is, the weapon itself, it is not the result of residual energy but of the poison it contains. Which forces us to defer the advent of a compressed air weapon almost to the modern era, specifically to the first half of the 17th century, in spite of the prior existence of a ballista activated by the thrust of compressed air.

### **18.9.1 *The Air Spring Ballista***

The label air spring ballista is highly suitable to a very special launching machine, invented and built by Ctesibius, but that cannot be considered an actual compressed air weapon as there is no emission of air. The air certainly did expand, but not in the cane of the weapon, nor did it come into contact in any way with the projectile nor was it aspirated from the exterior prior to compression, to be discharged immediately following expansion. As such, the weapon should be defined as adiabatic, lacking any exchange of gases with the outside, which is proven by the total absence of noise that would otherwise have been apparent upon launching. There is no mention of any sound or explosion, acoustic effects that if they had been apparent would, for the era, have been more terrifying than the shot.

The air in the motor of the weapon, whether compressed or expanded, was always the same that had been initially stored in the cylinders. It may have been periodically re-integrated but when in use the only thing that varied was its volume before and after firing, exactly like the variations of a helical spring inside a railroad buffer before and after impact.

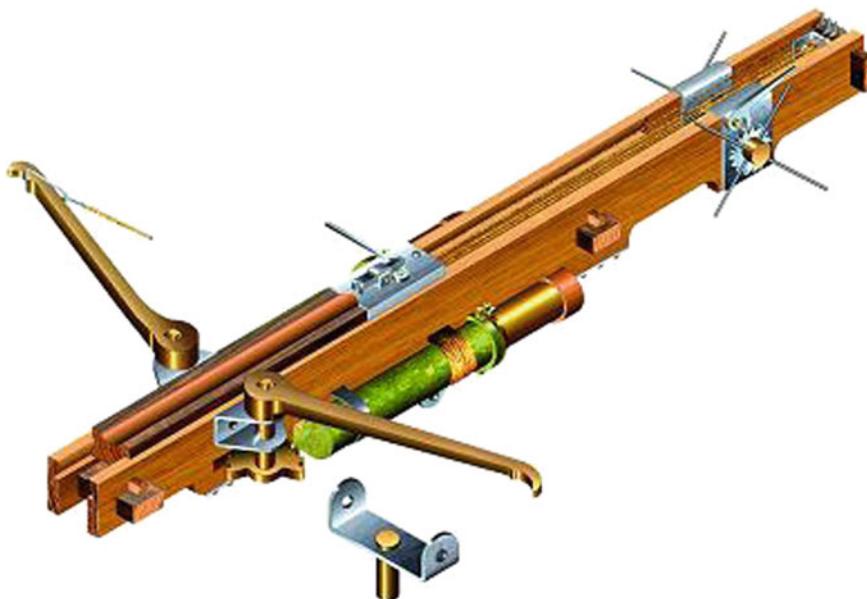
Philon of Byzantium was perfectly aware of this in the 2nd century B.C. Describing the weapon in his work *Belopoeica*, he defined it as an air spring ballista, aware of the function of the two cylinders with pistons, an additional

confirmation of the vast potential of Ctesibius' invention. After the double-acting pump, the fire fighting siphon and the organ, it was the turn of the weapon: achieved by making only minimum modifications to the usual cylinder-piston device.

In effect, the ballista propulsion device was achieved simply by blinding the cylinders, eliminating any exhaust hole, and permanently joining the pistons. Actually, even one cylinder would have been sufficient, but in that case in order to reach the correct volume it would have required a larger diameter and stroke, difficult to achieve at the time with any degree of precision. The basic principle of these weapons was the certainty of the absolute elasticity of the air, explained using the logic and terminology of the time. If the air is defined as the spirit, its initial volume was the greatness of the vase, and the expansion phase following compression defined as desire for the original state.

Archaisms and approximations that do not contribute to an easy interpretation of the description, but certainly do not obviate its understanding once we are familiar with the jargon. Thus we understand the reference to two sets of coaxial bronze cylinders, in which the interior diameter of the larger cylinder coincides with the external diameter of the smaller one, with a basically similar length. In effect, two cylinders with two pistons of equal length, all fused by an accurate wax mould.

In Fig. 18.44 is reported a virtual reconstruction of an air spring ballista.



**Fig. 18.44** Virtual reconstruction of the air spring ballista

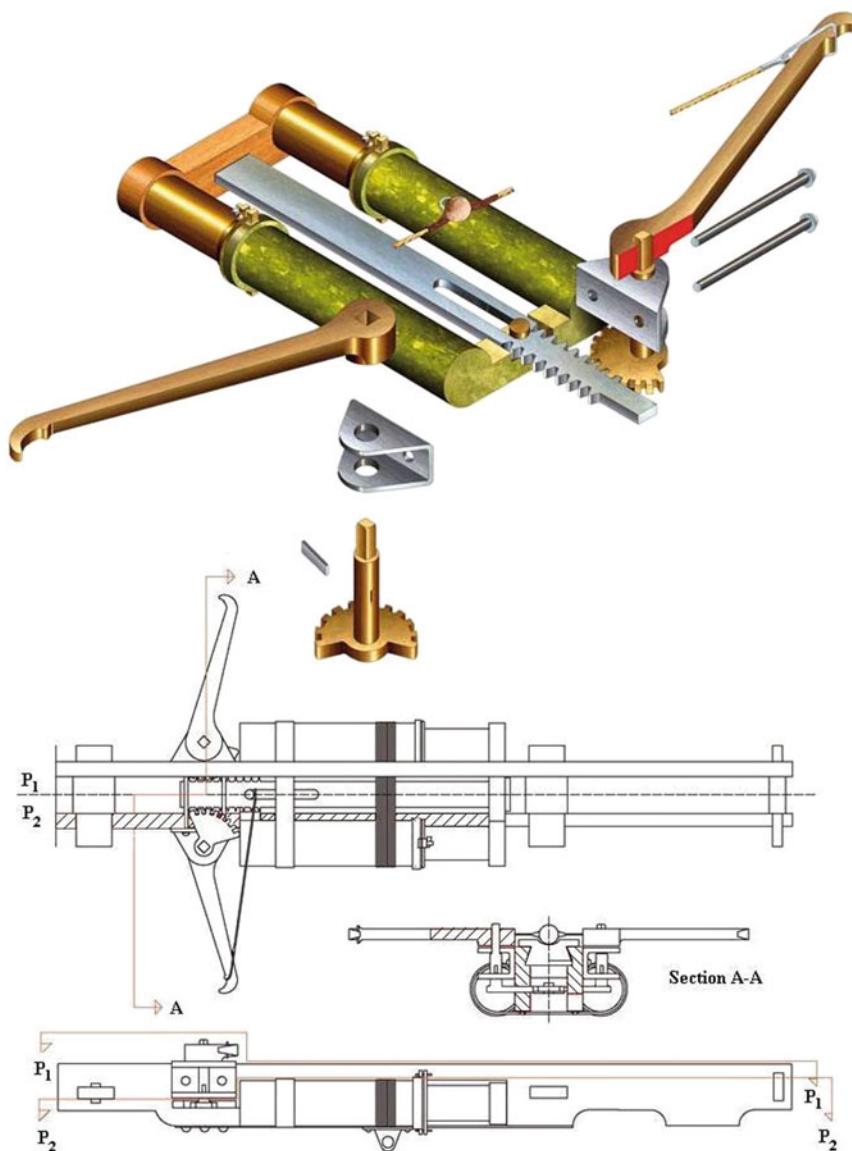
Philon stated that the cylinders were first hammered externally to increase their resistance, bored internally with a drill and then polished. As for the pistons, he mentions the geometric precision of the lathe enhanced by polishing. Since even the smallest tolerances cannot prevent loss of compression, recourse to gaskets is inevitable: Philon mentions two, one at the mouth of the cylinders and the other on the heads of the pistons, to prevent the air escaping. These were achieved by using an abundant layer of fish glue, which maintained its elasticity even when dry. In Fig. 18.45 are reported some details and an orthogonal drawing of the pneumatic ballista.

Philon continues that during the tests carried out by Ctesibius, he forced the cylinder's piston to violently release by applying a vigorous blow with a mallet. When it came out he was astonished to see that its internal gasket was on fire. But neither he nor his followers, almost up to engineer Rudolf Diesel, could know that a gas subjected to rapid decompression heats rapidly and abundantly. No one in the 2nd century B.C. had sufficient knowledge to describe such a prodigious event without having seen it personally. The fact that this effect could be achieved by the technological potential of the era, is evident from the existence of a pneumatic flint among some primitive ethnic groups in south-east Asia; it consists of a wooden cane containing a rudimentary wooden piston, to which a bait is attached. When the flint is lowered suddenly and unexpectedly it immediately catches fire. The violent compression causes combustion. It is impossible to ascertain today whether there was some cultural connection between the two in the remote past.

But the phenomenon does confirm the truth of the tale, the probable pressure reached by the air in the cylinders and, implicitly, their dimension. Which, with obvious reservations, lead to the conclusion that the cylinders had a diameter of a dozen or so centimetres and were approximately half a meter long. As for their conformation, we know from Philon that they were fused jointly at the base so that by forming a single body they could react jointly to any solicitation.

Once completed, the two Siamese cylinders with their respective pistons, were placed underneath the shaft of the ballista, using iron rings. Their location is confirmed by Philon's observation on the ballista's resemblance to an organ. A joint, probably serrated, was applied to the base of each of the pistons, not incidentally called clog. This allowed the two arms of the weapons, somewhat similar to those of a bronze spring catapult, to enter the cylinders. The usual loading crank was inevitable, as was the oscillating pawl release mechanisms: Philon does not mention them at all, thus confirming the conclusion.

Perhaps because of its complexity, or its difficult maintenance, perhaps because of its excessive cost, the pneumatic ballista does not appear to have had much success. Since it was totally immune to water, it may have been used on war ships but neither can we exclude that it may have remained a simple curiosity. An antithetical discourse in the scientific context: that strange ballista aroused great curiosity from the very beginning and, over time, instead of disappearing it became a sort of legend.



**Fig. 18.45** Details and orthogonal drawing of the pneumatic ballista

## 18.10 Small Spring Motors

If Roman metallurgy had difficulty forging good quality steel plates, it did succeed in making small steel listels of excellent elasticity. A large number of tempered steel springs were produced and used as return springs for release mechanism devices,

such as locks and padlocks. That this was a production of more advanced technology is proven by the fact that they were made not by the usual common blacksmith, but by a “magister clavarius” (master keymaker), a specialised technician.

For a capitalist society the lock in all its variants was a necessity, from the highly common ones for the doors to houses, to the more complex used for strongboxes and safes, as well as the vast range of padlocks of all sizes and resistance. Both had two things in common: a key and a return spring.

### **18.10.1 Locks and Padlocks**

The Roman lock of the Imperial Era had a traverse key. Mechanically it wasn't wholly secure, nor was it a novelty as it had existed for centuries. A great number of these keys were found in the Mediterranean area, especially in Pompeii and Ercolaneum (Italy). In Fig. 18.46 are reported some finds, a key with a lock plate, and a virtual reconstruction of the lock.

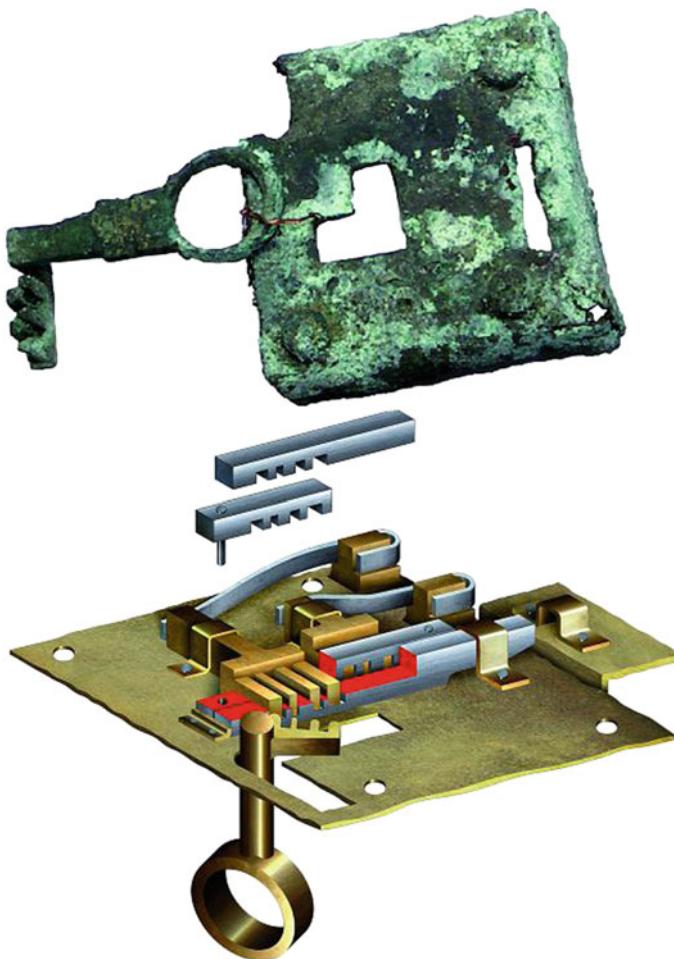
It had a very simple mechanism: a steel spring was attached to an iron plate that exercised pressure on movable counterpins. These had a unique shape, also called cipher, that made the lock and its key unique. The same shape, but perforated, was made inside the lock: thanks to the spring, the counterpin could penetrate the lock's cipher but only when there was an exact correspondence at the limit stop. In this manner the lock was blocked and could only be opened with a key. The key, fashioned with the same cipher as the counterpins, was inserted into the keyhole but from the side opposite the counterpins, pushing them outwards. At this point, by inserting the key into the horizontal slit of the keyhole it pulled the lock, opening it. Once the manoeuvre was completed, the key could not be extracted and remained in the lock until it was once again closed. The role played by the spring is obvious since without it the lock would not work.

There were also single return locks very similar to ours. In these, the key had a special mapping corresponding to the lock, when it entered the keyhole and rotated around a central pin it moved the lock, opening and closing it. Many had a keyhole shaped in such a manner as to prevent the introduction of other keys.

In these locks also, the spring stopped any oscillation of the lock and was fundamental to its functioning.

It is narrated that the lock patented by Linus Yale (1821–1848) in 1860 is based on a mechanism that was used by the Egyptians more than 4000 years ago; the mechanism of the Roman lock also reminds us the famous Yale lock.

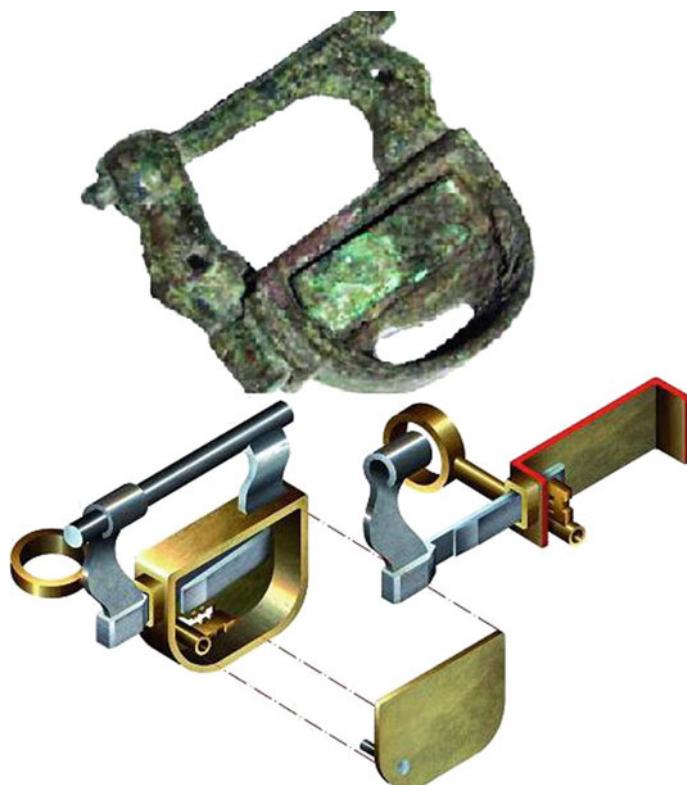
The Romans, like all people that travel often and systematically, used a large number of minuscule portable locks, better known as padlocks. Their production reached a variety and usefulness that was absolutely exceptional and unequalled until our day. Contrary to normal locks, the padlock did not require a door panel to which to be attached: a chain was sufficient. But like locks it, too, was activated by a key and a spring: at times the former was replaced by a stylet, shaped to enter through a special hole and remove the catch of the eyelet or lock.



**Fig. 18.46** Roman lock, finds and virtual reconstruction

One of these padlocks was called the Pompeian, for obvious reasons. The numerous specimens unearthed had an iron covering, some rare ones of bronze, with a central keyhole and an actual lock inside. The key released a long bolt, opening the door. This type of lock was used for less important doors, such as grain storage sites. In Fig. 18.47 is reported a find at Pompeii and a virtual reconstruction of it.

Other types of padlocks were very similar to ours, with an eyelet closing. The key would either lift or rotate the eyelet to open it, according to the model. These also had a spring to ensure the stability of the closing mechanism. In Fig. 18.48 is reported a find of a ring padlock and a virtual reconstruction of the padlock and a detail of its mechanism.



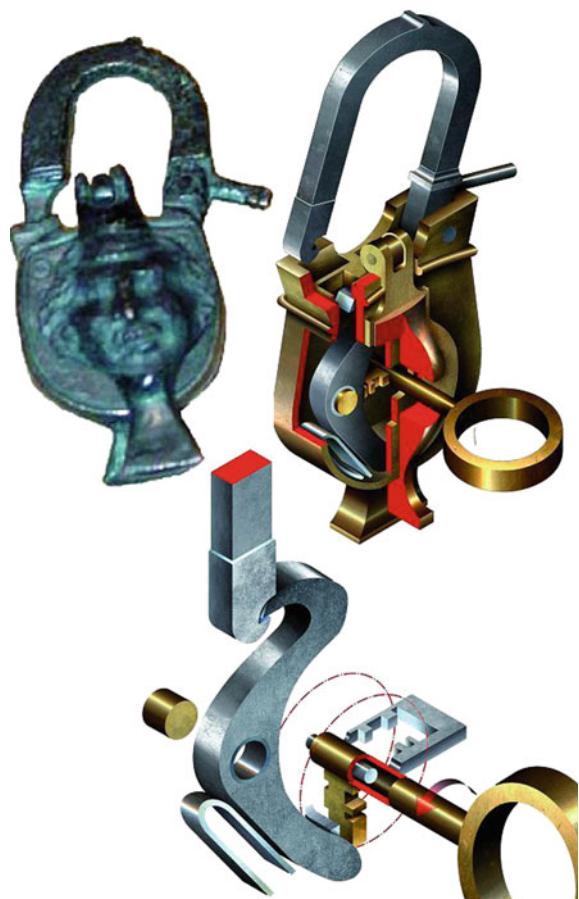
**Fig. 18.47** Pompeian padlock: a find and a virtual reconstruction

## 18.11 Ancient Steam Engines

The first motor as we understand it today was a curious steam turbine, called ‘wind ball’. Although it later underwent several modifications, it remained basically a toy. For another steam machine to be used as a reliable and systematic means of transportation, we will have to wait for Fulton’s steam boat, almost two thousand years later.

Our pragmatic and speculative mind finds it repugnant to think of conceiving devices of significant complexity and importance without a specific need and for no other reason than pure pleasure. Just as we find it difficult to imagine revolutionary technological processes and machines for the good of humanity, blocked at the amusement stage for well-to-do adults free of any work commitment. And yet this was the attitude of the greatest intellectuals of the classical era regarding some of their most advanced work. It explains the apparent paradox behind the many inventions that have changed the world in the last 2 centuries, inventions that would serve as the basis for inventions two thousand years later.

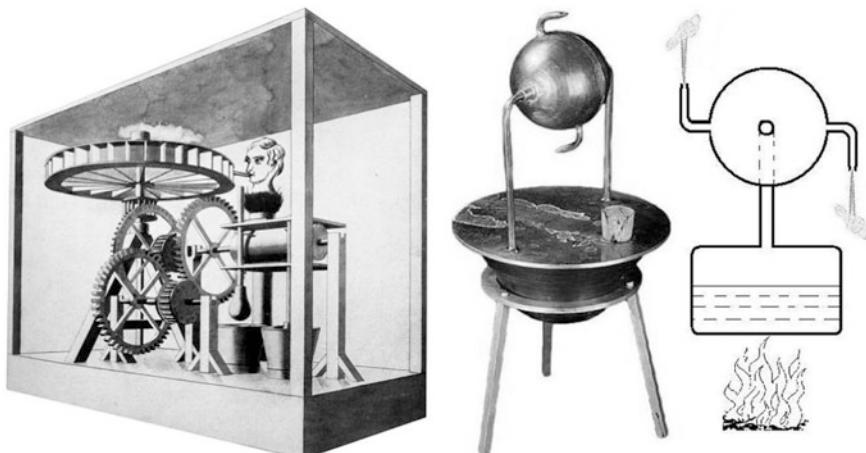
**Fig. 18.48** Ring padlock: find, virtual reconstruction and mechanism



### 18.11.1 Heron's Steam Turbine

It is no surprise therefore that around the 2nd century B.C. Hero of Alexandria conceived and made two very small, but revolutionary steam turbines of which one was a reaction turbine. Aware of the dynamic power of steam because of his multiple experiments and inquiries, he examined its use as a fluid for motors. In so doing he noticed that by placing a hermetically sealed metal container with a small hole, partially filled with water, over a flame, a whistle would soon announce the exit of steam. By placing a small paddle wheel in front of the jet of steam the paddle rotated rapidly, until all the water was consumed. Hero could never imagine that machines operating by a similar principle but of monstrous power, would provide most of the energy to the future metropolis.

Not satisfied with that first significant demonstration of the dynamic power of steam, he conceived a second object that was even more stupefying for the era. The



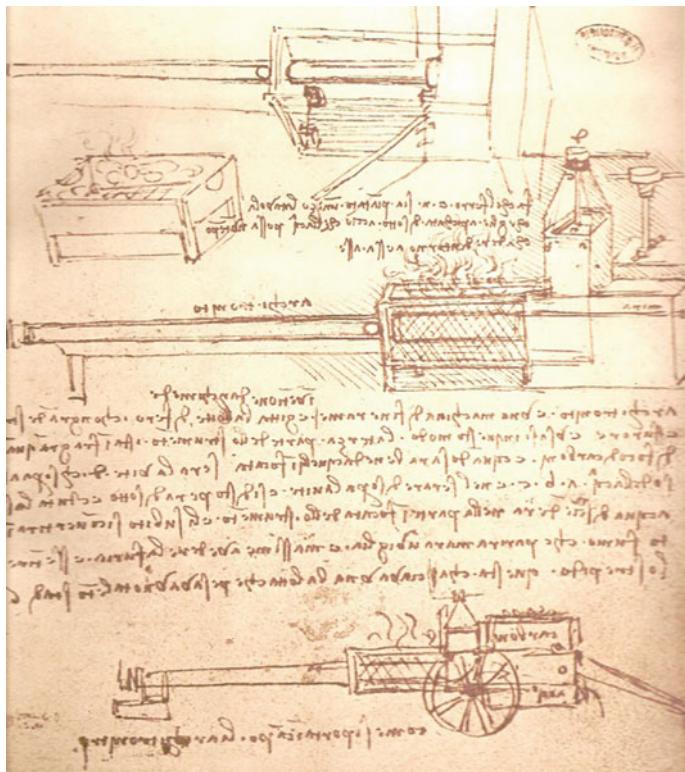
**Fig. 18.49** Heron's steam turbines

stimulus was provided by the observation that when this ‘boiler’ emitted steam, it moved slightly in the opposite direction. The phenomenon was not a novelty as the same thing happened with a floating bag when it deflated on a body of water. Studying the two analogies, he built a hollow sphere of bronze, equipping it with an axis and four nozzles angled on the related equator. When the sphere was partially filled with water and the axis placed on two forks, he placed the singular device on a brazier. Steam soon began to issue violently from the nozzles, causing a torque reaction on the container-boiler, making it rotate. Hero may have intuited the reason, he may even have imagined its importance, but he could in no way prognosticate its applications, limiting himself to calling that curious toy eolipile, wind ball. In Fig. 18.49 are reported reconstructions of Heron’s steam turbines: on the left a drawing by Fausto Veranzio (1551–1617), already mentioned in Chap. 9 for a water mill, showing his reconstruction (Mola turris rotunda, tav. XIII, Machinae Novae, Venice, 1695) of Heron’s steam turbine and on the right a reconstruction of the eolipile.

He never knew that the whistling top was the debut of a new type of rotor: his wind ball, in fact, was the archetype of the reaction turbine. He could never have imagined that on this action-reaction principle a motor would have been built that, 20 centuries later, would allow men to walk on the moon.

### 18.11.2 *The Architronitro*

According to the Greek-Roman concept of motor, a device that throws objects is a motor. Also from a modern point of view, a gun is a thermal machine. The device described in this paragraph is a steam cannon.

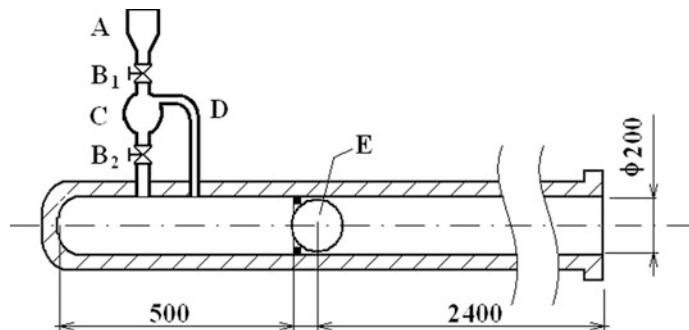


**Fig. 18.50** Architronito by Leonardo Da Vinci (Ms. B, f. 33 v)

At the end of the 15th century, Leonardo Da Vinci drew a steam cannon that he ascribed to Archimedes and that, for a tribute to Archimedes, he called “architronito” (Thunder of Archimedes); the drawing is shown in Fig. 18.50. On the same folio is reported the working principle. In Fig. 18.51 a scheme of the steam cannon is shown. The working principle can be explained as follows: a proper amount of water is put in the reservoir A, then the valve  $B_1$  is opened and the water fills the tank C. Next the valve  $B_1$  is shut and the valve  $B_2$  is opened: the water flows in the chamber of the cannon and vaporizes. Through the pipe D, the pressure in the tank C is equalized to the one in the chamber of the cannon. The steam pressure throws the ball E outside the barrel.

The Greek origin of the device drawn by Leonardo da Vinci is demonstrated also by the units of measurement he reports that are ancient Greek units unknown in Italy in those times.

Before Leonardo Da Vinci, several authors described similar devices; among them Francesco Petrarca (Petrarch 1304–1374) that, in a minor work (*De Remediis Utriusque Fortunae*) describes a steam cannon more than 1 century before Da Vinci.



**Fig. 18.51** Scheme of the Architronito

The Greek historian Plutarchos (Vite parallele, vol. II, Pelopida and Marcello 14–15) tells that, during the siege of Syracuse, when the Romans saw something similar to a pole protruded from the walls ran away shouting: “Archimedes is going to throw something on us now”. Now, no ancient throwing machine looks like a pole. In a piece by Niccolò Tartaglia (Italian mathematician, about 1499–1557) is reported that Valturius (Roberto Valturio, Italian engineer and literary man 1405–1475) “... States that ... there are many references to Archimedes having designed a device made from iron out of which he could shoot, against any army, very large and heavy stones with an accompanying loud report.”

Finally, as it was already remarked by several investigators, no mention about burning mirrors was made by the historians of the Greek-Roman era but this legend appears only during the middle age.

As for the burning mirrors, it must be told that in some experiments (1973 Sakas and Stamatis and 2005 MIT) were used a number of plane mirrors and little boats or mock-ups were really burned; nevertheless a practical use of such a device during a battle seems not very realistic. In fact it must be considered that in the experiment by Sakas and Stamatis about 50 sailors of the Greek Navy were necessary to point the mirrors and in the experiment at the MIT 300 mirrors were used; in addition, in both cases, the target was absolutely motionless. Very different conditions take place during a battle, hence it is difficult to believe that a big number of mirrors can be pointed on a moving target efficiently.

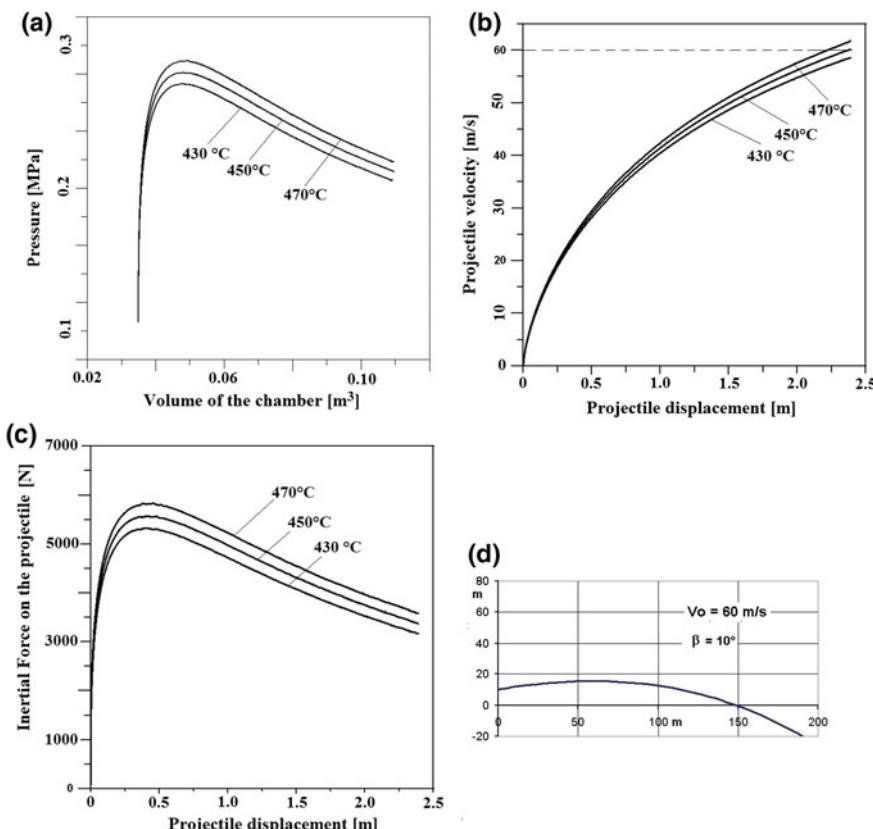
The authors supposed that such a cannon could have thrown hollow clay balls filled with an incendiary mixture called “Greek Fire”. The possibility that the roman ships were burned by Archimedes by means of something like the famous “Greek fire” is also suggested by Simms (1991), who reports that Galen (Aelius Galenus or Claudius Galenus or Galen of Pergamum 129–216) in his *De Temperamentis* says that “... Archimedes set on fire the enemy triremes by means of pureia ( $\pi\upsilon\rho\epsilon\alpha$ ).” Now, this word in ancient Greek indicates something used to light fire or can be translated as “brazier” but not as “burning mirror”.

To evaluate the feasibility of such a device, the authors computed the pressure diagrams in the cannon and the ball range Figures. The cannon dimension are those reported in Fig. 18.51 while the following assumptions were made:

- internal volume:  $0.111 \text{ m}^3$ ;
- minimum volume corresponding to the initial ball position:  $0.035 \text{ m}^3$ ;
- mass of water introduced inside the cannon:  $0.11 \text{ kg}$ ;
- mass of the projectile:  $6 \text{ kg}$ ;
- cannon temperature in three cases:  $430, 450, 470 \text{ }^\circ\text{C}$ ;
- friction between projectile and barrel:  $50 \text{ N}$
- heat transfer coefficient to the water:  $10 \text{ kW/m}^2\text{K}$

Considering a tangential inflow of the water, the heat transfer surface was considered as the internal surface of the cannon and the breech.

The results obtained from the algorithm are summarized in Fig. 18.52.



**Fig. 18.52** Simulation results for the Archimedes' Cannon: **a** the pressure volume diagram; **b** the projectile velocity versus its displacement along the barrel; **c** the inertial forces (in N) acting on the projectile along the barrel; **d** the projectile trajectory for a muzzle velocity of  $60 \text{ m/s}$  and a barrel elevation of  $10^\circ$

In the introduction we said that any argument is based on three historical proofs (literary, iconographic and archaeological) in this case just the literary and iconographic proofs are available but no object. In this case, our intent was to demonstrate that Archimedes could have designed and built such a device that was suitable to successfully attack the Roman ships. Moreover, in our opinion the steam cannon was much more likely than the burning mirrors.

### Observations

The existence of a pneumatic ballista shows that air weapons are much older than one can commonly think, but it was an arrow thrower weapon. Pneumatic weapons such as rifles and guns were invented later. The oldest were built around 1644 by Hans Köhler at Kitzingen. In Fig. 18.53 is shown a pneumatic rifle built at the beginning of the 17th century (from Rei W., 1976, The Lore of Arms, ABNordbok). Few decades later, in 1779, Bartolomeo Girardoni (Cortina d'Ampezzo, 1729–1799) designed a compressed air rifle. Two thousands rifles were adopted by some Jaeger units of the Austrian army as model 1780. Its caliber was 13 mm with a muzzle speed of about 300 m/s, the barrel was rifled and the air tank capacity was about 500 ml. The rifle could shoot 20 shots very quickly and was certainly effective since Napoleon's army ordered to execute by firing squad anyone owned that rifle.

For a wider autonomy of fire, the gun had interchangeable air tanks.

In 19th century also pneumatic cannons were developed. At the end of the 19th century it was still difficult to develop a reliable high explosive projectile because the explosives that were used as propellant (black powder or TNT) could cause premature detonation, of the charge in the projectile itself, due to the set-back shock when the gun fired. For this reason it was thought to use compressed air as propellant. Reliable air cannons were designed by Edmund Louis Grey Zalinsky. The latter was born in Kurnick in Prussia (now Poland) in 1849 but emigrated to the USA when he was four years old with his parents. He became an officer of the US

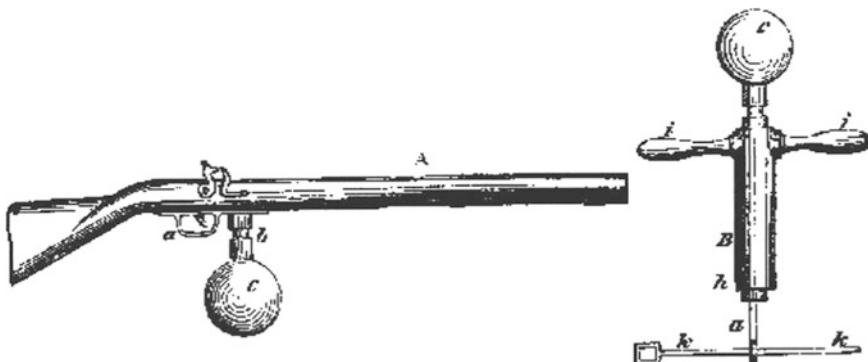


Fig. 18.53 Pneumatic rifle

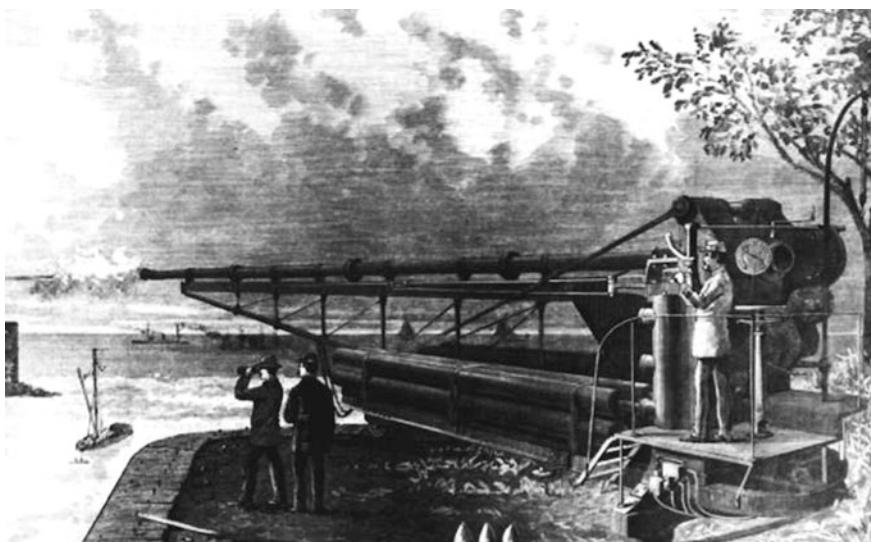


Fig. 18.54 Pneumatic cannon

artillery during the civil war and then professor of military science at the Massachusetts Institute of Technology; he died in 1909.

Zalinsky's guns were called "pneumatic dynamite torpedo guns" and widely tested by the US Navy, both on ships and in coastal defence installations. In Fig. 18.54 is reported one of these weapons the caliber of which was 381 mm. Tests demonstrated that, for shipboard use the gun was not very effective because, with the ship mounting, the barrel was fixed and hence the pointing had to be made by orienting the ship and the range should be adjusted by varying the air pressure (Fig. 18.54).

Between the end of the 19th century and the beginning of the 20th century, rapid improvements in propellants and projectiles were achieved; this eliminated the problems that had suggested this invention and pneumatic guns were withdrawn from service.

# Chapter 19

## Spinning and Weaving

**Abstract** In this chapter the evolution in spinning and weaving is presented, starting from the very ancient hand operated spindle and distaff, till the machines of the industrial revolution. What above can also explain how it was possible to obtain low cost fabrics and clothes in the last centuries.

### Introduction

Cloths are among the most important and most useful objects of common use by mankind; also, the development of cloths is a milestone in the history of human civilization since it can be considered a first step towards technology.

### 19.1 The Dawn of Spinning and Weaving

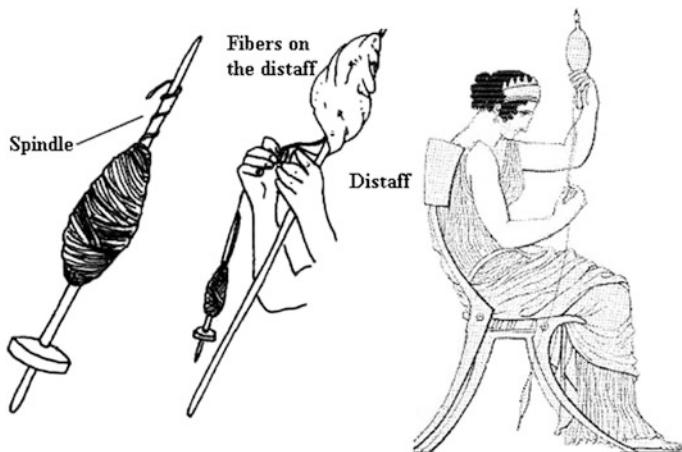
Almost all our cloths are woven; nowadays it is taken for granted that woven material exist and are rather cheap and has been available for barely two centuries.

It is well-known that weave is made by spun yarns that are joined together by weaving; this technology date back to the Neolithic. From the III millennium B.C. the spinning by spindle and distaff was certainly carried on in many parts of the world.

The first method used to obtain a spun yarn from natural (animal or plant) fibres is hand spinning that is one of the oldest human industries; it was still carried on in the European countryside (generally by women) till a few decades ago and is still used in several countries of the Third World.

Hand spinning principle is made by using two tools: the spindle and the distaff. Spindles are rather similar in all the civilizations and essentially consist in a cylindrical tool that can rotate around its axis.

In Fig. 19.1 is schematically shown the spinning process and a woman spinning with spindle and distaff from a painting on a Greek pot. The natural fibres are grouped on the distaff and, by one hand, are stretched in a thin band of quite parallel fibres and the band is tied to the spindle. Since natural fibres are relatively short, in order to obtain a strong enough yarn, it is necessary to twist them. A fast spin is given to the spindle by the other hand or by rustling it on the external of the thigh;

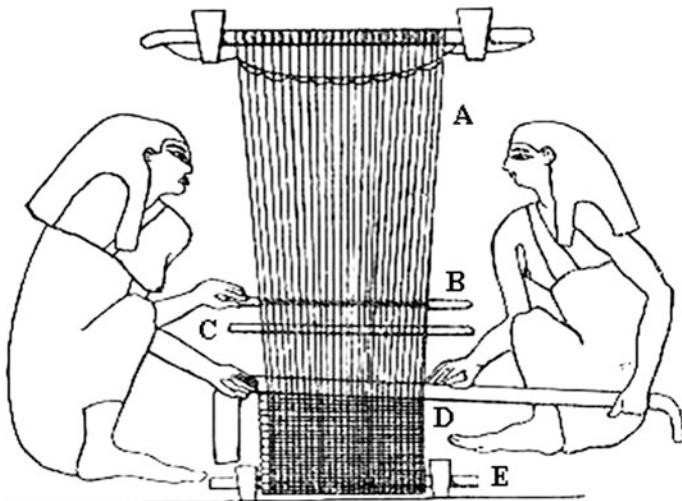


**Fig. 19.1** Spindle and distaff

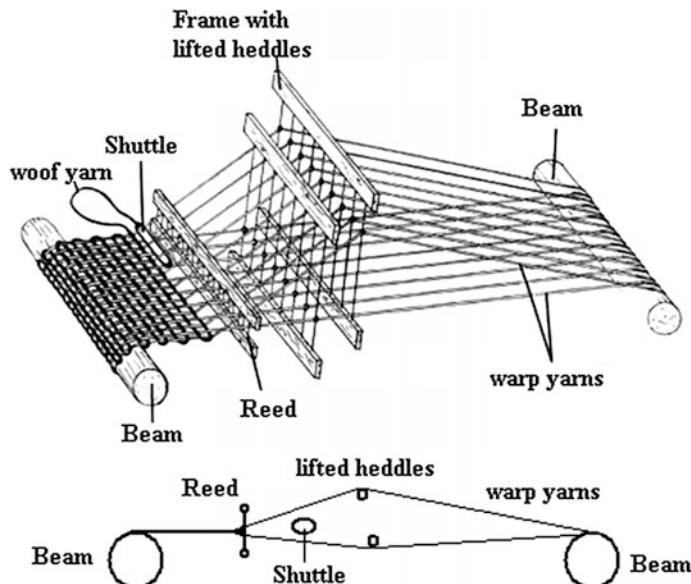
the spin of the spindle gives the band of fibres the desired twist. While the spindle goes down, some other fibres are stretched from the distaff. Once in a while, the spindle is stopped and the twisted yarn is bound onto it.

It is evident that in this way it is possible to obtain only a few hectograms of yarn a day, that is a very low amount.

Once the twisted yarn is obtained, the weave is made by weaving the yarns by the loom. Obviously the loom is as old as the spindle. In Fig. 19.2 is reported an Egyptian loom from the tomb of Chemhòpte at Beni Hasan, XII dynasty (1976–1784 B.C.).



**Fig. 19.2** Ancient Egyptian loom



**Fig. 19.3** Working principle of the loom with heddles

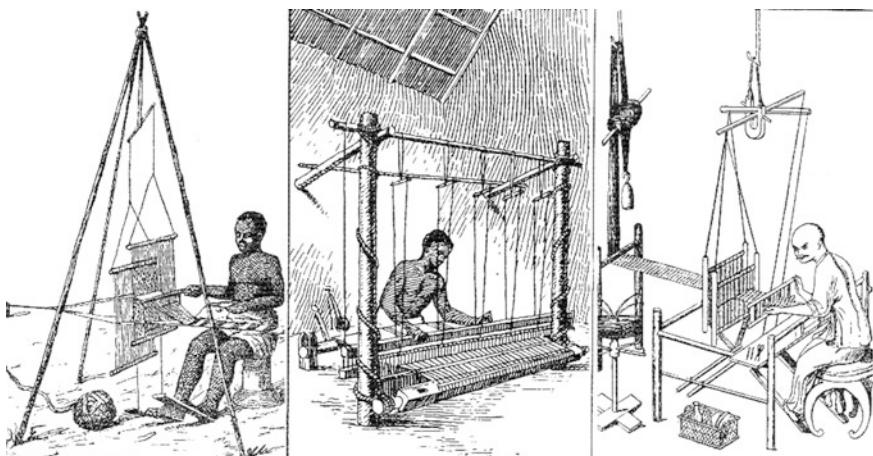
A number of parallel yarns A disposed on a frame, these yarns will form the warp. The weaver threads a shuttle B on which the yarn woof is bound through the warp yarns to make the woof. Before the Shuttle is threaded, one half of the warp yarns are lifted by a tool C. Once the shuttle has been threaded through the warp, the woof yarn is tightened by the reed C. The weave is rolled on roll D.

In ancient times the materials were not woven having a standard width and undefined length that can be joined by seams like nowadays. Hence, ancient Greek and Roman looms were built in different sizes because each cloth was weaved in one unique piece having well defined dimensions.

The early loom permits a low production because a considerable amount of time is requested to alternately lift the warp yarns. Devices to alternately move the warp yarns are made of wires (the heddles) linked to rings. The warp yarns pass through these rings and a couple of frames alternately move the heddles up and down; the frames are generally moved by pedals. In Fig. 19.3 is reported the working principle of a loom with heddles; the working principle is the same of the modern looms.

In Fig. 19.4 are shown some looms with heddles; the one on the right is African, the one in the centre is Indian, the one on the left is Chinese.

One of the oldest looms with heddles is the Indian one in the previous Figure; in it the heddles were moved by strings tied to the weaver's feet, the latter were put in a hollow that was dug in the ground under the loom.



**Fig. 19.4** Looms with heddles

The oldest attestation of a pedal operated loom was found in a Monastery near Thebe, Egypt that was established by Ephiphanius around 333 A.D. The excavations were made by expeditions from the Metropolitan Museum of Art in 1912–14 and showed foot powered looms used in the early centuries of the Christian Era.

## 19.2 The Spinning Wheel

The first step to increase yarn production is represented by the invention of the spinning wheel. In Fig. 19.5 is shown a castle (vertical) spinning wheel and a detail of the flyer.

A spinning wheel essentially consists in a wheel A that is moved by a foot treadle B through a rod C and a crank D; the last three pieces form a four bar mechanism. The wheel, that functions as a flywheel, transmits the motion to the flier E through a drive band F. The fibres G, coming from the distaff H are twisted by the flier rotation and bond on the bobbin I. Generally, the flyer has two pulleys in order to change the speed ratio depending on the type of fibres and the yarn count. In the spinning wheel the twist is given by the rotation of a mechanically operated device: the flyer.

This device appears in Europe in the 18th century and perhaps was invented in India a short time before.

With the spinning wheel, that is still used and manufactured nowadays, it was possible to significantly increase the production of yarn.

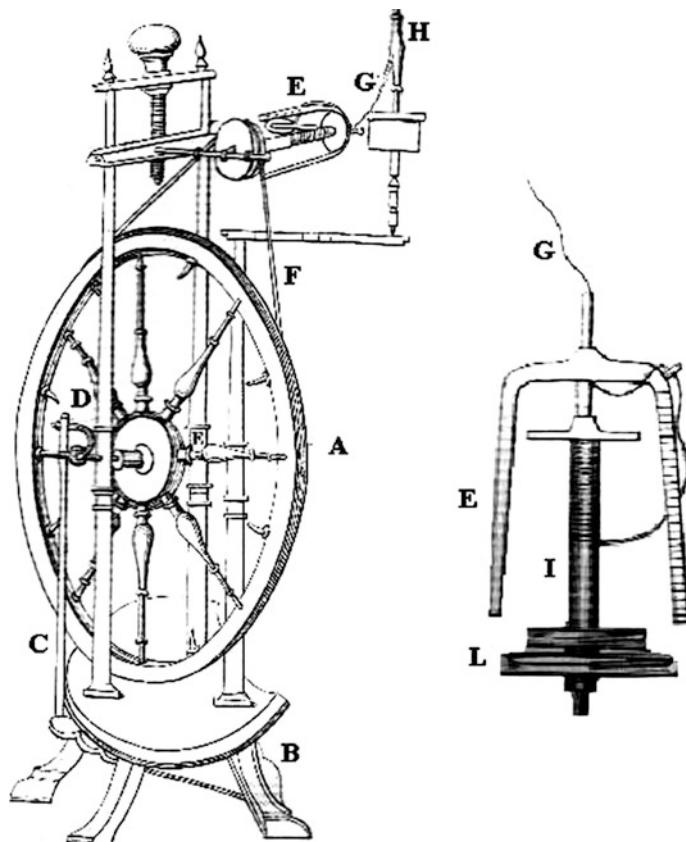


Fig. 19.5 The spinning wheel

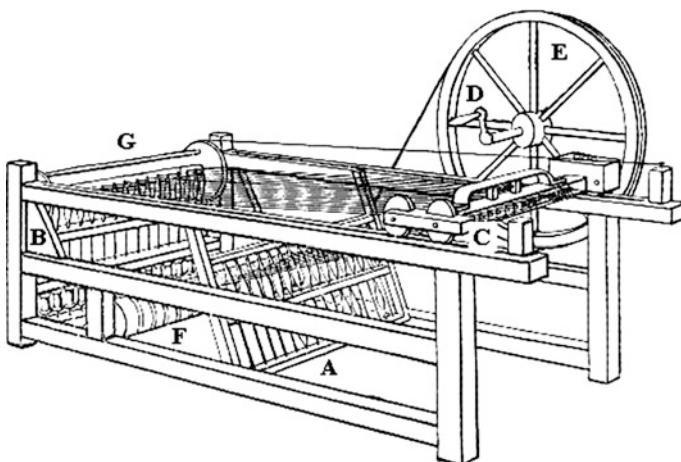
### 19.3 The Mechanical Spinning

Although the spinning wheel has some mechanical components, the fibres have to be stretched by hand before the twisting. This aspect and the presence of just one flyer does not permit the large amount of yarn needed in Europe in 18th century because of the population growth.

In the hundred years from the middle of the 18th century and the middle of the 19th century the basic machines for the modern process of spinning were invented.

#### 19.3.1 The Spinning Jenny

In the previous centuries some experiments were made in order to increase the number of flyers (e.g. some drawings from Leonardo Da Vinci show spinning



**Fig. 19.6** Spinning jenny

machines with two fliers) but such devices had, normally, no more than two flyers. A significant increase of the yarn production was obtained by the spinning jenny that was invented by James Hargreaves (1820–1878), a weaver from Lancashire, England between 1764 and 1767.

A legend tells the meaning of the name “spinning jenny”: Hargreaves daughter Jenny knocked over a spinning wheel and he watched the spindle that, while it was rolling across the floor, continued to spin the yarn. This gave him the idea of the machine; elsewhere it is reported, instead, that Jenny was the inventor’ wife. In any case the legend narrates that this episode suggested to Hargreaves that the spindle could spin the yarn in a machine in which its axis was vertical. Since he was also a good carpenter, he built the first machines himself. A spinning jenny is reported in Fig. 19.6. The roves made by parallel fibres are bond onto the bobbins A and pass through a press C that can be widened or grasped by the operator and then go to spindles B. The press can be moved along the frame of the machine; once the roves are grasped in the press the latter is taken away from the spindles, in this way the roves are stretched in order to obtain the desired yarn count. The worker does this operation with his left hand while his right hand rotates the crank D of the wheel E; the latter rotates, by a dive band, a horizontal cylinder F and from this the spindles are rotated with a band for each of them.

When a desired number of twists is given, the press is brought back to the starting position and the yarn is bound onto the spindles. On the spindles is located a stick G that keeps the yarn over the conical points of the spindles; this permitted the yarn to continuously slide on the points and hence the yarn was twisted and not wrapped.

The yarn production by this device was much higher than ever before; the first machines had eight spindles but soon machines were made with up to eighty spindles. Originally Hargreaves built machines just for his family and did not patent

his invention till 1770, therefore others copied the spinning jenny without paying him any money. Later, when he began of sell the machines, spinners from Lancashire, being afraid of lose their job, destroyed all Hargreaves' equipments.

In the spinning jenny are present all the elements of the modern self-acting: stretch, twist and intermittent binding. The stretch, however, wasn't obtained by couples of rolls having different speeds as it is done nowadays. This last invention was made by L. Paul in 1738, just before the invention of the spinning jenny but was probably not known by Hargreaves; nevertheless he has to be considered among the main precursors of modern spinning.

It has to be said that the yarn obtained by the spinning jenny generally was not strong enough to be used for the warp but it was only used for the woof.

### ***19.3.2 The Spinning Frame by Arkwright***

In 1768 sir Richard Arkwright (1732–1792) invented the spinning frame and patented it in 1769; for his work he was knighted in 1786. This device, later named water frame because it was moved by water power, could produce yarns thin and strong enough to be used for the warp. In Fig. 19.7 is reported a drawing of an Arkwright spinning machine.

The roves are bond on bobbins A pass through the rolls B; since the latter rotate at different speeds (lower the first couple and higher the last one) the rove is stretched up to ten times the length it had on the bobbin, hence its count becomes up to ten times lighter. The rolls are pressed by means of strings, levers and weights C. Then the stretched rovers were twisted by the fliers D and bond on spindles E. The rolls were made of bronze and covered with leather.

The device was also known as "throstle" probably because of the noise the fliers made.

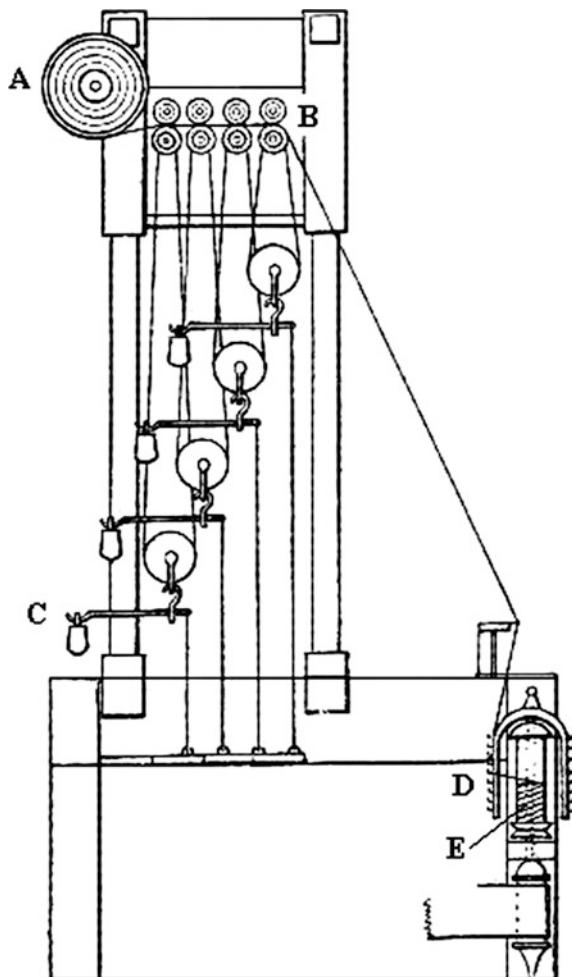
### ***19.3.3 The Mule by Crompton***

Both the spinning jenny and the spinning frame was outperformed by a new machine patented in 1779 by Samuel Crompton (1753–1827); the device was named mule or mule-jenny since it was a hybrid (like a mule) between the spinning jenny and the spinning frame.

In Fig. 19.8 is reported a mule-jenny built in 1812.

This device combines the spinning jenny and the spinning frame in one machine; that is to say the twist was obtained by the spindle rotation and the stretch by rollers. In Crompton's machine, on the contrary to the jenny, the spindles are located on a moving carriage while the rolls are fixed. As soon as a suitable rove length passed through the rolls, these last were stopped and the carriage was moved away from

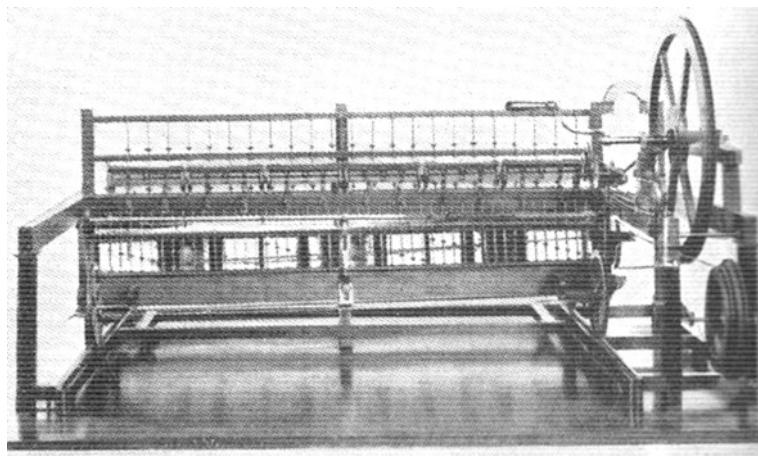
**Fig. 19.7** Arkwright's spinning frame



the rollers about 1.4 m, then the twisting began. Once the twisting was completed, the carriage was pulled back while the yarn was bound onto the spindles.

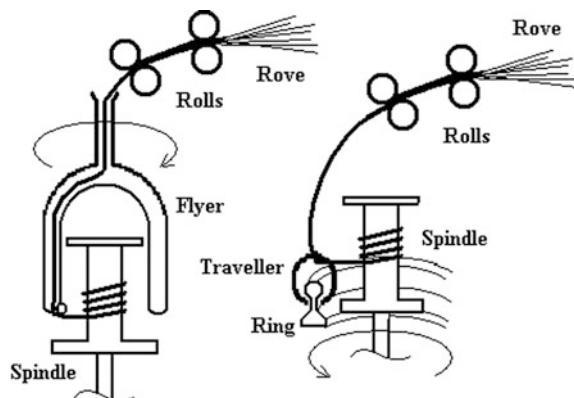
#### 19.3.4 The Ring Frame

The last invention in mechanical spinning can be considered the ring frame that was invented in 1828 by John Thorp (1784–1848) and developed by Manson in 1830. In Fig. 19.9 are reported, for comparison, the working principles of a flier spinning machine and of a ring frame; both types use rolls to stretch the rove and are commonly used nowadays. In the first type the flier rotation causes the twisting and



**Fig. 19.8** A mule jenny

**Fig. 19.9** Working principles of spinning machines



the binding of the yarn on the spindle, as it was done in the spinning wheel and in some subsequent machines. In the second one no flier is present, the rove A, coming from the rolls passes to a guide B and then through a traveller C that can run in a circular rail D located around the spindle, the ring. The spindle rotates and drags the yarn and the traveller. Because of the centrifugal force, the yarn takes a particular shape called balloon. The ring frame has the advantage of simplicity because no high speed rotating flyers are present; generally it is preferred to produce very thin cotton yarns.

Nowadays the spindle rotates up to 18,000 rpm. and the traveller speed is up to 25 m/s, but since the invention of these devices, no very significant inventions have been made in this field.

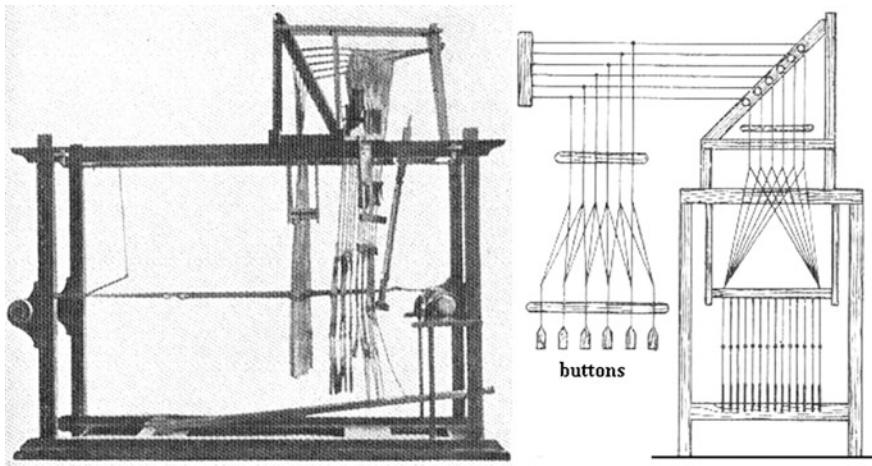
## 19.4 The Automatic Weaving

Once it was possible to obtain a wide production of yarns, the loom too had to increase its production. This was achieved by inventions in the field of automatic looms. In the following paragraphs the authors summarize the main steps in this field.

### 19.4.1 The First Programmable Loom

Generally the first programmable loom is considered the one by Jacquard or a similar device by Vaucanson, who also invented the automata “the duck” reported in Chap. 16. Really the first example of a precursor of the programmable loom dates back to the end of the 14th century and was built by Giovanni il Calabrese (John the man from Calabria), an Italian weaver who worked in Genoa and in France where he was known as “Jean le Calabrais” that has the same meaning in French.

It is sure that the first European places where the silk was worked, between the end of 9th century and the beginning of the X, were in southern Italy at Catanzaro (Calabria) and Palermo (Sicily). This was probably because Catanzaro was under the Byzantine dominion while Palermo was under the Arabs. Hence, both cities were narrowly linked to oriental culture. In 1466 king Louis XI decided to start an outstanding manufacturing of silk in France and called a large number of Italian workers, mainly from Calabria. The draw loom that appeared in those years in France was called loom by Jean le Calabrais. One of these looms is at the Musée des arts et métiers in Paris and is shown in Fig. 19.10.



**Fig. 19.10** The loom by Giovanni il Calabrese

The one by Giovanni il Calabrese was a loom for the production of diapered and damask fabrics. The drawings on such fabrics are obtained by lifting some designate heddles and by inserting in the warp a woof yarn having a designate colour and so on. As it is shown in Fig. 19.9 in this loom the heddles can be moved one by one by means of apposite buttons. Each button has a number to identify it; the weaver, every time, before inserting a woof yarn, reads which buttons he has to pull. This could be considered as an ancient example of a programmable device since the weaver does not need to see the fabric but just needs to read a sequence that was memorized on a worksheet.

The draw loom was improved in 17th century in France by Galantier and Blanche, and in England by Joseph Mason. While in the loom by Giovanni il Calabrese the buttons were operated by the weaver, in these last ones the buttons were located at the side of the loom ad moved by an apprentice; this permitted the weaver a faster production.

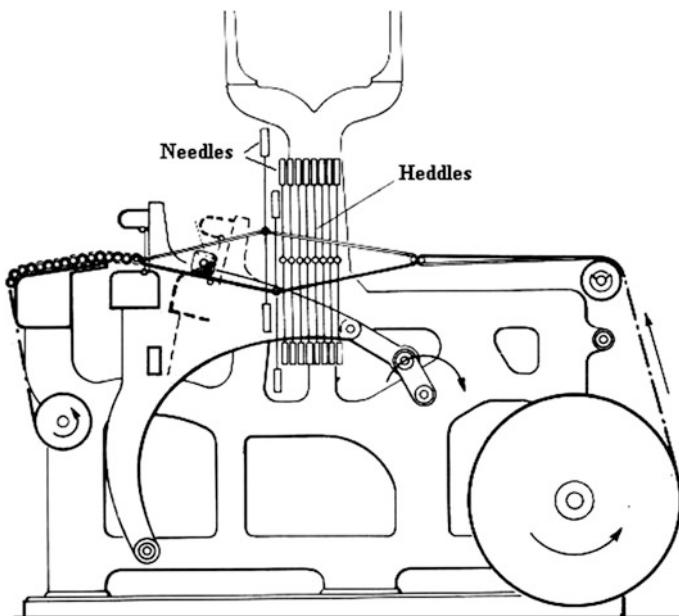
#### ***19.4.2 The Programmable Looms of the 18th Century***

The course through the programmable loom sees many improvements of the original idea of the draw loom. Among these, we can mention Basile Bouchon who was the first to use drilled paper on a loom in 1725, Falcon who improved it a few years later by using cardboard rectangles joined together, finally de Vaucanson who built, in 1744, a semiautomatic loom in which cardboards were substituted by a metallic drilled cylinder covered by a paper strip. In all these draw looms the heddles were no longer hand operated but they were connected to needles; the worker just had to press the drilled paper against the needles, the latter pulled the corresponding heddles if a hole was present in the cardboard. From this point of view, these devices can already be considered among the first examples of programmable machines by punch card.

The invention of the first “modern” programmable loom is attributed to Joseph Marie Jaquard (Lyon 1752; Oullins 1834). Jaquard was a weaving businessman who patented his programmable loom in 1804. In Fig. 19.11 is shown a scheme of Jaquard’s loom.

The heddles are grouped into small groups, each of them is independent from the others. On a rectangular cardboard some holes are drilled that correspond to heddles that must be lifted to form the warp; the other heddles that correspond to the undrilled areas of the card hold fast. At every turn the woof yarn is inserted, a new series of holes is faced. The working principle is the same of the previously mentioned programmable looms but in the one by Jaquard, the process and the card feeding is automatic. The number of holes on the card board can be up to 1200; this permits to obtain also very complex drawings.

The Jaquard loom was then improved by Vincenzi who used smaller card boards with smaller and closer holes, and then by Verdol who used a continuous card with very small holes.



**Fig. 19.11** Scheme of a Jacquard's loom

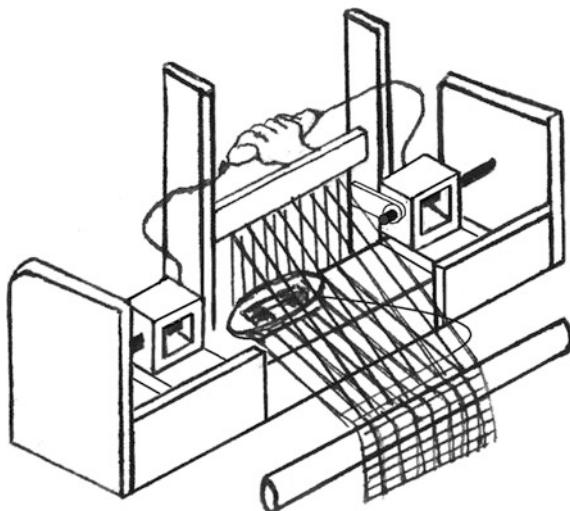
#### 19.4.3 *The Automatic Loom*

As long as the shuttle had been manually operated, the maximum fabric width was limited to about 1.2 m; this was because of the weaver's arms length. Wider fabric could be obtained by looms in which two weavers threw the shuttle from one to the other. In addition, up until the shuttle was manually operated, the production of fabric was rather slow. From this point of view, it has to be pointed out that little evolution was achieved into three millenniums before the 18th century: by the Egyptians, the woof yarn was threaded in the warp using a simple skein but soon it was bound in a bobbin that was the first spool and then the spool was put in an oblong box having pointed edges: the shuttle.

The most important invention about looms is the flying shuttle that was made in 1733 by John Kay (1704–1774), an English cloth trader; Kay, before that date, had already invented a machine to beat the wool. The inventor of the flying shuttle, John Kay should not be confused with the John Kay who worked with Arkwright at the invention of the spinning frame.

A scheme of the working principle of the flying shuttle is shown in Fig. 19.12. It essentially consists in a couple of boxes, each one at a side of the warp. In each box is contained a block that acts on the shuttle like a sort of hammer and is operated by the weaver by means of a string; this hammer throws the shuttle through the warp yarns. The weaver's operations are, hence, significantly simplified:

**Fig. 19.12** Scheme of the flying shuttle (courtesy of dr. E. Scoppa)



1. The weaver opens the warp yarns acting on a pedal.
2. Then pulls the string towards the empty box; in this way the hammer of the box containing the shuttle pushes the latter that “flies” through the warp to the opposite box.
3. Since the shuttle is operated by just one hand, the weaver has a free hand which he can use to move the reed.

This loom, even in its early versions, permitted to increase the production up to four times and also to obtain larger fabrics with just one weaver.

Later, in 1760, the son Robert developed the drop box that permitted the use of multiple shuttles; in this way it was possible to use woof yarns having different colours.

Successively was invented a device to obtain the contemporaneous walk of the fabric; this was made in about 1800. In this way the loom had been perfected in what all its movement is concerned and it was easy to obtain that all these movements were operated by one only motor.

The last evolution of the flying shuttle through the fully automatic loom essentially consisted in an automatic drive for the shuttle. This was obtained by a rotating rod or a sliding stick, both operated by cams. nowadays, for thin yarns, the shuttle is substituted by an air jet. Nevertheless, the flying shuttle by John Kay can be considered as the precursor of all modern automatic looms; in the same way, the Jacquard loom can be considered as the precursor of all the programmable looms.

### Observations

It is surprising that most or all the inventions that permitted a wide and cheap production of fabric and hence of cloths are practically grouped in few decades of the 18th century. Spinning and weaving certainly have a very important part in the

industrial revolution, but it is even more important that the mentioned inventions and their development have permitted to dress a highly increasing population tight up the present days.

# **Chapter 20**

## **Some Applications of the Fire**

**Abstract** In this chapter inventions and devices connected with the fire are presented. These are both for civil use like fire lighting, lanterns and thermal heating of the houses and for military use such as the Greek fire and the ancient flamethrowers. The last paragraph shows the early use of the asbestos as a protection from fire.

### **Introduction**

The discovery of fire is obviously the first man conquest, however it occurred, it sets the passage of humanity from the simple animal phase to the intellectual phase; any further development towards civilization starts from the capability of managing it.

Apart from the innumerable technical and material consequences, there are others that are even more important but that at first glance escape us completely. Fire shattered darkness and eliminated the cold: with the elimination of darkness man became master of the other half of the day, with the elimination of the cold he conquered all geographic environments with a rigid climate. An expansion of time and space that in turn triggered a series of further mutations: the flame around which they would sit for warmth or to pass the night, was the ideal catalyst for the exchange of news, the emulation of advantageous solutions and increased knowledge. The luminosity of the flame permitted voyages that the night discouraged. Visible bonfires indicated land to those travelling by sea, who then learned to communicate with those lights, overcoming otherwise insuperable marine space. Agamemnon used fire to announce his victory in Troy, unknowingly triggering his own murder. The light of flames were further exploited on a small island off the coast of Alexandria, with the strange name of Pharos: that became the most famous and suggestive naval infrastructure.

Fire and ocean, a struggle in which the former is always the loser even when the opposite would be preferable: torches touched by rain go out and lanterns struck by waves cease shining. But when Rome was still a Republic, someone invented a torch that not only could not be extinguished by water but that could also be ignited by it. Only an echo of these torches remains in the definition of fireworks called ‘Roman candles’. Others, in a much simpler manner, made shielded lanterns with

curved glass, with bases and lids of bronze, very similar to those still used on boats, though with electric bulbs.

The unnatural symbiosis of fire and water had already been abundantly used in the thermal systems, where by burning large quantities of wood in enormous boilers they heated the huge masses of water contained in the tanks. A sort of naval testudo placed on the bottom acting as a diffuser: like the blocks of fiery lava falling onto the sea beds causing the water to boil! Fire at sea became the greatest manifestation of war as it was the fastest way to destroy enemy ships. Such as the rudimentary but effective flamethrowers that were, in effect, colossal blow-pipes activated by large bellows. But also siphons, probably similar to those used to launch jets of water on fire, but that instead launched jets of incendiary liquids called pyrophorics, that in some cases could increase upon contact with water. Not a miracle but an application of technical concepts to be widely used in the future to conduct naval warfare, known by the generic term of ‘Greek fire’, a mysterious mixture that opened the horizons of chemistry.

But perhaps what most astonished the ancients, opening the way to a vast array of doubts among the modern thinkers, was the fire ignited by the burning mirrors of Archimedes on Roman ships. A fable for the credulous, but one that according to recent archaeological tests has turned out to be effective? Or a badly told truth too complicated to understand? Doubtless there were many mirrors, not necessarily hexagonal and certainly not of glass: perhaps they were the very glossy shields that concentrated the light of the sun on a single point in compliance with a specific command! Strangely, today we too use many mirrors to concentrate the light of the sun on a single point: they are called heliothermal plants and, together with the eolian plants, are used to reduce pollution while providing energy. A past returning to make the future less improbable!

It is difficult to enumerate the possible uses of fire; in this chapter, however, just some examples of the management of fire are presented.

## 20.1 Fire Ignition

The discovery of fire is frequently and justly considered the most important step forward in the evolution of man. But the real evolutionary progress was the mastery of fire rather than its discovery, when the man learned how to ignite and control it. For centuries, perhaps even millenniums, fire was used only when it occurred spontaneously, before man learned how to ignite it with sparks, friction and the sun. Archimedes studied the concentration of the rays of the sun towards one specific spot where the temperature became extremely high. He may have set fire to Roman ships off the coast of Syracuse using mirrors. What we do know is that several centuries later the Romans ignited fire and cauterised wounds by concentrating the rays of the sun using spherical lenses.

### 20.1.1 Optical Flints

It was well known that the strong percussion of siliceous stones worked to make blades generate sparks. From this they soon learned that these sparks could ignite tinder. And finally that if these stones were struck by an iron object, the resulting sparks were even more suitable to igniting tinder, because of their size and density. But it was only in a much more advanced historical context that a wholly different method was invented to attain the same result, one based on the use of glass spheres, the result perhaps of observing the effects of the rays of the sun through a glass container or a sphere of rock crystal.

Getting back to the production of glass as previously discussed, in addition to industrial production for construction, civil production for items of daily use and artistic production of many valuable artifacts, there was also another type of production that we would not hesitate to define as scientific. Of course it was limited, but highly important as it was the premise for current mass production. Among the latter are crystal prisms of extraordinary precision and regularity, used to break down light into the colors of the spectrum: for the era a household variant of a rainbow. In Fig. 20.1 are reported prisms of rock crystal of extraordinary precision, used to fraction light, found at Pompeii.

Even more curious were the small and slightly convex pieces of glass that enlarged images: actual magnifying glasses in the true sense of the word. Military doctors would cauterize wounds with a thick lens or a sphere of rock crystal, using it to concentrate the rays of the sun on one specific point. Pliny writes:

Invento apud medicos, quae sint urenda corporum, non aliter utilius uri putari quam cristallina pila adversis solis radiis.

I have discovered that doctors believe that there is no better way to cauterize the parts of the body (injuries) than to use a sphere of crystal so placed that the rays of the sun will cross it.

Such lenses have been found in various regions of the empire and even in Pompeii. The thickest were doubtless for medical use, but the thinner ones were of necessity used as eyeglasses, to give vision to the elderly and, especially, to



**Fig. 20.1** Prisms of rock crystal found at Pompeii

**Fig. 20.2** Magnifying glass found at Pompeii



engravers. How could one imagine the execution of microscopic settings and cameos, so admired by the Romans and frequently found among Roman ruins, without such help. Without considering the fact that artistic ability increased with age, exactly the opposite of visual acuity. In Fig. 20.2 is reported a magnifying glass found at Pompeii; similar crystal lenses were used by the Romans to ignite fire.

We are familiar with the use of emerald filters, such as the classic one used by Nero, to rest the eyes or to correct a visual defect. Perhaps, and this is one of the less supported theories, such lenses were also applied to the dioptres (see Chap. 3), making them much more precise by varying the visual approach and angle. Some medieval manuscripts depict astronomers looking at the sky through a tube. The well-known Roger Bacon (1214–1294), also known as Doctor Mirabilis (wonderful doctor), in his V book of the Opus Majus speaks with enthusiasm of the “ability of the ‘Ancients’ to enlarge small objects and to approach those far away with appropriate combination of lenses ... Before [him] the possibility of using refraction to reconstruct microscopes and telescopes was lucidly submitted by Robert Grosseteste”. The latter (Stradbrook, Suffolk, 1175–1253) was an English Franciscan known as statesman, scholastic philosopher, theologian and bishop of Lincoln. Specifically, Bacon wrote that it was possible to make distant objects appear to be near and, at his discretion, large objects appear to be small.

Was this a precognition of the telescope and microscope almost 4 centuries before their appearance, or the extreme memory of something that had actually been made almost 14 centuries before? To return to Pompeii, among other singularities unearthed was an absolutely exceptional sample of a lens, though of minuscule size, a perfect ellipse with the larger axis measuring 23 mm and the smaller one 20 mm, set into a bronze support with two threaded pins only a few millimeters large. These two insignificant screws alone are considered as a sophisticated product of the technology of the era as no other similar ones have been found. But the biggest surprise is the fact that on one side of the elliptical and convex glass is printed an excellent and highly faithful portrait. By standing behind the flame of a candle or a lantern, it would have been possible to project this image onto a white wall, thus realizing a rudimentary magic lantern.

Logical to conclude that this was a precursor of a device or system to visualize an ancient slide enlarged by the convexity of the glass and the rear light.

## 20.2 Marine Fire—The Roman Candle

The Byzantines named a mixture that could burn underwater or even be ignited by water, marine fire. Because of these terrifying properties they used it in naval warfare. Something of the sort was known also to the Romans many centuries prior but were candles that remained lit or were ignited when immersed in the Tiber River.

The definition of Roman candle relates to a special type of firework, widely used for its simplicity, that produces luminous streaks rising in the air for dozens of kilometers. In the past it seems that the Tartars were the first to use them as a combat device, making them from hollow bamboo canes filled with alternate layers of fire powder and incendiary material, mostly balls of cloth soaked in naphtha. The effect was a continuous emission similar to a jet of fire from a small flamethrower. However, the attribution of such a device to the Romans, or more generically to Rome, does appear to be wholly gratuitous and perhaps conceals a different origin, at least as archetype.

There is no doubt that the Roman army had incendiary weapons or projectiles, and that they used them systematically in sieges and battles, especially at sea. There were numerous incendiary mixtures of different potential and violence; much less known are the methods used to ignite them and to prevent their extinguishment. Something that would require more extensive research relating to the probable catalysts of oxidation reaction.

For such purpose, the inquiry would have to be extended to combustion boosters that not only speed up combustion but allow it to take place in otherwise negative contexts, including on and under water: flames that continue to burn even when struck by water or immersed in water! Of the latter we have a curious example from Titus Livius (about 59 B.C.–A.D. 17), who mentions it, without being the least bit surprised, in describing an orgiastic rite in 186 B.C. He writes:

... matronas Bacharum habitu crinibus sparsis cum ardentis facibus decurre ad Tiberim, demissasque in aquam faces, quia uiuum sulphur cum calce insit, integra flamma efferre....

The ladies dressed for the god Bacchus, their hairs loose, and ardent torches run down to the river Tiber and immerse the torches in the water, since [the torches] are impregnated by sulfur and lime, they are retrieved [from the water] with a flame still burning.

According to the quotation, the episode—which gave origin to a senate consult on the Bacchanals and consequent severe monitoring of god Bacchus' mysteries, already widespread by the priestess Annia Pacula in Campania and in Etruria—took place as follows. In the middle of the night, numerous matrons who were more or less possessed, or more likely drunk, went to the shores of the Tiber and therein immersed special torches impregnated with lime and sulfur, retrieving them aflame.

Either the torches were already ignited prior to the immersion or they became so as a consequence of the immersion, with the water acting as the ignition factor promoting oxidation reaction, as will later be said of Greek fire.

In both cases the phenomenon cannot be attributed to the simple presence of sulfur and quicklime, but implies more sophisticated reagents, the same that will later be used in Greek fire and, even before that, for the pyrotechnical effects of the Roman candle. Logical to suppose that a few decades later the Romans would have highly effective fire generating liquids to use in warfare.

### 20.3 Wind Lanterns

On the Trajan Column is a clear illustration of Trajan standing on a battleship with a lantern hanging off the prow. This may have been a navigation light or a lantern for the pilot. In Fig. 20.3 is reported a particular of the Trajan column.

We do know that it operated even in the presence of wind and rain. Such lanterns were widely used, spreading from the maritime context to the land, as proven by the numerous lanterns unearthed in Pompeii, in perfect condition and ready for use.



**Fig. 20.3** Particular of the Trajan column showing a wind lantern

Even if they were luxurious, Roman and Greek homes did not have an adequate lighting system for the night. In fact they only had three ways to provide even a minimum of light: small oil lamps, tallow candles and oil lanterns that were resistant to the wind by means of a glass shield. The latter was probably a derivation of the lanterns used on warships and in camps, where it was indispensable to ensure prolonged use and high resistance to wind and rain.

Pompeian archaeology has returned a discrete number of these, perfectly similar to those depicted on the Trajan Column on board navy ships. They consisted of a bronze container, formed by a base and a lid that could be raised along thin guides. Inside, fixed to the base, was a small container for combustible oil, similar to an inkwell, from which there protruded a piece of wool. Along the border of the base was a groove in which to set the glass, similar to the groove used for the lid. To light it, they raised the lid and after cleaning the glass, lit the wool, regulating the length for greater or lesser light. After which they closed the lid and once the glass was inserted, blocked the clasps.

At that point the lantern could be hung by a chain to its support and functioned even when there was a strong wind. This type of lantern, with the exception of replacing the oil with kerosene, was used until the middle of the 20th century and still survives as an emergency light. In Fig. 20.4 are reported a relict of a wind lantern found at Hercolaneum and an authors' virtual reconstruction of it.



**Fig. 20.4** Wind lantern found at Herculaneum and virtual reconstruction

## 20.4 Fire for Warming

The use of the fire for heating is certainly as old as the mankind's conquest of the fire itself. Real warming systems are, naturally, more recent; as far as the authors know, among the first well documented warming systems, very considerable are those adopted during the age of the Romans.

### 20.4.1 Domestic Heating

Anyone visiting Pompeii or Herculaneum cannot avoid the feeling of being among the ruins of a city of tropical climate, never touched by the winter cold or at the very most with a slightly lower temperature in the dead of winter! Which might have been true, as the historical context of those residences coincides with one of the many warm cycles of the past two millenniums. Not so however in other regions of the empire where the cold season was very much felt. There the windows had glass and the homes a heating system, one that was even more logical than the modern one. This was a domestic variant of the hypocaust, a system widely used for thermal baths. The hypocaust was simply a boiler that functioned using wood, producing a large quantity of warm air that, because of the different pressure of the cold air, was able to circulate under the pavements and behind the plaster on walls. For this purpose they built special columns and supports, called *sospensure*, to raise the floor while hollow bricks called *parietes tubulati* were installed along the walls in connection with the space underneath the floor, discharging the warm air after it had heated the walls.

Obviously the temperature of the air circulated was relatively low but a couple of days were sufficient to bring the inside of the building to an agreeable warmth and there was certainly no lack of wood to keep the boiler continuously operational. This same boiler was also used to heat the water of the domestic baths and bathrooms, exploiting it to the maximum, which was nevertheless extremely low.

### 20.4.2 Thermal Heating Systems

A concept similar to the above heated the waters in the vats and rooms of Roman baths. Like the aqueducts, the baths were a distinctive characteristic of ancient Rome. The Romans went to the baths not simply to bathe and exercise, but also to walk, for leisure, to meet others, to talk business, to eat and drink, to see shows and to admire art. In brief, to live more intensely in an environment that, like our beaches, encouraged contacts and facilitated socialization.

It is no surprise therefore that the construction of thermal baths was a precise political commitment both for the emperors and for local notables as well as

wealthy private individuals. And one of the first tasks of military engineers, the *faber* of the legions, when the camp was a permanent one. Behind these systems were hygienic and sanitary needs and standards that could not otherwise be fulfilled.

One thermal system that has come down to us almost intact, though of medium size, are the Stabian springs of Pompeii, which meet very specific requirements. Historically it is the most ancient of the known Roman baths, dating from the 2nd century B.C. The baths were: "divided into two sections, one for men and the other for women, placed along a single longitudinal axis along the sides of a common kiln, extending over a surface area of more than 3500 m<sup>2</sup>, including a wide courtyard with porticoes along three sides, used as a gym. A large pool was later added with dressing rooms and other services, sufficiently large for physical exercise in a covered area".

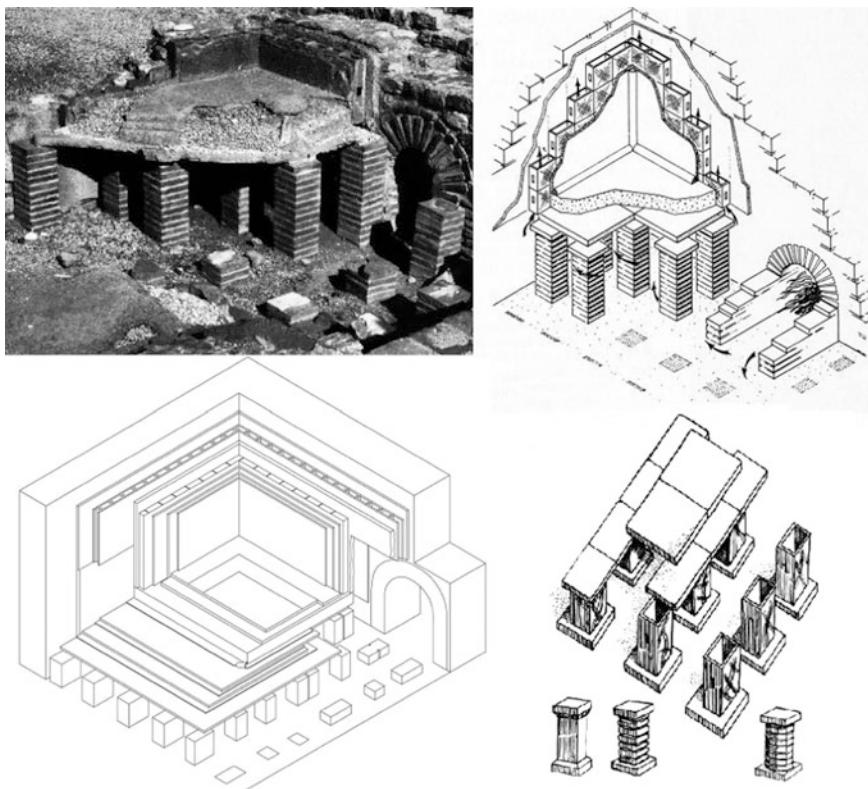
To better specify the technical aspects of these systems, we note first the enormous requirement for water: for his thermal baths Agrippa, the founder of the Roman navy, had a special aqueduct built called the Aqueduct of the Virgin, that brought approximately 100,000 m<sup>2</sup> of water a day from Marino to the heights of the Pincio. Before it could be used, the water was collected in a colossal cistern that probably stabilised the quantity and pressure of the flow. Beginning with the: "cisterns, through a detailed distribution network formed of lead or terracotta pipes the water was introduced into the cold bath tanks and into the swimming pool, while the water to be heated was conveyed to the oven area, where it then went into the warm bath tanks by means of pipes and shunts issuing from the boilers".

The oven (*hipocaustis*), which in the first *balnea* was often located underneath the only heated room, was located in the central part of the building used for baths ... The usual fuel was wood, stored in special sites in a quantity sufficient to last... up to a month ... the boilers used to heat the water were usually of bronze, or bronze in the lower section, which was directly touched by the flames and lead sheets for the upper section. They were usually placed in a «jacket» of masonry to ensure stability and to limit the dispersion of heat. The battery system was very common, using two or three boilers in which the water was heated at different temperatures.

These boilers were connected by pipes equipped with faucets, so that as the warmest water from the first boiler was supplied, it was replaced by the tepid water of the nearby boiler...with great saving of time and fuel.

One way to prevent water from cooling inside the tanks or to maintain a constant temperature was described by Vitruvius and used a *testudo alvei* (literally «affixing of plates to the tank»): "a bronze, semi-cylindrical container, in the shape of a testudo or tortoise. This was heated externally, directly by the oven and placed on the bottom of the tank with the convex part directed upwards, so that heat would be relayed to the water in a continuous and uniform manner".

Whether warm or cold, the pools were fed by running water, since there was no way to purify water as we do with filters and pumps. This meant a conspicuous discharge of water to the exterior of the baths that was used for various purposes, according to its temperature. In one case, it appears that it was even used to operate



**Fig. 20.5** Finds at Saint-Romain-en-Gal

a mill, a confirmation of the logical nature of these systems, intended to minimize any loss and waste.

As for heating rooms, this was done by a system of air circulation as described above, using the hot air produced by the boiler.

In the next figures some examples of Roman bath are shown. In Fig. 20.5 is reported a picture of the finds at Saint-Romain-en-Gal (central eastern France) and some axonometric drawings showing the heating system.

In Fig. 20.6 is shown a picture of the large Roman thermal baths at Bath, England.

### 20.4.3 Ancient Samovar

A walk around the roads of ancient Pompeii reveals the large number of public rooms used to drink hot wine in its various mixtures. It would be obvious that the wealthier classes would manage to enjoy the same drink at home with their meals.



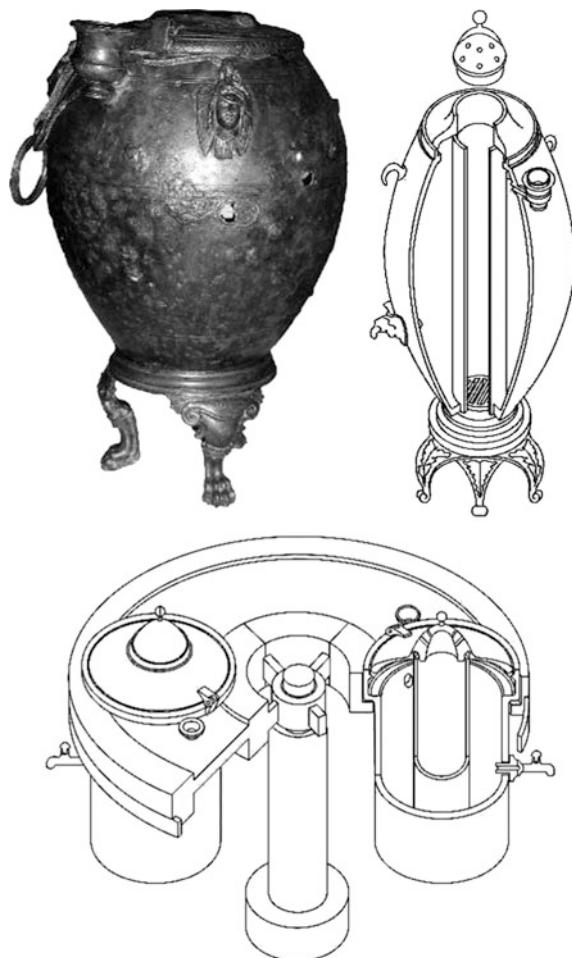
**Fig. 20.6** Roman thermal baths at bath, England

For this they used a large capacity samovar. Several of these samovars have been excavated, all basically similar in form and capacity. Contrary to modern samovars, once the Roman ones were filled with embers in their central compartment, with a grid on the bottom to remove the ashes, it could be continuously filled using a special side funnel. Its location prevented the particles of coal or embers from contaminating the drink.

This samovar was a large bronze amphora that held about forty litres, with a tap on the bottom, similar to the shut-off valves described previously. The lower section stood vertically on three supports. The upper extremity was completely open and was inserted into the central cylinder used for the embers, with a grid at the bottom, and into the belly of the amphora. A ring shaped lid was used to close this final section, leaving the cylinder open so that new embers could be added and the underlying grid emptied and cleaned.

If wine was preferred warm, water however was preferred cold, a condition that could be satisfied only by using ice, preserved for three entire years in snow-fields. These were underground rooms, caves or wells, located in mountains where snow accumulated during the winter and that was transformed into compact ice so that it could be preserved through the summer. Cut into pieces it was sold as a refrigerant or to make sherbets. In the first instance, pieces were placed in amphorae such as described above to lower the temperature of the water.

We know of a double samovar, described in detail, that was built by a Roman general to provide his guests with warm wine and cold water. The choice was made by rotating the support of the two vases, located on the central pin of an annular

**Fig. 20.7** Roman samovar

table, bringing the desired tap to the cup. In Fig. 20.7 is reported a Roman samovar found at Pompei, an axonometric section of it and a graphic representation of a rotating double samovar for cold water and warm wine.

## 20.5 Fire for Warfare

The use of fire as a weapon is probably quite as ancient as the use of it as light and heat source. But a burning torch and its use cannot be considered really an invention and even less a device. Ancient examples of a “technical application” of fire for warfare are found in the Greek-Roman Era.



**Fig. 20.8** Print depicting the use of burning mirrors

### 20.5.1 Burning Mirrors

There has been much talk of the burning mirrors used by Archimedes to set fire to distant ships of the Roman fleet trying to attack Syracuse, but no proof has ever come to light, thus relegating the event to pure fantasy and legend. In Fig. 20.8 is reported a print from 18th century depicting the use of burning glass in the defence of Siracuse.

But such a singular story cannot be wholly invented as there is always a technical basis for any fantasy. No one, then or after, could know about, and even less so test, the possibility of concentrating the rays of the sun using mirrors to ignite a given object. And since they did not have this knowledge they could not reach a conclusion: logically, one may presume that something of the sort must have existed. Perhaps it was not a large mirror divided into hexagonal sections, but many small mirrors, or highly polished shields, used to attract the rays to the various sections of the ship.

Experimental archaeology has demonstrated that such a system could be used to ignite a wooden ship and its sails even if hundreds of meters away.

Any doubt is dispelled by our very modern heliothermal plants, in which a large number of mirrors are used to direct the rays of the sun toward a single boiler, such work performed not by vigilant servants but by special servomotors.

## 20.5.2 *Flamethrowers*

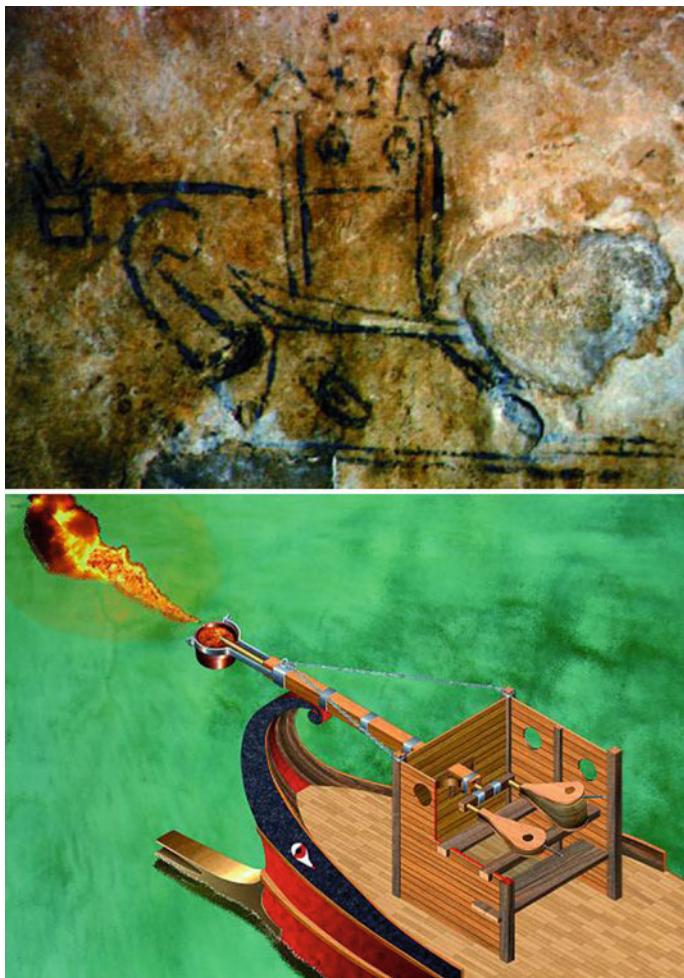
The fire in a battle was the classic ally of iron, which completed the devastation inflicted by the former. At sea the role was reversed. Ships made of seasoned wood, saturated with pitch and oil were the ideal prey for flames, thus the need for adequate launching systems. Hulls of seasoned wood frequently caulked with pitch and oil were the ideal prey for flames. It was a logical step forward to use solid and liquid incendiary devices in naval warfare, hurled towards enemy ships by sophisticated launch mechanisms.

In Chap. 8, a twin cylinder operated flame thrower, designed by Ctesibius, has already been presented as an example of a reciprocating pump.

### 20.5.2.1 The Flamethrower by Thucydides

The flamethrower designed by Thucydides was probably the most effective one as it spread fire by means of a blowpipe. Thucydides describes the prototype of these machines, attributing it to the Boeotians, who used it in the Peloponnesian war to attack the fortified Athenian camp of Delius. The rudimentary flamethrower consisted of a wooden tube covered in sheet metal, its rear extremity connected to large bellows and the front to a brazier. In his “The War of Peloponnesus”, Thucydides writes: “A large beam cut into two parts, emptied and adapted to resemble a flute. At one end they suspended a brazier into which they placed an iron tube that extended from the beam; the rest of the beam was also reinforced with iron. They brought it close to the walls using carts, especially towards sections of wall containing screws and wood. When the machine was near, they placed large bellows at the ends of the beam and used them to blow inside the beam. When the gust of air suddenly reached the brazier filled with burning coals, sulfur and pitch, a great flame would ignite and set fire to the wall, such that all had to flee: in such a way they took the wall”.

Rather than an actual flamethrower, this device was more of a gigantic blow-pipe, of the type used for millenniums by Egyptian jewelry makers. As such it could generate a high temperature, arrow shaped flame, limed even the stones of the wall and set fire to all wood structures in an instant. Because of its simple and terrible effectiveness it was surely used in naval combat, obviously with a few significant but not excessive modifications. The empty beam thus became a sort of bowsprit supporting a large brazier well outside the bow, for understandable reasons of safety, that could incinerate any enemy ship that should incautiously approach even by a few dozen meters.



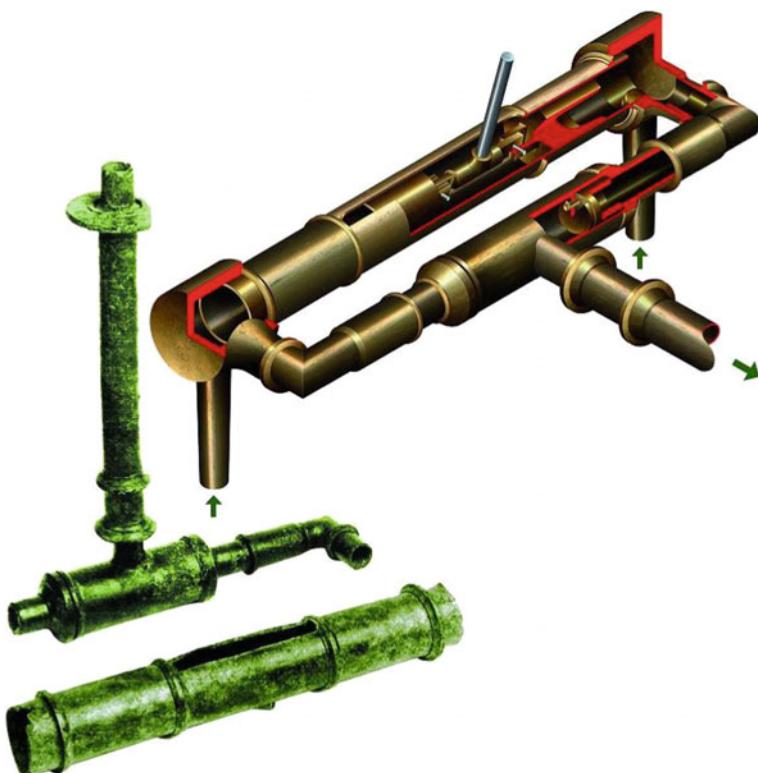
**Fig. 20.9** Flamethrower: Egyptian graffiti and virtual reconstruction

An exceptional graffiti found on the frescoed walls of the necropolis of Anfushi, near Alexandria, Egypt and ascribed probably to a soldier of Julius Caesar, represents the prow of a ship surmounted by a curious combat tower. In Fig. 20.9 are reported the Egyptian graffiti and an author's virtual reconstruction of the flamethrower. On the tower is a long pole that supports a container similar to a cauldron, from which rise tongues of fire. Even in the approximation of the graffiti, this is obviously a flamethrower of the type just described, duly modified and made lighter to make it suitable for naval use, with the bellows located inside the tower.

### 20.5.2.2 A Probable Single Cylinder Pump Flamethrower

A singular relic is stored in the municipal Antiquarium of Rome, of which we ignore the age and the site in which it was found. Its historical placement is also uncertain: the only certainty is its acquisition in 1888. A cursory study reveals that the object consists of two parallel cylinders, one larger than the other, that appear to be respectively a piston pump and an accumulation tank. The pump, although having obvious similarities with those found in Spain and Great Britain dating to the 3rd–4th century A.D., has one peculiar feature that makes it even more interesting—both the cylinder and the connecting rod are single for both pistons and they have no rocker since they are activated by a single lever. In Fig. 20.10 are reported the finds and an authors' virtual reconstruction.

The solution appears extraordinarily innovative and complies with a technical scheme that finds precise historical confirmation in the curious Chinese piston bellows and flamethrower, probably built in the same chronological period, perhaps even by the same inventors.



**Fig. 20.10** Single cylinder Roman pump: finds and virtual reconstruction

This pump also could have been something other than a simple hydraulic machine of enigmatic use. The fact that the machine of Ctesibius could be used in sophisticated weapons is demonstrated by its pneumatic spring ballista (see Chap. 13).

### 20.5.3 Incendiary Projectiles

A recent movie shows in its initial sequences the field preparations of the Roman tension/torsion artillery, loaded with incendiary projectiles. Because of the usual lack of confirmation its reconstruction has raised some perplexities: did such projectiles really exist around the 3rd century A.D.? Or liquids that could produce such incendiary results? And how can we deduce their existence, since we cannot hope to find any such specimen?

In reality some hints are found in the classics, and given the sensitivity of this issue, even these few hints are important: thus we learn of incendiary arrows with harpoon points fired into enemy machines or setting fire to wooden structures. We also know of the incendiary arrow, described by Livy, as a weapon with a lighted point launched from a ballista. A weapon that, according to Ammiano Marcellino, could only be extinguished by covering it with soil. In a collection of 10th–12th century instructions for mixing pyrophorics, clearly of the Roman if not Hellenic era, called *Mappae Clavicola*, the authors write of sulphur, turpentine, resin and naphtha. This collection: “describes fire carrying arrows as empty arrows, whose internal cavity was filled with a mixture of naphtha, pitch, sulphur, salt and flax: often the pipes were covered in copper to prevent the incendiary composition from consuming itself before the arrow reached its destination.”

The fire vases were clay containers (*vasa fictilia*) filled with flax soaked in a mixture of liquid bitumen, pitch and sulphur, with a sulphonated fuse. They were hurled using special machines. When they fell, the vase broke and the incendiary composition came into contact with the object it struck. These types of projectiles are mentioned by: Appiano, *sulphur et picem in vasis fundis emittebant*; Dionysius of Halicarnassus, *bitumane et pice fervida vasa repleta fundis inferentes*, and Frontino, *amphoras pice et teda plenas... iaculatus est*. They were widely used in many locations, especially by Demeritus during his naval attack against Rhodes (304 B.C.), and in the naval battles that took place during the second Punic wars. They also launched porous rocks after filling their cavities with flammable material and setting them on fire”.

Not to mention the Greek fire considered by many scholars, at least in its basic recipe, to be older than is commonly believed. As to any traces left of their use, perhaps we can detect one that is certainly significant.

In the beginning of the 1900s in Pompeii, after more than a century and a half of excavations, the northern region of the city also came to light, beginning with a section of its surrounding wall. When the ashes were removed, on the extrados of the walls imprints of ballistic impact were found. Easy to determine the cause and the

era: the siege of Silla in 89 B.C., although some of the imprints are anomalous and difficult to attribute to traditional balls. Their outline is clearly polygonal, hexagonal or pentagonal, of little penetration, not more than 30–40 mm and with a flat bottom. The projectile is shaped like a prism: an articulated series of traces and confirmations led its investigators to assume they were produced by the metal or stone head of incendiary projectiles of the type called *vasa fictilia*. Many of these also have a small central hole made by a sort of stinger, ready to puncture a wooden structure upon impact and set it on fire.

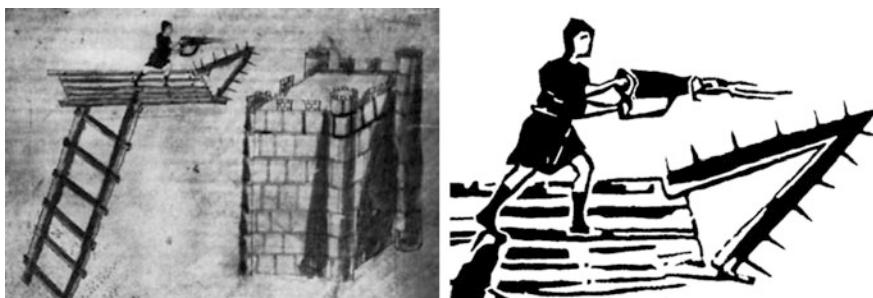
## 20.6 The Protection from Fire: The Asbestos

Very old is also the use of the first material that was used as a protection from fire: the asbestos; this word comes from the ancient Greek  $\alpha\sigma\beta\epsilon\sigma\tauο\varsigma$  (asbestos) that means: inextinguishable; this word was used by many ancient authors like Pliny (Gaius Plinius secundus 23–79 A.D.), Strabo, and Plutarch. Persians and Romans used fabrics woven with these mineral fibers to make the shrouds in which the kings were covered to be cremated; this, in order to avoid that the king's ashes were contaminated.

In ancient times, asbestos was also called “salamander's wool” since it was believed that this amphibian could stay in the fire without suffering any damage.

Pliny has left us many references about the asbestos: it was used to make fire resistant fabrics, wicks for oil lamps and towels on which animals were sacrificed to the gods; such towels could have been cleaned and purified by just leaving them in the fire.

In Fig. 20.11 is reported an ancient illustration showing a portable flamethrower (see Sect. 20.5.2.2) used during a siege and a particular of it. Since the fire resistant properties of asbestos were known in antiquity; in the particular it is possible to interpret the dress and the boots of the man as fire resistant protections, possibly made from asbestos.



**Fig. 20.11** Portable flamethrower and possible asbestos defences

Pliny also refers to asbestos as a soundproof material: he says that big towels made from asbestos were put around the trees that had to be cut down, in order to avoid any noise during their fall.

Also the danger of asbestos for health was known in ancient times: the Roman historian Livy (Titus Livius 59 B.C.–17 A.D.), tells that the men who worked in the asbestos mines often got ill.

# **Chapter 21**

## **Automata (Towards Automation and Robots)**

**Abstract** This chapter is about the early automatic devices in general and the automata in particular. Automata are presented starting from the Hellenistic era till the early 19th Century. Among the automatic devices, the repeating catapult, conceived by Greek scientists but widely used by the Romans, is particularly interesting since it represents the ancestor of the modern automatic weapons.

### **Introduction**

In the previous chapters it has been demonstrated that the knowledge of mechanics (both in the solid and in the fluid field) was present in remote centuries. The idea or the desire to build automatic devices is almost as ancient as the early knowledge in the in the field of mechanics. In Greek Mythology the god Hephaestus (*Iliad*, XVIII, vv. 519–525) built some “automata” (today we could call them androids) that helped him in his smith works. Another legend tells that king Minos used a bronze mechanical giant, named Talos and forged by Hephaestus, to patrol the isle of Krete (Fig. 21.1).

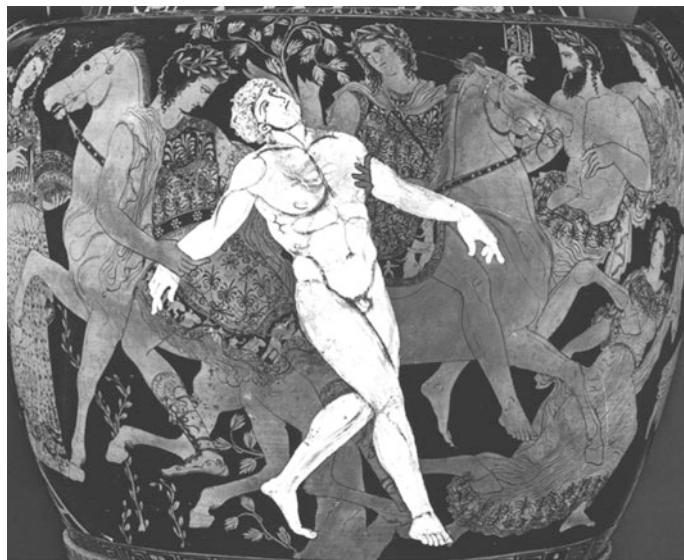
In this chapter some inventions and devices are presented in the field of automation and automata. The aim is to show the path that engineers and inventors of the past made to reach modern devices in the field of automation.

Since in other chapters some other devices in this field have been presented, the authors will confine themselves to those that represent examples of automata. That is to say those devices that have been designed before the electronic control system was invented.

The chapter is divided in paragraphs that pertain to historical periods.

### **21.1 The Hellenistic Age**

The first examples of devices powered by a mechanical source of power can be considered the ones by the scientists belonging to the Hellenistic school. It has to be said that the Hellenism, from a historical point of view, is the period of time that starts with the death of Alexander the Great (323 B.C.) and ends with the Roman conquest



**Fig. 21.1** Talos

of Egypt (31 B.C.). But the influence of the Hellenistic thinking and knowledge on science and philosophy was very strong for some centuries after the I sec. B.C.

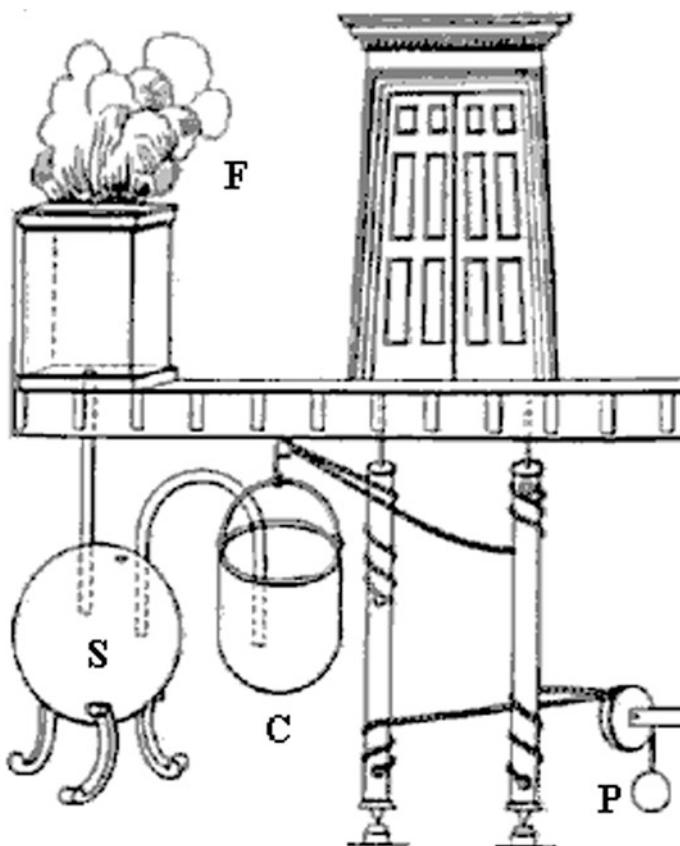
### 21.1.1 *Heron of Alexandria*

Heron of Alexandria (see the biographical notes in the Appendix.) was probably the best known designer of automatic devices in ancient times. He has already been mentioned in this book for a number of his inventions in different fields.

In some of Heron's treatises (e.g.: *Pneumatica*, *Automata*) Heron described statues having human semblances (automaton) that were moved in a theatre acting as actors, animals that drank, singing birds and other devices, all moved by steam or water.

The most famous device by Heron is probably the mechanism to open and close the doors of a temple that is shown in Fig. 21.2

A fire was lighted on the brazier F; so, the hot air heated the water in the pressure tank S. The pressure in this last tank pushed the water in the mobile water container C through a U-shaped pipe. The mobile water container was connected to the temple doors by means of ropes or chains wrapped in coils on the door hinges. As the water container was filled with water, because of its weight the ropes were unrolled and the doors were opened. When the fire was extinguished, the steam in the pressure tank condensed, hence, the pressure in it decreased and the water was sucked up from the water container. As soon as the weight of the latter decreased enough, the counterweight P acted on the door hinges in the same way, but closing the doors.



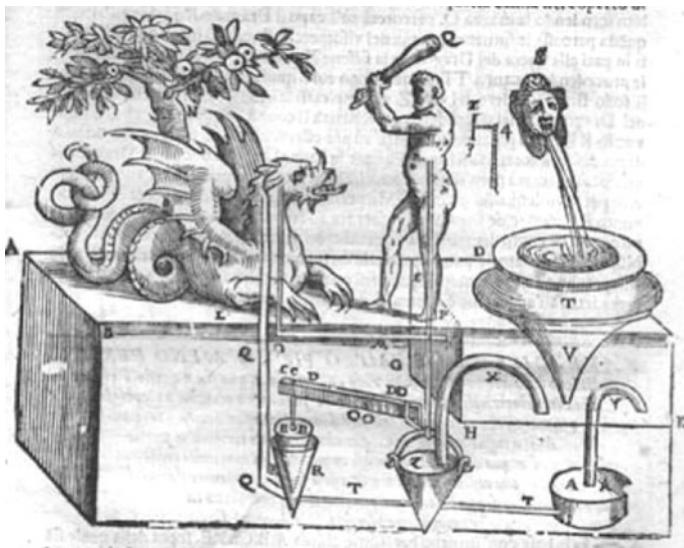
**Fig. 21.2** Heron's mechanism for temple doors

In Fig. 21.3 is shown a reconstruction, made by Giovan Battista Aleotti in his “Gli artificiosi et curiosi moti spiritali di Hero Alexandrinus” (The artificial and strange pneumatic motions By Heron of Alexandria), Ferrara 1589, of a famous Heron's automaton. This automaton was made up by two main characters: Heracles and a dragon.

In a few words: the dragon hisses, Hercules beats it with a club and the dragon spits on Hercules. The working principles can be deduced by Aleotti as follows.

A water flow from S fills a tank H through a funnel T. When the tank H is filled the air flows through a small pipe M that is linked to the dragon's mouth and this one hisses.

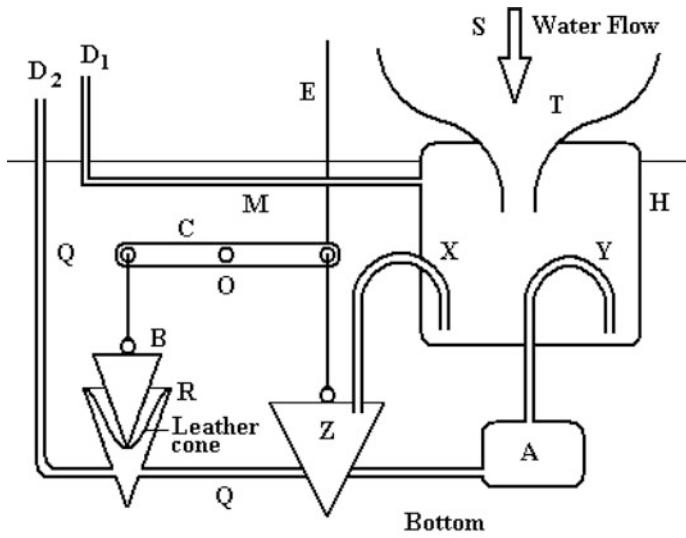
A rocker C can rotate on a pin O, one of its arms is linked to a cone B and to a rope E, while the other arm is linked to a water container Z; the latter, if empty weighs less than cone B. As the water level in the tank goes up, the water fills the mobile water container Z through the U-shaped pipe X. When the mobile container Z is heavier than cone B, the rocker C rotates clockwise and rope E moves



**Fig. 21.3** Reconstruction by G.B. Aleotti of an Heron's automaton

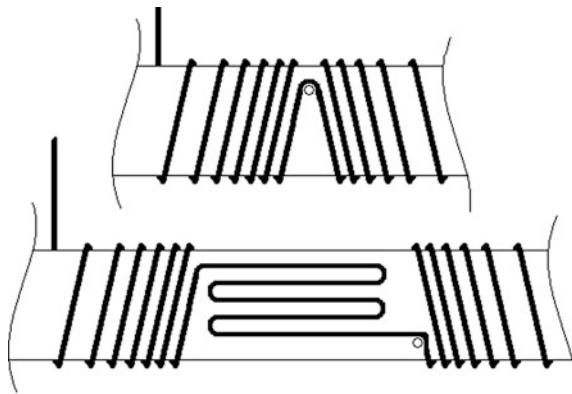
Hercules' arms through a simple T-shaped mechanism, not represented. In this way the club is lifted up. At the same time, through pipe Y, tank A, pipe Q, and the cone R are filled.

The working principle is shown in Fig. 21.4.



**Fig. 21.4** Working principle of hercules and the dragon

**Fig. 21.5** Ropes wended on cylinders



Since the mobile water container is conical, when it reaches the bottom, it turns upside down and the water in it is unloaded. Now cone B is heavier than container Z and the rocker rotates counter-clockwise. The rope R is tightened and the club beats the dragon's head. At the same time, cone B gets inside cone R that is full of water and so the pressure in the pipe Q rises. This pipe is linked to the dragon's mouth and so the latter spits a water jet onto Hercules.

In order to obtain this pressure rise, G.B. Aleotti suggests that between cone B and cone R a leather cone must be installed as shown in the authors' drawing reported in Fig. 21.4.

Heron probably also designed the first programmable moving robot. This device was recently reconstructed at the University of Sheffield, UK in a very simple way. The “motor” was a weight that moved the wheel axle by ropes; the latter were wound on a cylinder that was the wheel axle. This permitted to program somehow the motion.

In Fig. 21.5 an example of motion programming by means of ropes wound onto cylinders are reported.

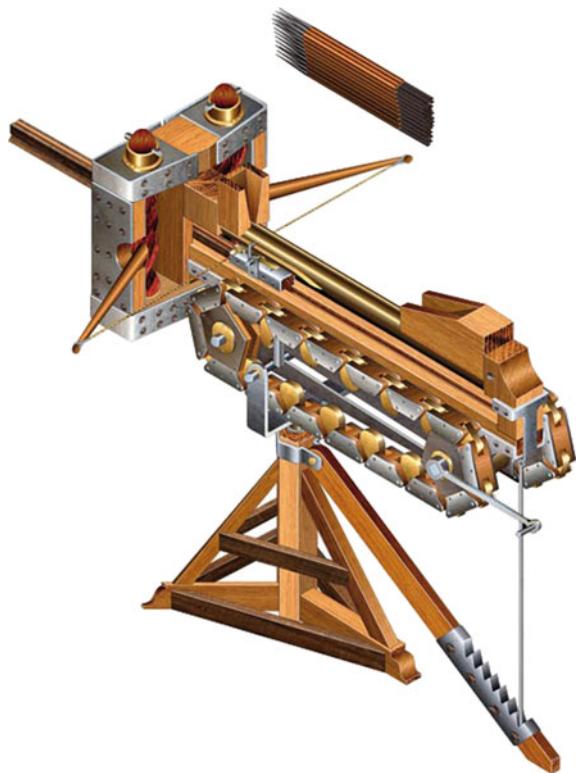
In the Figure the ropes are wound onto a cylinder with different pitch and winding direction. By pulling the rope the cylinder rotates and its law of motion is programmed by how the rope has been wound. On the cylinder some knob can be located in order to obtain also the reverse motion of the cylinder itself. Pauses could be obtained by some kinks glued with wax.

It is related that some other scientists belonging to the Alexandrine school (e.g. Ctesibius, Archytas from Tarentum, Philon from Byzantium) made some automatic systems, and also automata, moved by water or by steam.

### 21.1.2 *The Roman Empire: The Repeating Catapult*

The catapult, the meaning of this term and the working principle of this device have already been reported in Chap. 13. In this paragraph a repeating version of this device is presented.

**Fig. 21.6** Pictorial reconstruction of the automatic catapult



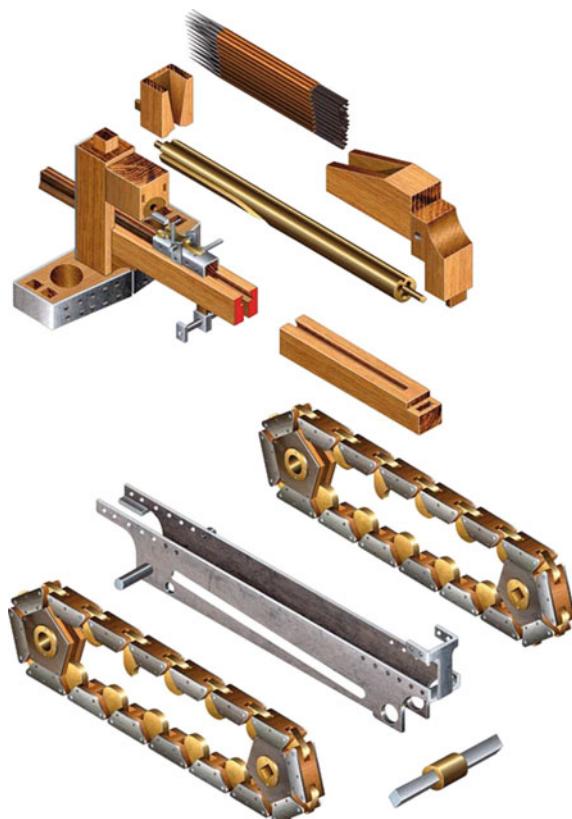
A pictorial reconstruction of the repeating catapult is shown in Fig. 21.6. The device is described by Philon of Byzantium and can be considered as a futuristic automatic weapon that throws 481 mm long darts. This machine was attributed to Dionysius of Alexandria and, apparently, it was used around the 1st century B.C.; it was a part of the arsenal of Rhodes that may be considered as a concentration of the most advanced mechanical kinematic and automatic systems of the time, many of which are still widely used.

The repeating device essentially consisted in a container holding within it a number of arrows, a cylinder feeding device and movement chain.

The description left to us by Philon, as is easily understandable, was not written to eliminate all doubt, as it lacks a technical glossary and an analytic style. In Fig. 4 some details of the mechanism are shown.

According to Philon, the arrows were located in a vertical feeder (see Figs. 21.6 and 21.7) and were transferred one at a time into the firing groove by means of a rotating cylinder activated alternatively by a guided cam, in turn activated by a slide. A simple rotation of the crank was sufficient to move the cylinder, the slide, the slide hooking mechanism and the trigger mechanism. The cycle repeated automatically without interruption or inverting the rotation of the sprocket until the magazine was empty, a magazine that could be re-loaded without suspending firing.

**Fig. 21.7** Details of the mechanism



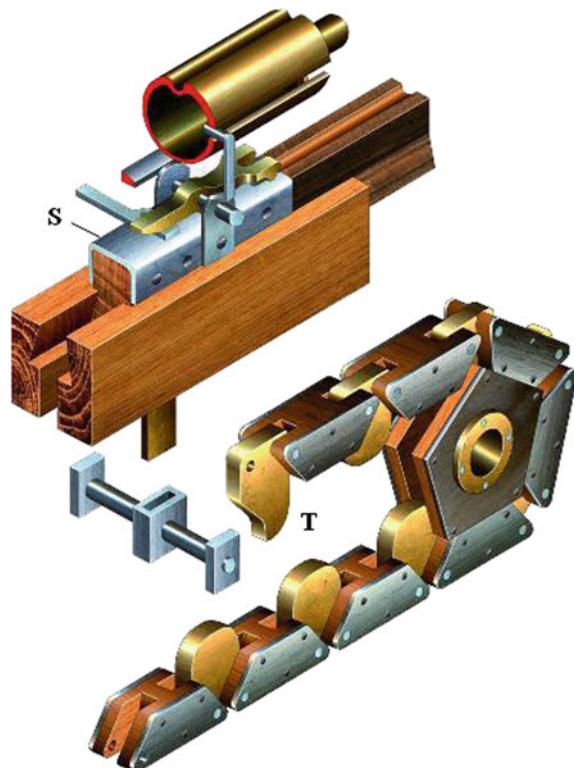
It is interesting to note that the motion from the “motor” shaft to the other parts occurred by means of two flat link chains pulled by pentagonal sprockets, as shown also in Fig. 21.7. These, similar to modern electrical saws, had interior teeth that were inserted into the spaces of the pentagonal motor sprocket and the return sprocket, preventing them from exiting. Similar types of chains, called *Galle*, are attributed to Leonardo da Vinci and transmit motion in bicycles and motorcycles.

Reconstruction of very ancient devices is often difficult. The one of the repeating catapult, for instance, is based on old texts (e.g. Baldi B. *Heronis Ctesibii Belopoiika, hoc est, Telifactiva.* Augusta Vindelicorum, typu Davidu Frany 1616), on the work made by Schramm (Schramm E. *Die antike Geschütze del Saalburg* Berlin, Weidmannsche Buchhandlung, 1918) that is also reported by Marsden (Marsden E. W., “*Greek and Roman Artillery Historical Development*”, Oxford University Press II Ed. 1969) with the original description by Philon of Byzantium. As for this last description it has to be pointed out that ancient Greek has not technical terms: for instance in “Ta Filonos Belopoiika 75, 33–34” the chainmail is called “πλινθία” = little brick and the teeth of the chain are called “περονάις” = fin.

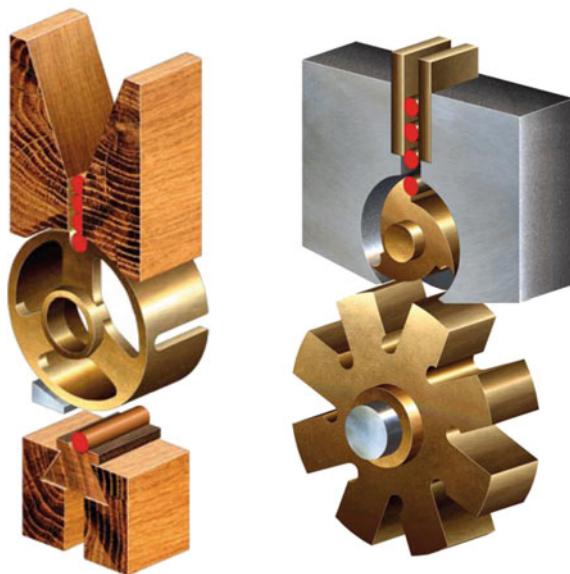
The difference between our reconstruction of this device and the previous ones mainly consists in the reload sequence: the other Authors suppose that the crank handles had to reverse the rotation for each strike, while we suppose the direction of rotation was always the same. This seems to us more believable also because, in this way, the ratchet could have worked correctly and the rate of fire could have been maintained quasi constant.

In our reconstruction shown in Fig. 21.8 one of the longer interior teeth T pulls the slide B which in turn pulled the cord, loading the coils of the motor. When in motion, an attached cam caused a 180° rotation in the direction of the loaded cylinder, drawing an arrow from the loader and placing it in the channel in front of the rope (see Figs. 21.8 and 21.9). When the slide reached the rear of the weapon, the cog released it, while another opened the release mechanisms. An instant later, upon completion of sprocket rotation, the same cog coupled with the slide from underneath, pulling in the opposite direction. Near the top of the weapon, the second device closed the hook after it had retrieved the cord, while the feeder cylinder picked up another arrow from the feeder. A half rotation in the sprocket and the cycle was repeated.

**Fig. 21.8** Chain and trigger mechanism



**Fig. 21.9** Repeating catapult (left) and Gatling machine gun (right) feeding mechanisms

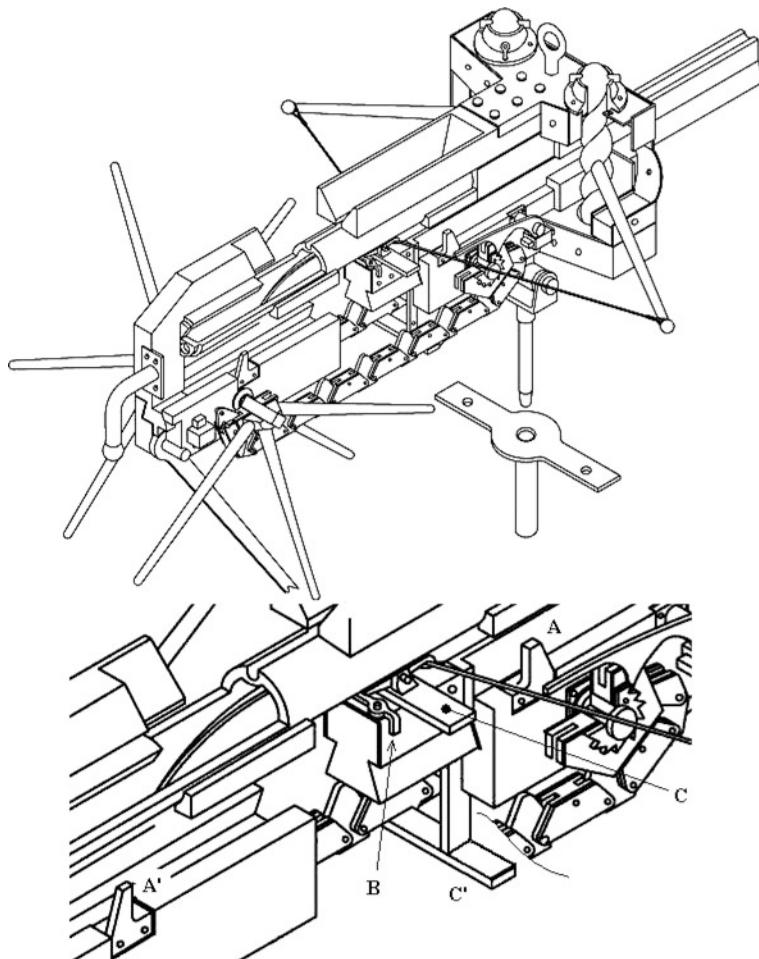


In Fig. 21.9 is shown the feed mechanism compared with the one of the Gatling machine gun; the latter is considered as the first (1862 U.S. patent) machine gun and its working principle is still used for modern aircraft automatic weapons.

In Fig. 21.10 is represented a perspective section of another authors' reconstruction and a particular enlarged. In the Figure are shown the trigger lever B that is activated when the slide reaches the end of its backwards run as soon as the trigger lever touches cog A'; during the forwards run of the slide, the trigger lever is re-armed when it touches cog A. In the same Figures are also shown the two bar lines C and C' that are connected to the slide and permit the chain to hook up the slide.

In Fig. 21.11 are reported side view of the authors' reconstruction; from top to bottom: unloaded catapult, a particular around the front sprocket and loaded catapult. In this reconstruction the crank is substituted by levers disposed in radial direction on the hub. From the Figure it is possible to observe: the two bar lines C and C' that are connected to the slide and hooked by a knob D that is one of the chain mails; the bar line and pin E that rotates the feeding cylinder by means of a helicoidal groove on the cylinder itself when the slide moves back and forth. The authors also supposed the presence ratchet mechanism F that probably was adopted to avoid a dangerous retrograde motion if the bars of the "motor" were released during the loading cycle.

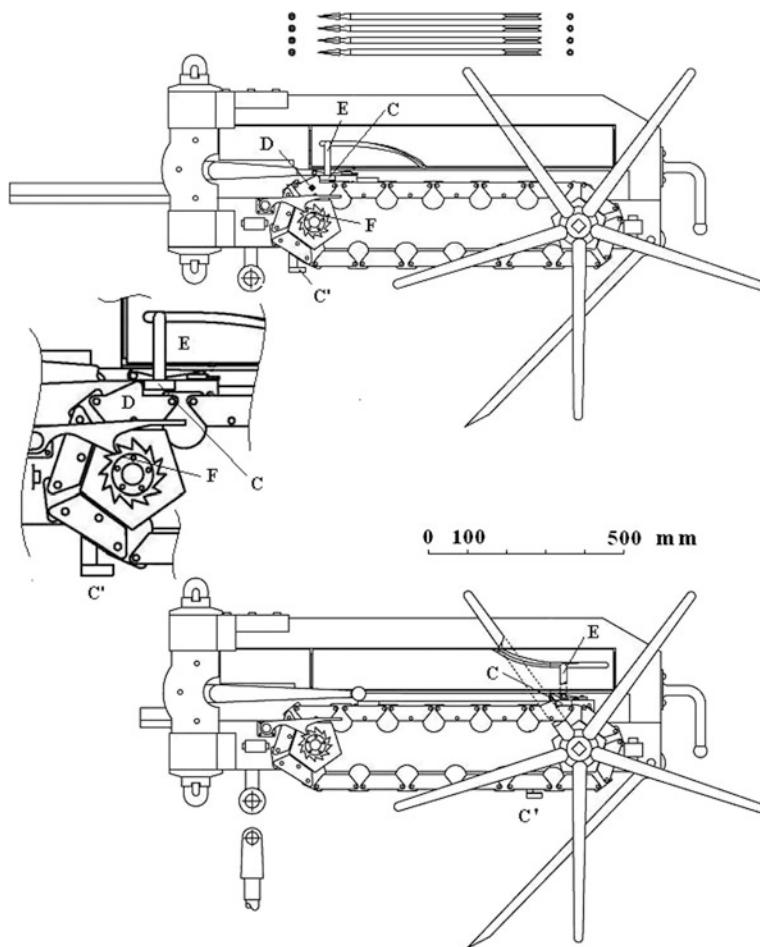
The authors believe that it is more simple (and hence more believable) that the hooking up of the slide by the chain was obtained by means of the chain cog as shown in the last Figure. In any case, it must be remarked that, according to the



**Fig. 21.10** Perspective section of the repeating catapult

authors' reconstructions, all the sequence was obtained by rotating the shaft always in the same direction.

From a ballistic perspective, the speed of firing must have been an average of five strokes per minute: very little when compared to our automatic weapons, but certainly impressive for the era. Paradoxically, this would have been useless as it concentrated all the arrows in the same location in such a short period of time that it continued to strike the same target. An unquestionable demonstration of its potential was confirmed in the early 1900s, when a life size reproduction was made in Germany: during the testing performed in before the Kaiser, one of its arrows split another arrow exactly in two!



**Fig. 21.11** Side view of the repeating catapult

## 21.2 The Middle Ages

In the Middle Ages some developments were made on the devices designed by the Greek and Roman engineers.

One of the inventors of automata in the Middle Ages is considered Pope Silvestro II (Gerbert d'Aurillac c.a. 950–1003 A.D.), a very controversial Figure of Pope. He was an appreciable mathematician and was very interested in scientific experiments but he was also suspected of being a magician. This bad fame was probably due to his interests in some machines that, at that age, could seem magical. He contributed to the introduction of Arabic numerals and the zero in Europe and built devices like planetariums, lighting rods, abaci, mechanical clocks and steam

pipe organs. Pope Silvestro II is also considered among the automata inventors because legend says he made a golden (or bronze) talking head that was able to reply “yes” or “no” to every question the inventor asked it. The legend also tells that, unfortunately for him, Silvestro II was not able to understand an automaton’s reply about his fate.

Talking heads are quite common in the Middle Ages up to the Renaissance. Another legend talks about a talking head made by Albertus Magnus (c.a. ~1200–1280 A.D.), a great German philosopher and theologian who evocated peaceful coexistence of science and religion. Another legend tells that the head was a real and complete android made of metal, wood, wax, glass and leather that could also talk and that it was made to work as a servant at the Dominican monastery in Keln. This automaton was destroyed by Saint Thomas Aquinas that was one of Albertus’ students. By the way, the term “android” was probably invented by Albertus Magnus and used to indicate living creatures made by man by means of alchemy.

### ***21.2.1 Al Jazari and the Arabs***

During the Middle Ages several Arab scientists studied many academic disciplines continuing the investigations of the Hellenistic scientists. Among these, Al Jazari (1136–1206) is probably the most famous Arab engineer and inventor. He was also a very brilliant artist, mathematician and astronomer. His name comes from Al Jazira, the ancient name of northern Mesopotamia (actually north Iraq and northeast Syria) that is the land where he was born in the 12th century.

Al Jazari is known for a number of significant inventions in many fields like mechanical control devices, water pumps, astronomical clocks and automata that he described this inventions in 1206 in his “Book of Knowledge of Ingenious Mechanical Devices”.

Among his automata the most interesting is the Elephant Clock; in Fig. 21.12 is reported a drawing of it from Al Jazari’s book. This device has several interesting mechanisms. The elephant’s body was partially filled with water and a bowl floated on it. The bowl had a hole that was calibrated so that it sank in half an hour; hence its weight was the motive power. When the bowl sank, by means of a string, it activated a mechanism on the top of the castle on the elephant; so a steel ball dropped activating the phoenix and falling in the mouth of a snake. The latter, lowering its head moved a Figure in the tower and activated the elephant driver that struck the hours. Once the snake left the steel ball, it rotated back to its original position and, by means of a chain, lifted up the bowl and the cycle was repeated. Under the castle, another automata was fitted that rotated on its axis.

The Elephant Clock originally was probably about 1.2 meters long and 1.85 meters high. A modern reconstruction of it, 8 m high, is at Ibn Battuta Mall, Dubay.

**Fig. 21.12** Elephant clock

### 21.2.2 *The Astronomic Clock of Strasbourg*

One of the most famous and interesting automata of the Middle Ages can be considered the cock of the astronomic clock in the cathedral of Strasbourg (or Strassburg).

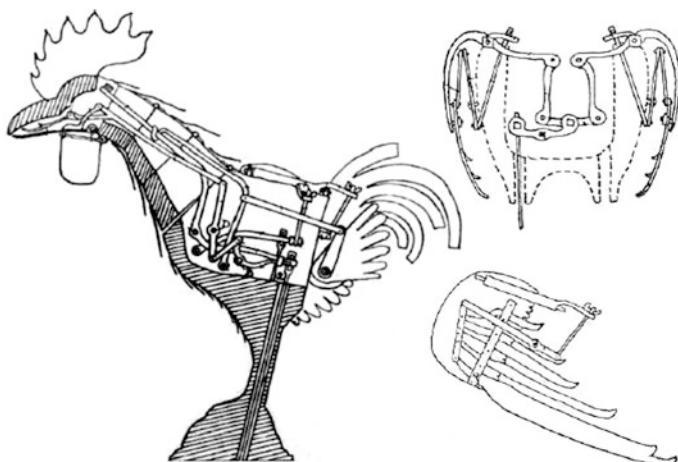
The first cock, at present in the Musée de l'Œuvre Notre Dame, is shown in Fig. 21.13. The clock has a long history reported by Alfred Ungerer, a clock maker who describes also the present clock's mechanism. The first one was made by an unknown clock maker probably to compete against and to overcome some clock in Northern Italy and was completed in 1354. It worked for about 150 years and then stopped working. In the middle of the 16th century it was slowly rebuilt; this new one worked till a short time before the French revolution. The clock that at present is working at the Strasbourg cathedral was restored by Jean Baptiste Schwilgué (1776–1856) between 1838 and 1842. All the clocks have a moving and singing cock that probably refers to Saint Peter's betrayal.

In Fig. 21.14 are reported the cock's interiors and sections showing the pinions' mechanisms.

The clock made in 1354 was also known as The Three Kings (Magi) clock; it consisted in a case about 12 meters high including a calendar dial and an astrolabe dial. Every hour, moving Magi kneeled to a statue of the Virgin with the Holy



**Fig. 21.13** The cock of the Strasbourg cathedral



**Fig. 21.14** Cock's interior

Child. At twelve o'clock a cock moved its pinions, opened its pecker, moved the tongue and sang three times.

This device can be considered one of the first examples of automata moved by a clockwork motor, while those of the classic ages were powered by steam or water.

## 21.3 The Renaissance

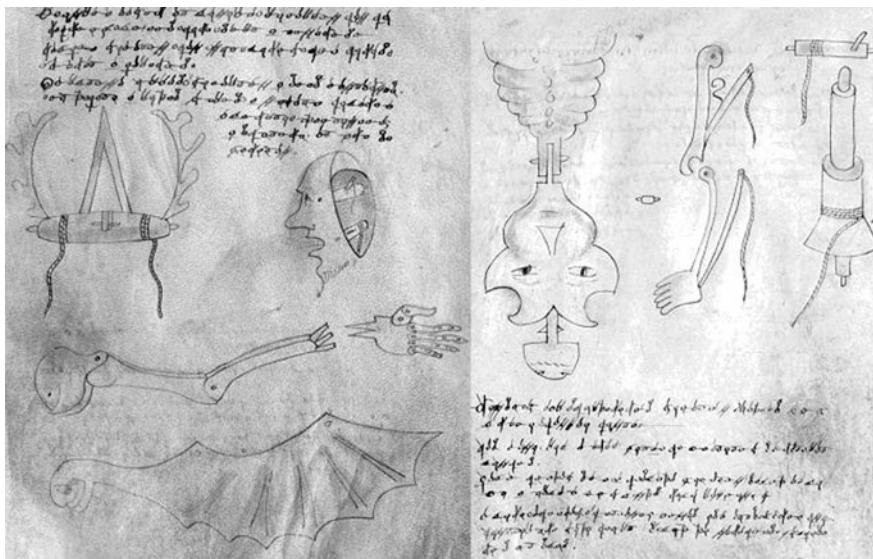
During the Renaissance studies and works on the automata increase considerably. It is possible to suppose that, in those years, ancient Greek-Roman codes were discovered and studied once again.

One of the first automata makers of the Renaissance is Giovanni Fontana. He was born in Padua (Italy) ca. 1395 and died after 1454. After a medical degree he studied optics, art of memory and pneumatics on Greek, Roman and Arabic codes.

The automata by Giovanni Fontana are described in his “*Bellicorum instrumentorum liber*” (Book on the war devices). The book that was written between 1420 and 1449; now at the Bayerische StaatsBibliothek and can be read on line on the Munchener Digitale Bibliotek. In the book many interesting devices are reported and are generally described by using a text in cipher; the drawings in the book demonstrate Fontana’s considerable knowledge in hydraulics and mechanics. In Fig. 21.15 an automaton representing a witch is reported (op. cit. folio 63 verso). The automaton, known as the blazing witch, can advance along an inclined rail and is controlled by a cable on a capstan. A spring permits to the automaton to throw an arrow or an explosive bomb. The witch body is articulated and can oscillate, move the head and the wings that are linked to the arms and the tail. A candle inside enlightens the automaton that spits rockets out of the mouth and the ears. On the right side of the Figure it is shown a hamper that shields the inner mechanism.



**Fig. 21.15** Automaton by G. Fontana



**Fig. 21.16** Joints of Fontana's automata

In Fig. 21.16 (folio 59 verso, 60 recto) some particular of the wings and legs joints of another of the Fontana's automaton are reported and some lines of the text. The text, that is ciphered and written in Latin, says:

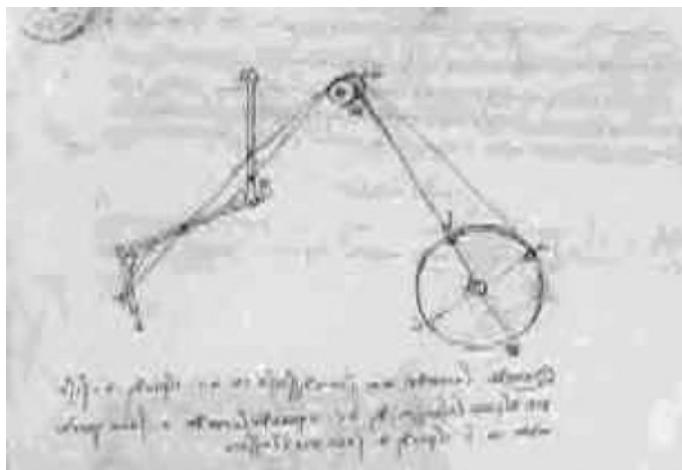
Ingenious making of a mechanical devil that time ago was built to provoke terror in those who looked at it. The horns and the crown move contemporaneously by means of a roll with some springs the pins of which are located in the ears. The tongue is moved by a roll whose pins are in the face. All the body joints move in their articulations like the fingers in us (humans), the hand in the wrist, the forearm in the elbow, the arm in the shoulder and likewise all the other parts.

Recently, several researchers have studied the drawings by Leonardo Da Vinci (Vinci, 1452—Amboise 1519) and have concluded that he had designed a programmable robot and programmable moving devices. Among these researchers Mark E. Rosheim and M. Taddei have made many detailed reconstructions.

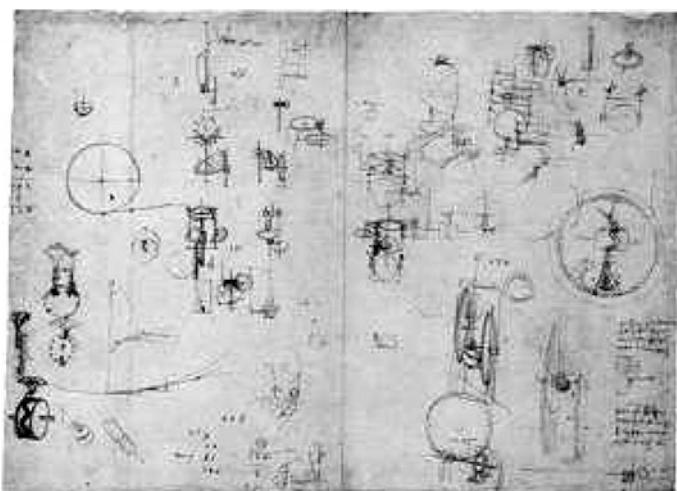
In Fig. 21.17 is reported, a drawing by Leonardo on the leg study (from Madrid Ms. I) and in Fig. 21.18 a drawing interpreted as a study of elements of the robot.

Another renowned mobile device by Leonardo is the mobile cart that has been recently reconstructed from Atlantic Code. In Fig. 21.19 is reported the folio 812r. It must be observed that working reconstructions are very recent after some non working attempts. The most recent working reconstructions are based on the assumption that the “motor” was not the two big leaf springs, shaped like the arms of a crossbow, that are clearly represented on the drawing but a spiral spring motor.

According to a chronicle Da Vinci built one (or two) walking lions as an homage to Francis I, king of France. The lion walked for a while and then opened his front



**Fig. 21.17** Study of the leg by Leonardo Da Vinci

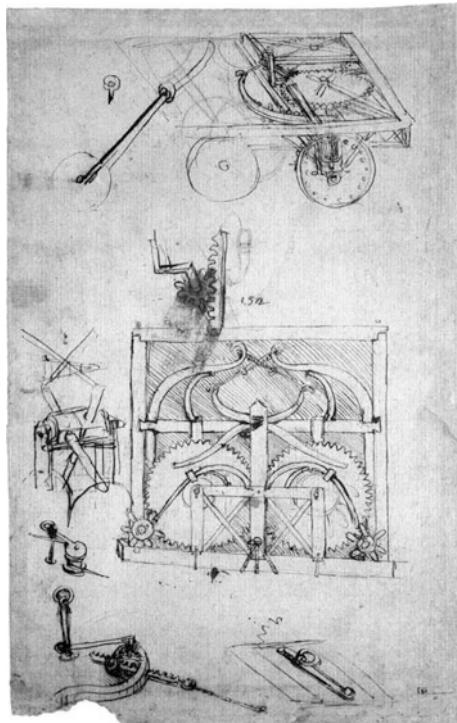


**Fig. 21.18** Drawing by Da Vinci interpreted as a study of elements of a robot

part showing lilies, the flower that is a symbol of the French monarchy. Unfortunately the reconstructions of this device are based on devices by French clock makers since the drawings by da Vinci or descriptions are not available.

Another interesting device was designed by Parè Ambroise (Bourg-Hersent, Laval, 1509—Paris 1590), a French surgeon that is considered as the father of modern surgery. He did not have an academic education and did not know Greek and Latin, hence he wrote in common French; this was an advantage because it helped the circulation of his treatises.

**Fig. 21.19** Atlantic Code f.  
812r

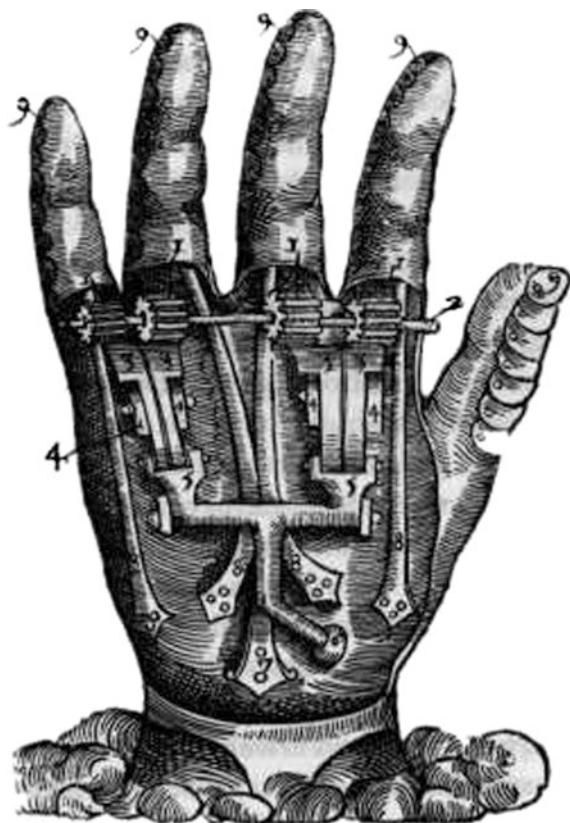


Parè Ambroise designed a number of prostheses that are described in his “Dix livres de chirurgie”, although cannot be considered automata to all intents and purposes, they are very surprising because of their modernity. In Fig. 21.20 is shown a hand prosthesis that was made for a French officer who lost a hand in battle. The design of actuators and joints looks very modern.

Among the mechanical prostheses the one made to replace the right hand of a German knight, Gotz von Berlichingen in 1508, must be mentioned. The prosthesis weighed about 1.5 kg and had five separate fingers that could be set opened or closed from an external button.

It is impossible to mention the automata designed and built during the renaissance. In that period the spiral spring motor was widely adopted to move mechanisms and devices, so, a new kind of mechanical clock, conceptually different from the previous ones, was developed. A lot of mechanic clocks were designed and many of them had moving puppets. Up to the 17th century these devices were considered as automata. Among these clocks we can mention the famous clock of the tower clock in Venice. It was built from 1496 and 1499 by Gian Carlo Rainieri. In the clock it can be observed the dial made with blue enamel and gold images where time, day, moon phase and zodiac are indicated; a mechanism (set in motion only on Epiphany) that every hour moves on a rail line a procession of automata representing the characters of the Nativity and the Three Kings (Magi). Then the

**Fig. 21.20** Hand prosthesis by Parè Ambroise



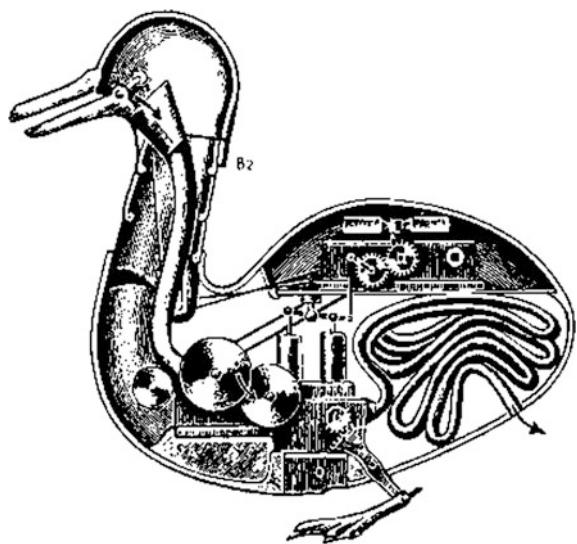
winged lion representing Saint Mark and Venice and, on the top, two automata. The latter are the famous “Mori di Venezia” and consist in two articulated bronze statues 2.6 meters high representing two shepherds that, every hour, hit with a hammer a big bell.

## 21.4 The 18th Century

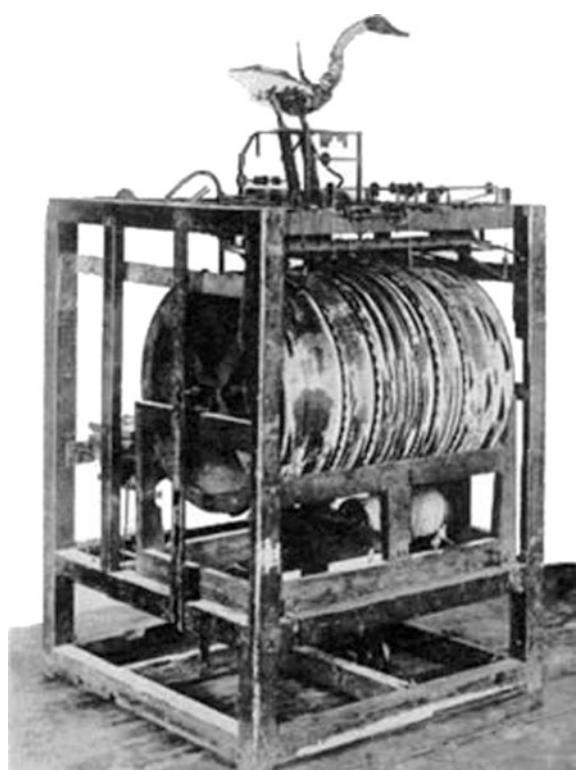
In the 18th Century together with a great progress of science a great advancement of technology and crafts occurs; this also applied to clock making. This century also represents an ideal context in which mechanical wonders can be developed to be shown at the European courts and to be given as a gift for kings and emperors.

One of the most famous automata builder was Jaques de Vaucanson (Grenoble, 1709–Paris, 1782) that is mentioned also in Chap. 19. Between 1737 and 1741 he built some automata, the most famous of which was the duck shown in Figs. 21.21 and 21.22.

**Fig. 21.21** Inside view of the Vaucanson's duck



**Fig. 21.22** Vaucanson's duck



This automata has been lost but it is mentioned in the “Encyclopedie”(1751) by Diderot (1713–1784) and d’Alembert (Paris 1717–Paris, 1783). One of the particularities of this automata is that for the first time an automaton designer reproduces, by mechanical devices, not only the movements but also the working of the internal organs of an animal. Actually a copy of the original automaton, made by Frederic Vidoni in 1998, is at the Musée des Automates in Grenoble, France.

The duck is made of more than one thousand pieces, in order to copy as best as possible the movements and functions of a living duck. The automaton really moves like a real duck, drunk and peck at grains.

Inside the duck surprising details are contained: the water and the grains, ground by the beak, are sucked into a little bag that imitates the stomach; here a sort of digestion was simulated and then the duck evacuates.

Detailed descriptions of how this pseudo digestion occurred are not available; Vaucanson himself, describing his automaton, said he would have explained the digestion’s working principle on another occasion. The well-known conjurer Robert-Houdin said he had restored the duck and that the evacuation of the bowels was made by a trick: a small amount of wet and coloured breadcrumbs were used to simulate this function. In 1783, an observer, also noted that between eating and evacuation it took a very short time. It must be also said that, possibly, several copies of the automaton were made.

Each one of the automaton’s movements was operated by toothed cylinders as shown in Fig. 21.22.

A few decades after the duck by Vaucanson, Pierre (1721–1790) and Henri-Louis Jaquet Droz (1752–1791) made exceptional automata. The Jaquet Droz were two Swiss clock makers, father and son.

The best known work by these inventors is represented by the three automata that are preserved at the Musée d’Art et d’Istoire, Neuchatel, Suisse. All the photos showing automata by the Jaquet Drozes have been kindly sent to the authors by Madame C. Junier, the curator of the automata at the museum.

The three automata are shown in Fig. 21.23.

They were three mechanical dolls moved by clockwork motors: the Writer, the Musician, and the Draughtsman.

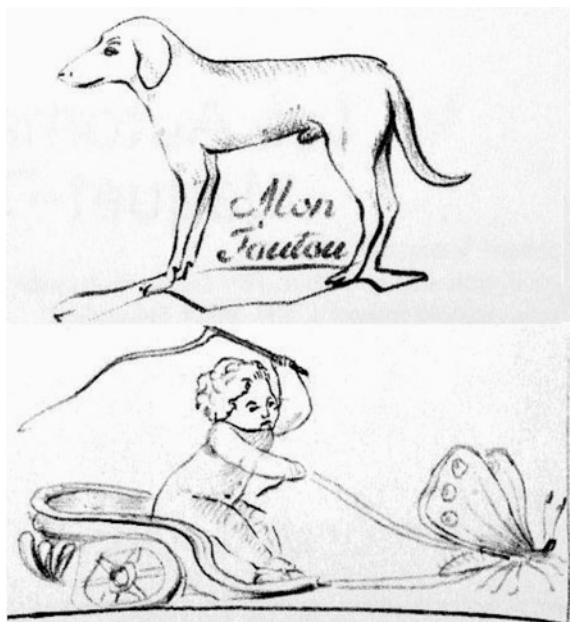
The writer, was made by Pierre and is the most complex, being made of 6000 pieces; it is able to write a given text up to 40 letters long with a goose feather that it inks. The eyes of the automaton seem to follow the text and the head is moved when the pen is inked. All the movements are obtained by cams located in the doll’s bust. The letters of the text written by the automaton are coded on a wheel.

The other automata were made by Henri-Louis and their mechanism is less complex: the musician is made of 2500 pieces and the draughtsman of 2000 pieces. The musician represents a young woman who can play different pieces on a real little keyboard. The draughtsman can draw four different images: a portrait of Louis XV, a couple of faces representing Louis XVI and Marie Antoinette, a dog with the writing “mon toutou” (my doggy) and a Cupid on a chariot pulled by a butterfly. These last two are reported in Fig. 21.24.



**Fig. 21.23** The automata by Jaquet Droz

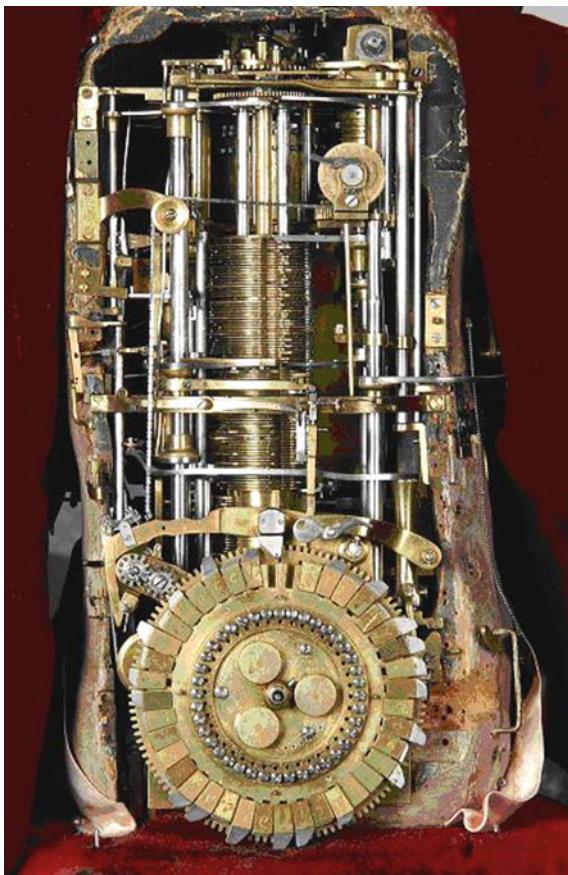
**Fig. 21.24** Drawings by the Draughtsman



In Fig. 21.25 is reported a photo of the writer's back, opened in order to show the mechanisms.

On the bottom a wheel can be observed; on the wheel circumference are installed some relieves that, when the wheel rotates, act on a rocher. Each relief corresponds to a certain letter or manoeuvre. Above the wheel are visible three sets of cams that

**Fig. 21.25** Writer mechanism



function as memory and activate the levers that move the automaton's hand in the three directions. Depending on the receives' height, another lever moves vertically the three sets of cams.

Since all these automata could make different works (although chosen from a restricted number of them) they can be quite considered as a first example of programmable robot.

The Jaquet-Drozes were helped by Jean-Frederic Leschot (1746–1824), an adoptive son of Pierre; in addition to automata, Leschot made prostheses to replace amputated limbs. It is possible to suppose that the musician's hands that had mobile fingers was designed by Leschot.

## 21.5 The 19th Century

At the beginning of the 19th Century, three Swiss brothers Jaques-Rodolphe, Henri and Jean David Maillardet made a series of automata. Henri was first an apprentice and then a partner of the Jaquet-Drozes; in 1805 he made an automaton that drew pictures and wrote verses in French and in English. The automaton was donated to the Franklin Institute of Philadelphia in very poor condition. Once restored, the automaton wrote a poem and the words “Ecrit par L’Automate de Maillardet”—Written by the Maillardet’s Automaton and revealed his inventor.

The following Figures of Maillardet automaton are reported with the kind permission of the Franklin Institute of Philadelphia. In Fig. 21.26 is shown the automaton.

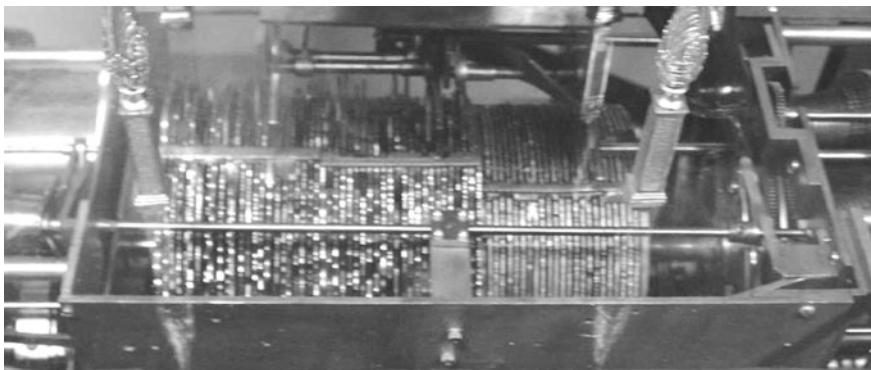
The one by Maillardet has the largest memory any automaton has ever had: it can draw four drawings and can write three poems, two in French and one in English. In this automaton also the memories are represented by a number of cams. While the automata by Jaquet Drotz had the memory in their body, the one by Maillardet has the cams mechanism in a large chest at its base. In Fig. 21.27 a view of its mechanism.

In Fig. 21.28 are reported a drawing and a poem from the automaton.

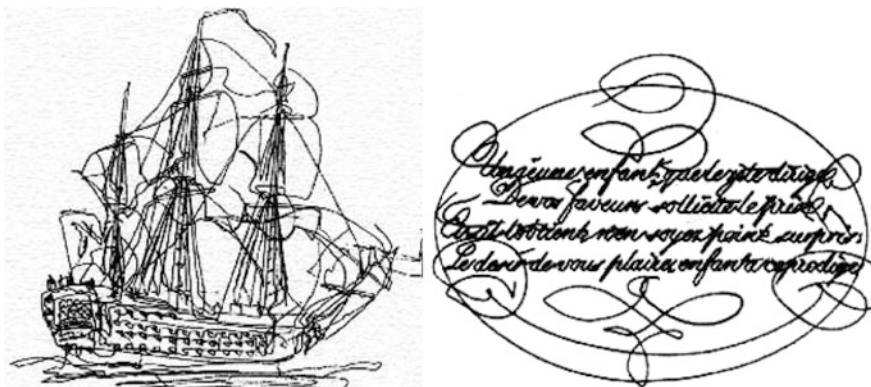
As it can be observed the quality both of the writing and the drawing is very high, especially if one thinks that any of the marks is obtained by a cam.



**Fig. 21.26** Maillardet’s automaton



**Fig. 21.27** Particular of the cams

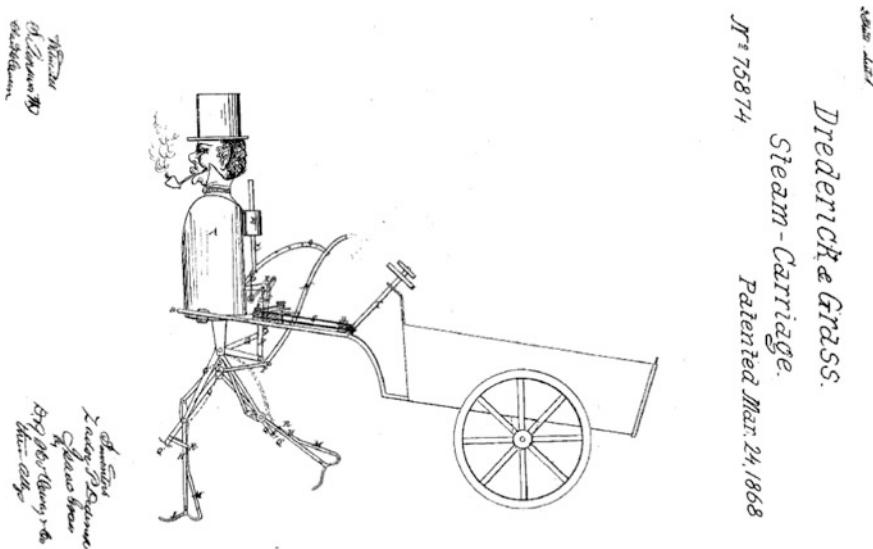


**Fig. 21.28** A drawing and a poem by Maillardet's automaton

With the industrial revolution the number of automata inventors rises but, generally, these automata are not so refined as the ones above mentioned. This aspect can be explained if we consider that both inventiveness and mentality of the inventors in the middle of the 19th Century were directed to more practical problems and devices. The automata that were built in the previous Century were masterpieces both in the engineering and in the fantasy fields. They seemed to be suspended between the real world and the land of dreams and they belonged to a time that was irreparably lost. In the following years many automata were designed or used by inventors or conjurers that were anyhow interested in conjuring that, in that age, was very fashionable.

The steam engine had reached its maturity and permitted to make machines that were capable of covering rather long runs and exerting considerable tractive efforts.

In 1868 Zadock P. Dederick, an American inventor, built and patented an automaton having the shape of a man that pulled a cart. The man was powered by a



**Fig. 21.29** Dederick's automaton, U.S. Patent 75874

steam engine, whose boiler was the man's body, rated about 3 hp. This automaton was about 2.36 m high and its mass was about 227 kg. In Fig. 21.29 is reported a drawing of the U.S. patent 75874.

Dederick's automaton inspired a long series of fantasy stories on an automaton made by Frank Reade Sr. called the steam man and later on another one, the electric man, built by Frank Reade Jr.

At the end of the century the Canadian inventor George Moore built another steam powered automata representing a walking man with an armour from 16th century. The steam engine was entirely contained in the body, the gas exhaust was emitted through the helmet and the steam through a cigar; its speed was about 14 km/h.

With the first world war, the automata era practically came to end.

## 21.6 Automata of the Far East

Automata were built also in the far East, mainly in Japan, China and India. These automata generally consisted in mechanized dolls having very high aesthetic qualities. Among these automata, the puppets of the Karakuri Ningyo are well-known; they were developed in Japan in 18th and 19th century. Karakuri means mechanical device to tease, trick, or take a person by surprise and Ningyo means doll. The best known automaton is the tea serving doll.

The cycle is started by placing a cup of tea on the tray, in this way the doll starts to move forward; when the cup is removed the doll stops and when the cup is placed again on the tray the doll turns around and goes back. These dolls are about 36 cm high and their motor is a wound spring made of whalebone, and the actions are controlled by a set of cams and levers.

## 21.7 Between the Two Millenniums

It has to be pointed out that a modern serial robot is made by a number of “rigid” elements, called links, arranged in an open kinematic chain. Each link is moved by a servomotor and its motion is independent of the other ones. In a parallel robot or parallel platform, also, each of the actuators’ motion is independent of the others. The movement of the machine is obtained by controlling and “synchronizing” the motions of the servomotors. The control of such robots has become possible just because of the modern computer and of the evolution of electronic components that occurred from the late ’40.

There are many definitions of what a modern robot exactly is, one of the most commonly accepted is given by The Robotics Institute of America (RIA) defines a robot as: “A re-programmable multifunctional manipulator designed to move materials, parts, tools, or specialized devices through variable programmed motions for the performance of a variety of tasks”. Hence, the modern robot seems to have very few common aspects with the automata from the past.

Nevertheless, in the last decades several industries have built machines that, somehow, could show a “revival” of the automata. Among these machines the most famous probably are the androids (or humanoid robots) of the P series and ASIMO built by the Honda and those by Toyota, Sony and Fujitsu and the doggy AIBO built by the Sony. P3 is 1.60 m tall, can walk (about 2 km/h) keeping its balance on its legs, accomplish some tasks with the arms and the hands and even go up and down the stairs. All its limbs have the same joints of the human ones. ASIMO is very similar to P3 but is 1.30 m high and can also run up to 6 km/h. The doggy AIBO walks on its four legs and can detect a ball and send it in a certain direction.

Until now these machines have the main function of technological demonstrators; from this point of view, although they differ under many aspects from the ancient automata, the humanoid robots could be considered as the last evolution of them.

Today, walking machines and robots, less complex than those mentioned above, can be bought and assembled from kits or separate components very cheaply by anyone with just a little knowledge or simply just a little good will. Many of these “toys” are re-programmable multifunctional devices since they have an eeprom that is programmable by means of a PC. Therefore, the diffusion and the low cost of the electronic components permit many people, nowadays, to build quite “grand-nephews” of the 18th century’s automata. However, it has to be said that these modern toys have neither the mechanical perfection nor the fashion of them.

## Observations

Whether the ancient automata were ancestors of the modern robots or not is a frequently discussed subject. About this argument the authors think that two aspects must be considered: a technical one and a conceptual one.

From a technical point of view, the term robot indicates a re-programmable multifunctional device; although many automata had a sort of re-programmability, certainly none of them was multifunctional. In addition, as aforesaid, a modern robot is moved by a number of servomotor and the motion of each of them is independent from the motion of the others; hence it is a multi degree of freedom mechanism. An ancient automaton, instead, was more complex from a mechanical point of view. It was made of many mechanical parts moved by cams, rods and so on and the same motor gave the motion to all; hence, it was a single degree of freedom mechanism: once the motor shaft position was assigned, the position of all the components was determined. This mainly because no complex control systems were available. For this reason, from a technical point of view, it seems the automata were not the ancestors of the modern robots to all intents and purposes.

From a conceptual point of view, it has to be observed that modern robots are designed and built for practical utility purposes; generally they are used to substitute or to improve manual labour in all those fields in which this substitution is useful. Automata, instead, were designed and built mainly for amusement. Although in many cases selling or exhibiting automata gave profits to their owners, it is quite evident that the inventors' main aim was the yen to fulfil a desire of their own, to surprising even themselves and, may be, also to run after a dream. From this point of view also, and perhaps mainly, the automata aren't the ancestors of industrial robots. Anyway it seems to be meaningful that the automaton's age ends quite completely at the beginning of 19th century.

The authors feel that it has to be remembered that in past centuries there were many scientists/engineers/craftsmen whose mechanical knowledge was much more advanced than one can commonly think, and it is correct to give them our tribute. Therefore, from this point of view, automata are interesting examples of the development of human knowledge and of human ability to invent new things.

It may be excessive to think that in some of these machines science and technology joined art and poetry; though excessive, one is tempted to think so.

# Chapter 22

## Some Ancient Building Techniques

**Abstract** In this chapter the main ancient building techniques are presented. The latter concern almost all the ancient civilizations, mainly in the Mediterranean area, and the Roman age in particular. Some examples of anti-seismic building techniques are also presented and some authors' virtual reconstructions of ancient seismic isolators.

### Introduction

In the previous parts mainly machines, devices and systems have been considered as inventions. From a wider point of view, however, also some building techniques and criteria are inventions. For this reason, in this last part, some building techniques and criteria are presented. They were adopted during a period of time ranging from the prehistoric age to the Roman era and named after their Latin name; to this end, it must be remembered that the Latin word “opus” means in English work. These techniques can be divided in two main categories: stone buildings and concrete buildings.

The examples reported in this chapter mainly (but not only) pertain to archaeological finds in Italy but are, in most cases, of general interest.

### 22.1 Stone Buildings

This kind of building is made of a number of stones just put together without using any mortar. The latter is a mixture of sand and a binder like cement or lime; the mixture is kneaded with water and then, after being applied as a paste, it hardens over time.

#### 22.1.1 *Opus Siliceum—Opus Poligonalis*

Opus siliceum and opus poligonalis are almost synonyms and can be translated in English as “polygonal masonry”; this technique essentially consists in piling up a number of non squared blocks of stone, even with very wide dimensions, without using any mortar, staple or pin. Examples of this technique are found all-over the



**Fig. 22.1** Examples of stone walls: opus poligonalis and opus quadratum

world in walls and retaining walls for embankments; it was also very common in the Italian Peninsula between the 6th and the 2nd century B.C. Polygonal masonry can be divided into different categories.

### 22.1.2 *Opus Quadratum*

This word can be translated into English as “squared work”; it essentially consists in a number of squared stone blocks, having all the same height and set in parallel courses without using any mortar.

Example of stone buildings are shown in Fig. 22.1: opus poligonalis on the left and opus quadratum on the right.

## 22.2 Concrete Buildings

The inventions of a binder for building materials represented a very important innovation in building techniques: a binder permitted to build walls by using bricks or different small sized stones that before this invention were unusable. Today buildings made by reinforced concrete are the most common ones.

The first binding material that were used by the Romans were: gypsum ( $\text{CaSO}_4 \cdot \frac{1}{2}\text{H}_2\text{O}$ ), lime (hydrated lime ( $\text{Ca(OH)}_2$ ) and a volcanic dust widely known as “pozzolana”. The latter was the best one and its performances are comparable to those of the Portland cement.

### 22.2.1 *Opus Caementitium*

This term, that can be translated as “concrete work”, describes the building techniques used to build structures by using concrete. The period of time in which it

was used starts from the Roman Republican Age and goes up to the end of the Empire. This technique just consists in using a mixture of aggregate and one of the binders reported before.

Often the raw surface obtained by using concrete was disliked and was covered by more pleasant materials.

### ***22.2.2 Opus Incertum***

This technique essentially consists in random inserting stones or small irregular shaped tuff blocks, in a core of opus caementitium.

The word “tuff” comes from the Italian “tufo” and indicates a volcanic stone (widely used in Southern Italy as building material till today) that has a relatively low density ( $1.34\text{--}1.68 \text{ kg/m}^3$ ) and whose color is often light yellow or, sometimes, light gray with darker areas.

### ***22.2.3 Opus Quasi Reticulatum***

This technique is half way between opus caementitium and opus reticulatum. It essentially represents an opus incertum where more regular stones have been placed more neatly and by using a smaller quantity of concrete.

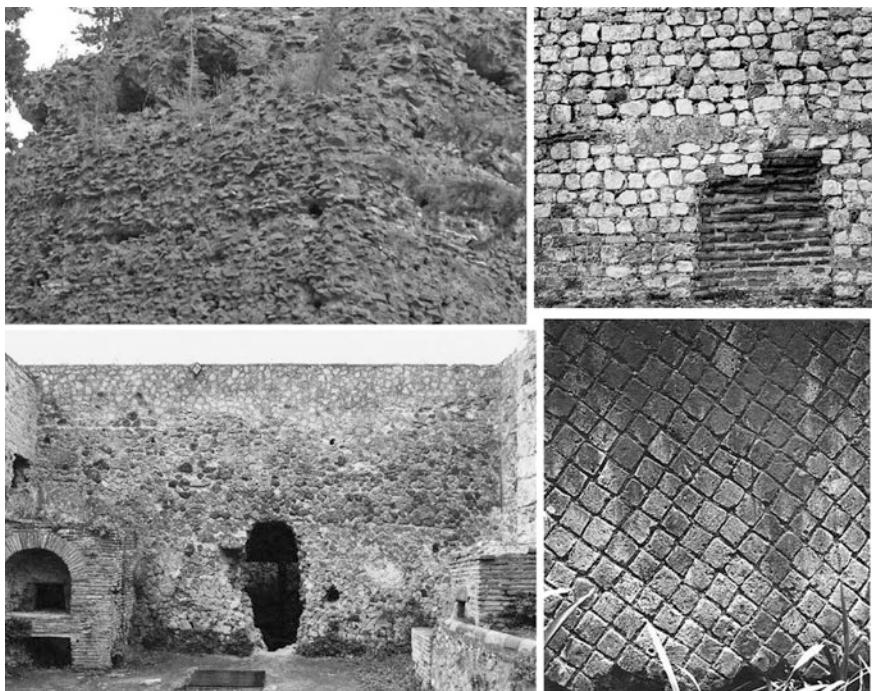
### ***22.2.4 Opus Reticulatum***

This term, can be translated into English as “reticulated work”; it describes a building technique that consists in a number of rather small bricks, all equals and having the shape of a perfect square (called cubilia), placed so that their side was inclined by  $45^\circ$  respect to the horizontal. In this way two thin walls were obtained and the interstice between them was filled with cement that constituted the main structure of the wall.

In Fig. 22.2 are reported some examples of Roman concrete building techniques; from above to below and from left to right: opus cementitium, incertum, quasi reticulatum, reticulatum.

### ***22.2.5 Opus Latericum***

The word “lateres” means in English “bricks”. This technique was described by Vitruvius and was the main one used during the Imperial Era; it essentially



**Fig. 22.2** Examples of Roman opera caementitia: cementitium, incertum, quasi reticulatum and reticulatum

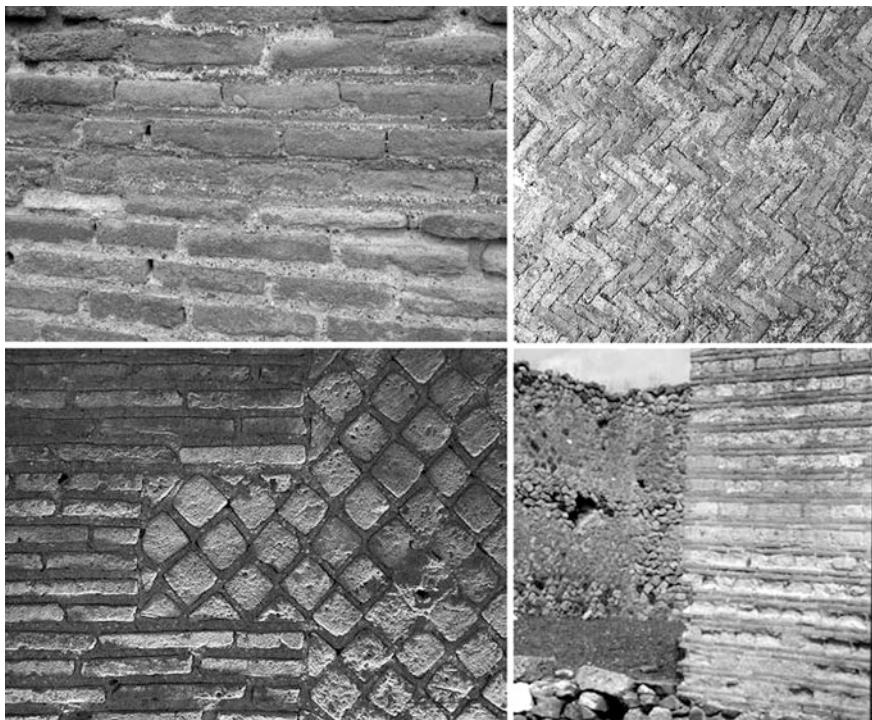
consisted in a coarse laid clay bricks cemented by a binder. Sometimes these walls represented the face of a core made by opus caementitium.

### 22.2.6 *Opus Spicatum*

The Latin word “spicatus” can be translated as “herringbone”. This technique was mainly used for pavements and for decorative purposes; it essentially consisted in bricks or cut stones disposed in herringbone shape.

### 22.2.7 *Opus Mixtum*

This term can be translated into English as “mixed work” and indicates a building technique that consists in a mix between opus reticulatus and opus latericum: the walls were made using the opus reticulatus while the corners were built by using the opus latericius. This technique was mostly used in the 2nd century A.D., during the reign of emperor Hadrian.



**Fig. 22.3** Examples of Roman opera caementitia: latericum, spicatum, mixtum and vittatum

### 22.2.8 *Opus Vittatum—Opus Listatum*

This technique was mostly used to build walls (an example is represented by the Aurelian Walls in Rome), mainly from the beginning of the 4th century A.D., and consisted in courses of bricks alternated with small tuff blocks.

In Fig. 22.3 are reported some examples of Roman concrete building techniques; from above to below and from left to right: opus latericum, spicatum, mixtum and vittatum.

## 22.3 Considerations on the Polygonal Work

The polygonal work is building technique used in early Italic fortifications technique this at least during the first four centuries, is known in its many variants as polygonal, megalithic, Pelagian, Mycenaean, to cite only the principal definitions. Simply put these are walls erected by putting together large, irregularly shaped

stones, made to fit together as closely as possible without any bonding agent (Rudofsky 1979).

The ancients also used the adjectives ‘Saturnian’, ‘Tirynsina’ and ‘Lesbian’. These categories and specifications at times appear to indicate the geometric nature of the stones, their incredible number or their supposed ethnic origin, but also stupor and marvel for the laborious work required for their assembly. It was this latter state of mind that was the basis for the more fantastic and suggestive classifications that disregarded the human paternity of the structures and attributed them to the intervention of supernatural beings; thus walls of fairies, of the devil or of witches but in all cases manifestations of magical power, the only ones believed to be capable of such obtuse grandiosities. For the Romans however, who were very familiar with this type of construction as they had been using it since the beginning of their history, it did not merit a special definition, apart from the much abused one of *opus incertum*, absolutely incongruous and misleading.

Polygonal construction, especially in its most refined and precise phase, justly reputed to be the evolutionary apex of this technique and chronologically the most recent, is not a prerogative of the Mediterranean people, for it existed in raised structures and with identical geometric features, also in Japan, Asia, Africa, Britannia and even in Peru and the Andes, between the II millennium B.C. and the 15th century AD. To overcome so much uncertainty scholars have: “searched in their form and structure for chronological, ethnographic and historical clues, but they exist in all eras, among all peoples and in all countries” (Guadagno 1988).

In the beginning of our century Ashby introduced (Ashby 1905) a basic distinction between polygonal and cyclopean works, stating that: “one should use the term polygonal only for constructions where such intent is manifest, applying to all others consisting of irregular blocks the name cyclopean...”.

To remain with Italy, we must note that its territory is not homogeneously representative of the polygonal technique. The majority of such works are found in Etruria Marittima, in Sabina, in Marsica, in the territory of the Hernici, the Volscians and the Samnites. They are less frequent, but not completely absent, in Northern Italy and in Magna Grecia, as well as in Lucania and Sicily. This can doubtlessly related to the vast uses of this technique in antiquity, summarized as follows:

1. City walls, especially those that were irregular and without towers
2. Individual strongholds or citadels
3. Mountain defence barriers, incorrectly called hillside entrenchments
4. Bases for temples or podiums
5. Road construction and related works
6. Paving stones for military roads
7. Agricultural terracing
8. Concrete beds for the construction of villas
9. Sepulchres and cisterns
10. Isolated towers or “monopirgi” (isolated towers). Nuraghes also belong to this category
11. Abutments for bridges and, more rarely, the bridges themselves.

### 22.3.1 *Construction Criteria*

Regarding the interpretation and classification of these constructions according to the typological and structural criteria of the polygonal technique used, one of the first scholars to analyse it is Gerhard (Gerard 1831) who attributed the technique to the Pelagians or to the Aborigines, but reiterated the difficulties and arbitrariness of establishing the date solely on the basis of formal connotations. The same writer noted that Roman roads were influenced conceptually as irregularly shaped paving stones were used on its surface but he did not analyse the reason for this choice. The work was continued by Dodwell (Dodwell 1834) who began to classify the construction according to different manners or types:

- 1 Rough manner, consisting of boulders with a rough surface and of irregular form, installed without any smoothing or shaping, using chips of smaller stones as wedges to achieve better linkage and stability.
- 2 Perfect manner, achieved by ensuring the masses of stones shaped as irregular polygons and made to fit together perfectly, with tolerance reduced to the minimum for accurate smoothing of the contact surface.
- 3 Horizontal manner, using hewn stones that, although they had yet to acquire an orthogonal configuration, tended to a flattening and an approximately horizontal direction.

Obviously the same scholar noted the existence of intermediate techniques and subtypes, all of which could be attributed to the above manners. Promis, (Promis 1836) who studied ancient fortifications, also studied the dates of these constructions, attempting to classify them: “according to the greater or lesser accuracy of work in order to compare them in the usual manner, although history and observation demonstrate that polygonal work, rather than being attributed to certain periods and certain peoples, should be attributed to locations and to the materials of the various countries and that it is from this information that one may judge its greater or lesser perfection” (Lugli 1957).

For the first time geomorphology is placed in strict correlation with this technique, even if only to explain the greater or lesser accuracy, representing an acute intuition of the role played by the natural context in its use and optimisation. The same scholar did not neglect to note the horizontal variant of the polygonal in the paving stone of numerous Roman roads, yet again without arriving at a plausible reason. His observations were shared by many other authors, such as Niebuhr, Gel and Canina, while Poletti (Poletti 1838) further detailed the formal classification of the polygonal, classifying it into four “manners”, corresponding to as many separate eras. But he avoided establishing the relative chronology, limiting himself to observing that, undoubtedly, the most ancient had to be the crudest.

The reasoning, apparently self-evident, had until then always been frustratingly limited to the facile observation that in the same circle of walls, presumably constructed without interruption, can be found extremely varied elements of executive skill. Thus if it is absurd to determine the crudest section of a wall in a single work

to be much older than the more accurate ones, the generalisation that the crudest fortifications are incontrovertibly the most archaic is just as arbitrary. Between backwardness and ancientness there is in fact a univocal type of correspondence, thus if the fortifications built in remote eras are the result of rudimentary knowledge and abilities, that doesn't mean that crudeness necessarily indicates ancientness. In fact, if we compare the accuracy of the polygonal scheme of a fortification with its obsidional exposure, we note that even in the evolved ones the sections reputed to be unassailable are always cruder than those supposed to be at risk and this for obvious motives of economic and human savings. However, when even the sections that are exposed are approximate and crude, this means that the constructors did not yet have the necessary skills and the works must therefore date to an earlier era. Once this concept became known, the inter-relationship of accuracy-period became recurrent in subsequent classifications of the polygonal. Fonte a Nive, for example, though adhering to the three distinctions, indicated the time periods, thusly:

*“1st era, isolated stones joined in an irregular manner with the interstices reinforced by smaller stones...”*

*“2nd era, blocks flattened in the corners and in the crevices and facades so that they were joined without interstices; the fronts are rounded with a bumpy surface, similar to rusticated work; the tapering still preserves the projections... The trapezium masses appear to be from this era...”*

*“3rd era, the masses of stone are completely flattened and smoothed externally, cutting off all projections; the stones, even the squared ones, are posed in horizontal layers with the vertical joint lines inclined toward different directions. The layers of blocks are not always horizontal but tend to curve. This may be attributed to the method of squaring the boulders and the nature of the terrain that obligates the levels of installation rather than to a predilection for curved lines, which would presage a future use of arches,...”* (Lugli 1957).

The architect Giovenale (Giovenale 1900), after surmising the existence of a different cultural matrix for the polyhedral and megalithic walls, agrees on the correspondence of the three manners with as many eras. In any event, he admits that these are very ancient works requiring a great number of specialised workers or itinerant teams of specialists, perhaps of oriental origin. The theory that such structures might in some way derive from Mycenaean fortifications was at the basis of the tests undertaken the beginning of this century in Norba, by the Italian Ministry of Education. But the results only demonstrated the significant modernity of this construction compared to similar ones of the Argolis. On the basis of the ceramic fragments found, in fact, it was ascertained that the city dated to almost a millennium after the latter, to be exact to around the 3rd cen. B.C., thus: “Norba was an essentially Roman fortress, of clear Italic character, as were Italic the people whose tombs are found underneath the plain; and that the walls of Norba, as we see them today, are older than the era of Roman colonization” Further research highlight the significant differences between the perimeter city walls and the interior walls of the acropolis, the typical Italic citadel, estimating that the latter corresponded to the original nucleus of the garrison, dating to the VI-V sec. B.C.,

basically contemporaneous with the proliferation of these fortifications. Although it chronologically reiterated the indirect Mycenaean influence due to the presence of the apical citadel, it also seemed to enhance it as an archetypical stimulus.

Returning to the formal characteristics of the polygonal technique, after an attentive assessment of all preceding classifications and subdivisions Lugli elaborated yet another more accurate and detailed theory that has become the classification *par excellence*. First of all he observed that: “it’s a question of *ma-nners* and not *eras*, and the inclusion of a monument in one manner rather than another does not in the least prejudice its chronology... Furthermore, the *manner* is established according to the assessment of the entire masonry complex, since the characteristic of polygonal work is to be significantly varied even in the same building...” (Lugli 1957).

In summary:

## I MANNER

The material is collected on the ground, or detached from the rock with levers or beaten wedges... using the deep fissures and the cavities; it is hewn using sticks or other stones, sufficient to remove the excessive projections leaving the exterior and the sides in the rough state. The heaps of boulders, that are never too large, are rolled by means of poles, proceeding from top to bottom, with the work being performed by a small group of workers... It is difficult to put a date to these walls, representing the first efforts of man for a stable construction... in Italy the initial date may be the end of the 7th century B.C. or at the latest the beginning of the VI...” (Lugli 1957).

Examples of fortifications erected in this manner obviously abound and the most significant may be divided ethnically as follows:

**Etruscans:** Populonia, Roselle, Cortona

**Volscians:** Segni, Preneste, Cori, Terracina–Pesco Montano, Circei, Atina.

**Samnites:** Aufidena, Piedimonte Matese–monte Cila, Sepino–Ter-ravechia, Faicchio–monte Acero, monte Monaco

**Sicilians:** Termini Imerese

## II MANNER

The boulders were completely detached from living rock along the surface, taking advantage of the stratification. “...The initial work began on site using sticks and chisels, making the front facade lightly convex. In this manner the blocks already assume a polygonal form with the sides straight, but of different lengths; the corners are still rounded and the joining is not perfect; the tendency to the polyhedral form begins. The bearing surface is intentionally avoided, except near the doors and corners. The chocking wedges are still frequent... The walls are generally built close to hills: rarely are they isolated on both sides... The blocks are installed tapering from the bottom to the top, by means of offsets... a disadvantage for

defence because this allowed attackers to introduce... poles into the crevices and scale the walls with a certain facility... An Italic tradition begins to emerge, following a specific development that, once affirmed, becomes a constant rule... The builders know that it is easy for attackers to use the interstices between the different masses as levers, introducing large beams and thus make large openings in the walls; for this reason the size of the blocks increase, they make the joints fit together better... smooth the exterior walls..." (Lugli 1957).

It should be noted that in the polygonal work, especially beginning with the second manner, since the lateral stability of the construction depended on the mutual contrast of the blocks, it was not possible to interrupt the wall vertically without collapsing. A perimeter fortification did not allow for any angles, either acute or obtuse: the inclined bearing surfaces would have immediately torn away the terminal hewn stones, those lacking a counter-thrust. When this need became inevitable, and the examples though rare are not lacking, such as near the doors or the even thinner towers, this was resolved by closing the polygonal scheme with a section in square work, consisting of large orthogonal blocks placed on a horizontal flattening. This detail explains the reason for the curvilinear movement of the polygonal circle of walls, which also demonstrated, if there was a need, that the builders were perfectly aware of the characteristics of the parallelepipedal hewn stones but preferred the irregular ones, though they were more complicated to make and more laborious to install.

Concerning the alleged siege machines used to demolish polygonal walls, we must suppose them to be substantially similar to reinforced beams, like a giant palanquin, and far removed from the classical battering ram. Unfortunately we have no iconographic or material representations of these devices: a single exception being the bronze head recently found during excavations in the Olimpia stadium, a probable military ex voto.

Returning to the second manner, its significant examples, also distinguished ethnically, are:

**Etruscans:** Populonia, Vetulonia

**Umbrians:** Amelia, Spoleto

**Volscians:** Preneste, Segni, Sezze, Norba, Terracina, Arpino, Montecassino

**Hernici:** Fermentino, Alatri, Olevano

**Samnites:** Pietrabbondante, Isernia, Calaza, Treglia

**Lucanians:** Atena, Accettura

### III MANNER

The blocks take the form of regular polygons, with straight sides and sharp edges; they fit together perfectly, facilitated by triangular wedges inserted into the spaces. There are frequent insertions of blocks by means of a tooth-like outwork in the mass of stones already installed. It appears that the blocks were worked on site, using a bevel or a lead lamina to bring the corresponding angle of the one ones that had to

connect with in the wall under construction. This process was no longer performed by rolling the boulders from the top to bottom, but by carrying them from the excavation level to the work level using wood scaffolding... the work proceeds by means of two teams of skilled workers coming from opposite directions... until the two work sites are joined by means of a keystone... The thickness of the masses and the interior levels are in relation to their static function... The exterior surfaces are worked in gradines to make them perfectly smooth, while the bearing surfaces are cut using a stick and chisel; the face is then aligned with the plumb line, considering the necessary inclination... In the corners, near the doors and towers, there is greater emphasis on horizontal levels... to avoid the lateral thrust of the boulders..." (Lugli 1957).

The ethnic examples are:

**Etruscans:** Cosa, Orbetello

**Umbrians:** Amelia

**Volscians:** Cori, Norba, Segni, Atina

**Hernici:** Fermentino, Alatri

**Samnites:** Pietrabbondante

**Sicilians:** Cefalù

#### IV MANNER

The imitation of square work is obvious here although it is not exact, both because they preferred the irregular aspect and also because the material used is almost always calcareous rock, which is very difficult to cut. The blocks are flattened using long bearing surfaces that follow a sinuous direction and that are periodically interrupted due to the different height of the courses; they are cut according to four levels that are not parallel and the vertical joints are almost always oblique; their cubic volume and depth varies; they are always installed lengthwise.

Figure 22.4 illustrates some examples of the four manners (Lugli) of the polygonal works.

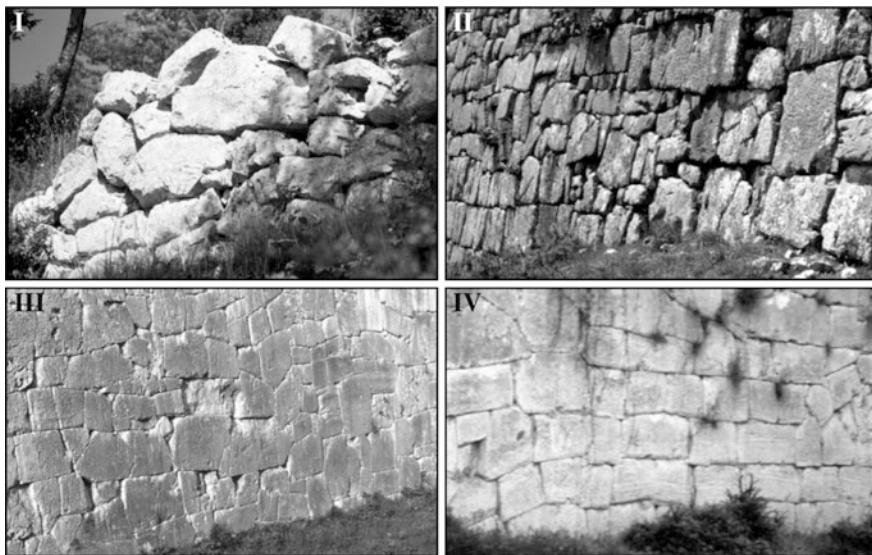
The walls are slightly convex, as the dressing of the facades begins from the periphery of the blocks toward the middle, thus the frequency of rusticated work, accompanied by *a-na-thyrosis*. At times the polygonal work is coupled with cement work, acting as external facing or simply as angular bonding element. The principal examples of this last manner are:

**Etruscans:** Cosa, Perugia

**Umbrians:** Todi

**Volscians:** Palestrina, Sezze, Terracina

**Hernici:** Fermentino



**Fig. 22.4** The four manners of the polygonal work

### 22.3.2 *Theories on the Reasons for Polygonal Work*

The architectural subdivision of the polygonal technique and its detailed distinction, apart from the chronological uncertainties, leaves unanswered the basic question. Why did so many populations recently issuing from prehistory use such a laborious and complicated building technique, progressively refining it instead of abandoning it? Why is it that in the subsequent centuries Roman engineering, much more evolved and rational, extended it even to road construction, preferring irregular polygons to rectangular paving stones?

To construct using the polygonal technique, especially according to the second and third manner, meant shaping every enormous block to fit closely with those already positioned in an increasingly accurate manner. The slowness and difficulty of this procedure, certainly not justified either by military objectives or alleged aesthetic effects, difficult to imagine in the case of road surfaces, is understandable. The presence of square work segments near rooms or corners, as mentioned previously, forces us to exclude the possibility of ignorance or inability to build according to this enormously simpler and faster method of construction. The use of parallelepiped blocks, as well as rectangular paving stones implying an exact dimensional standardisation, allowed for abundant prefabrication in the quarry. Which not only would have provided an uninterrupted supply, as their number was based only on the number of workers, but would have allowed for a faster and more economical progress of the works, a significant characteristic in such important

structures. Without considering the fact that only finished and infinitely less heavy hewn stones needed to be transported to the work area.

Nor is it seriously admissible that the Japanese, Peruvians, Mycenaean, British, Italics, Sicilians and North Africans, in different eras and circumstances but in complete autonomy, would all work out the same mad manner of assembling enormous stones skilfully shaped. Lugli perceived this singular affinity, stating that: "the phenomenon of genuine and spontaneous polygonal work is found in Mexico and Peru, where there are numerous inviolable enclosures and fortification walls from the pre-Columbian era..." (Lugli 1957).

It is amazing to note that in all ethnic-geographic contexts listed, the use of polygonal construction was used constantly for structures intended to last for an extremely long time and to sustain powerful strains caused by natural and artificial stress, such as fortifications, roads, bridges, temples and privileged burial places. But how can one define as spontaneous and genuine a technique chosen in the full awareness and acceptance of the difficulties and exasperating slowness of execution? What was the common factor that persuaded the Incas of the Andes and the Volscians of the Apennines to erect their walls in that specific manner?

If we reflect upon this, starting with the mentioned resistance to extremely intense and brief stress, it is the analysis of the characteristics of the regions involved that provide the probable solution to the enigma. These features are associated unequivocally with another that is regularly reiterated every time there is a seismic catastrophe: all users of the polygonal technique, from the prehistoric Hittites to the very recent Peruvians resided on mountain plates or in their immediate vicinity! In other words always in locations that were systematically and terribly devastated by frequent and horrendous earthquakes caused by the lifting of the Andes-Alpine-Himalayan tectonic plate. The polygonal technique, with its careful elimination of horizontal "flattening surfaces", (the parallel surfaces of a block that are onto contact with the ones of the upper and of the lower blocks) prevented the hewn stones from sliding when subjected to the powerful solicitations of telluric quakes. Thanks to their irregular configuration as soon as the quakes stopped the blocks, though undergoing a significant rotation, repositioned themselves exactly in the initial position, dissipating the murderous destructive energy in imperceptible movements without any perceptible consequences.

This type of polygonal construction, from the second manner on, is certainly and ancient and widespread anti-seismic type of construction and the hundreds of works that have come down to us basically undamaged in geologic contexts where no other construction, even those built much later, survived, confirms the hypothesis (Pantoni 1980).

As for the road paving, the reasoning is identical, as it is sufficient to replace the telluric stress with the unceasing mechanical stress caused by the passage of heavy carts that went on for centuries (Mondini 1973).

And after all what sense would it have made to erect fortresses or systems of fortresses, as did the Samnites, that were not able to sustain the first earthquake to hit the area? Without adequate structural resistance the seismic recurrence, that along the Alpine-Apennine fold does not exceed 30 years, would have numerous

reconstructions of the fortifications, economically impracticable and militarily dangerous. During the interminable conflicts of the era, a potential aggressor could have easily launched a massive attack immediately following a violent quake, as the quake could be heard from hundreds of kilometres, relying on the radical destruction of any static defence.

The solution just mentioned is based on criteria that from the technical perspective are in clear contrast with those currently in use. Contrary to our structures in reinforced concrete, that tend to avoid destruction by reacting, as a whole, to stress, those in polygonal work oppose a sort of prefragmentation that cannot be separated any further. It is no accident that the use of this technique ceased with the arrival of concrete, when the engineers of antiquity were finally able to make relatively monolithic constructions.

Polygonal work did not disappear in applications in which concrete could not replace it exactly because of its rigidity, as in the construction of roads that only in the modern era and for financial reasons adopted rectangular paving stones.

### 22.3.3 *Polygonal Bridges*

Polygonal construction was systematically in areas with high seismic activity and in those areas that were exposed because of their destination and location to continuous albeit modest or rare but much more violent mechanical stress. Such as the stress caused by vehicular traffic or the fury of flood waters over bridges, commonly neutralized by the polygonal construction work, horizontal for roads and vertical for all other cases. Figure 22.5 illustrates a bridge of polygonal construction located near Cusano Mutri, Benevento, Italy over the Titerno stream.

In these cases a moderate amount of help was provided by the fact that the builders were familiar with the direction from which the thrusts issued: indeed, the



**Fig. 22.5** The polygonal construction bridge over the Titerno stream, Italy

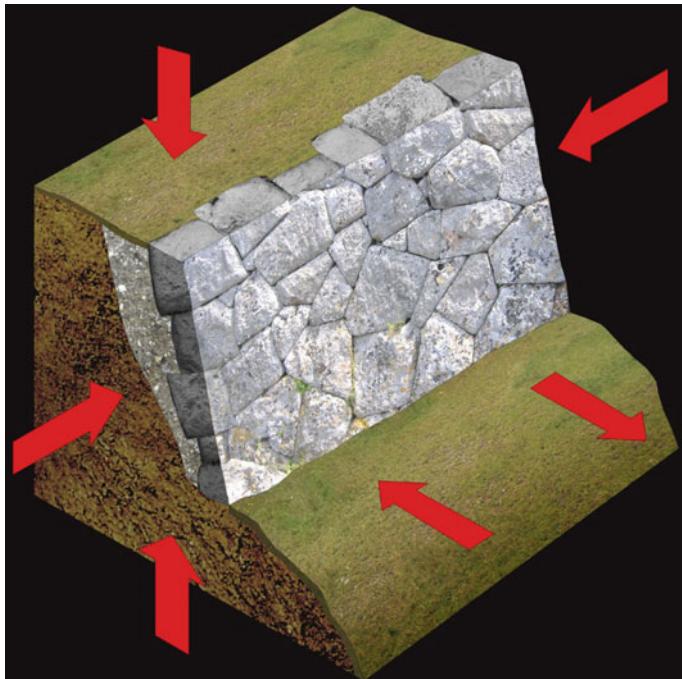
force of a seismic event did not always strike only the sides of a construction, that is from lateral directions, or from bottom to top, but could come from any direction.

In fact, if we study the method used for polygonal construction work, we can easily see that the structures were erected directly on the rocks of hill slopes, with a significant uphill inclination, a system still in use for retaining walls so that the weight of the stones compensates for the weight of the overlying soil. In this particular case the inclination neutralizes most of the transversal seismic stress, leaving only the neutralization of longitudinal stress to the polygonal mesh.

In Fig. 22.6 a scheme displaying the resistance to stress of a polygonal structure is shown.

Thanks to their irregular shape the polygonal quoins, though oscillating during seismic activity the minimum amount tolerated by the slot-in system of construction, upon conclusion of the thrusts immediately returned to their initial position thanks to the greater strength of the masses, without any appreciable consequences. A dynamic condition that takes place on the abutments of a bridge battered by the flood.

Although the above explanation may be considered an extreme simplification of what actually takes place, nevertheless it effectively explains the advantages of the polygonal technique used both for the heretofore described fortification structures as well as for bridges made in this manner and of which there are still significant



**Fig. 22.6** Scheme displaying the resistance to stress of a polygonal structure



**Fig. 22.7** Fabio Massimo Bridge near Faicchio, Benevento, Italy

examples that have remained intact, especially at the base. This method was one of many conceived to contrast seismic activity. And it is among the ruins of Herculaneum and Pompeii that we find a second criterion, one that even after the appearance of reinforced concrete cannot be considered as exhausted.

Figure 22.7 is a photograph of the recently restored Fabio Massimo Bridge, located in the area of Faicchio, in Benevento, Italy, whose base in Roman polygonal work dates to the II c. B.C.; in the lower section of the picture are details of the base. Below, to the right, we can see a quoin that sticks out of the wall revealing sides perfectly perpendicular to the front.

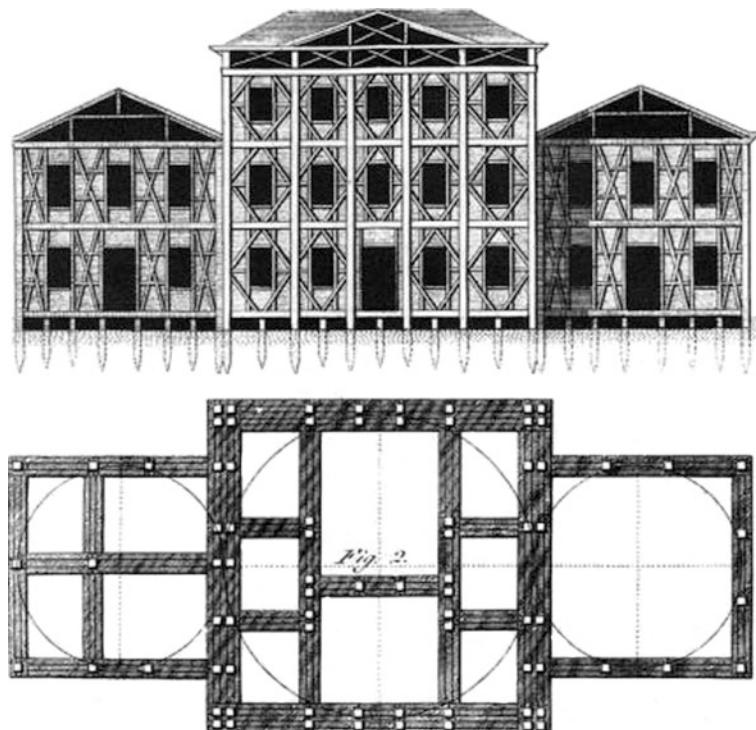
## 22.4 Earthquake-Resistant Buildings with Wooden Ribs

Following the earthquake that devastated the city of Lisbon in 1775, it became necessary to construct public and private buildings using a special construction technique called ‘baraccata’, which entailed building structures that had a strong wooden frame englobed inside the walls. Its purpose was to link the entire structure by joining the various parts thus reducing the tendency to separate if struck by seismic quakes.

In 1783 it was Reggio Calabria that was destroyed by the earthquake and the Bourbon government, aware of the above described effective technique, issued a construction regulation ordering all constructions to be made in accordance with the ‘baraccata’ method. Figure 22.8 shows two drawings for a baraccata house by Vincenzo Ferraresi, taken from “Istoria e teoria de’ Tremuoti in generale ed in particolare di quelli de la Calabria e di Messina avvenuti nel 1783 di Giovanni Vivenzio, cavaliere dell’Ordine Regale e Militare Costantiniano di S. Giorgio”, Royal Printing House of Naples 1788 (History and Theory of Earthquakes in general and in particular of those occurred in Calabria and in Messina in 1783, by Giovanni Vivenzio, knight of the Royal and Military Order Costantiniano di S. Giorgio). In Fig. 22.8 a plan of a ‘casa baraccata’ is reported.

In 1860 the Pontifical State also implemented the same regulation in building the municipality of Norcia, using as reference type the baraccate houses that had already been built in Naples. This was followed by Casamicciola which, after the terrible quake of 1883, used the same technique, as did various towns in Liguria after the earthquake of 1887.

From a historical perspective the method of ‘casa baraccata’ was invented in Italy, specifically in Calabria in 1638, and we point to the palace of the Count of



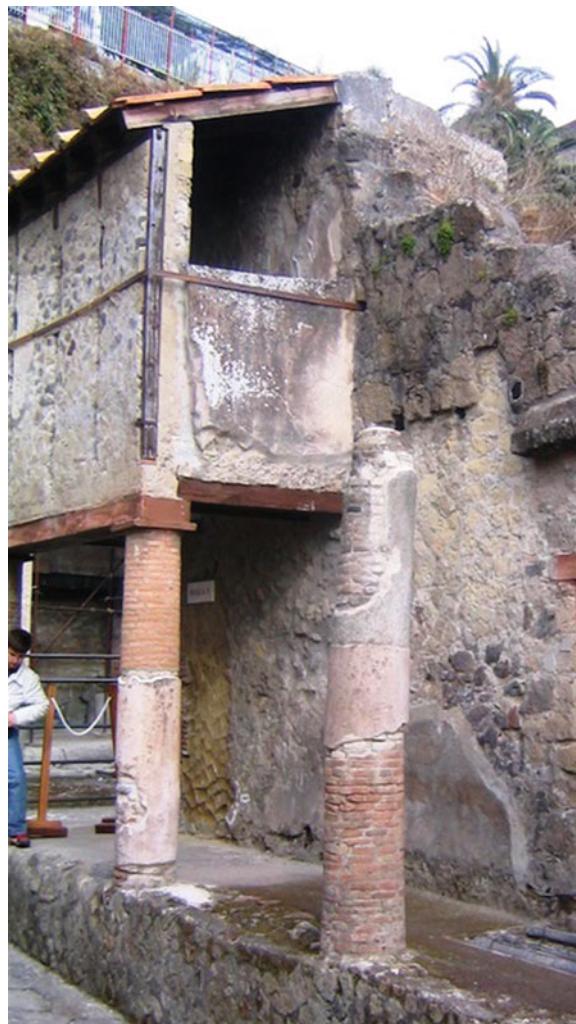
**Fig. 22.8** Plan of a baraccata house

Nocera as symbolic example. It was also in Calabria that we note a diversification between the ‘casa intelaiata’ and the ‘casa baraccata’, both with wooden ribs, visible in the former, as in German cottages, and inserted into the masonry in the latter. This method continued to be used until 1915, when the extraordinary tenacity of reinforced concrete in anti-seismic structures was recognized. For completeness of information, we must state that among the photos of the terrible consequences of the earthquake of Messina in 1908, one stands out—a ‘casa baraccata’ certainly built shortly after 1783. In spite of the fact that it was a century old and the evident violence of the earthquake it did not suffer any significant damage, an eloquent confirmation of an ideal intuition!

A quick overview of the architecture of the classical era reveals that the technique underlying the ‘casa baraccata’ was no more than a revisit of the ancient Roman ‘opus craticium’, of which there are relevant examples in Herculaneum and Pompeii, and not only in the internal dividing walls but also in the load bearing perimeter ones. This was, in fact, the most widely used mixed masonry structure in the Vesuvian area and its employment must be related to the particular geologic nature of the region and its frequent seismic events, of low intensity but certainly not innocuous. This is therefore a second anti-seismic construction technique that, contrary to the previous one used for large public works, was used for private residences. And especially, if we may say so, for popular housing as it was very economical and rapid. The opus craticium, a timber frame construction, makes use of a load bearing skeleton of sectioned vertical wooden parts, poles and square timbers, linked to slightly less thick horizontal ones slightly less thick, beams, stringers and listels, joined together by joints and iron braces. The former having a thickness between 8 and 12 cm and the latter between 6 and 8 cm. When they crossed they formed panels measuring approximately 50–80 cm per side, bricked up in opus incertum, using small size stones, mounted and fixed using abundant lime. There was usually a thin external and internal layer of plaster to protect the wood from water and especially from fire and to further reinforce the structure.

The thickness of the walls made in this manner, about 20 cm, was more than sufficient from a static perspective for houses with only two floors and for their interior divisions. This method was especially preferred because of the solidity it provided to the dividing walls on the ground floor and, its lightness, for the perimeter walls of the upper floors. As for dating this method was used since the III c. B.C., although other sources claim that it was used in Italy since the VI c. B.C., surviving the Middle Ages and spreading to Turkey and the villages of north-west Europe, where it will be used up to the present. It must also be said that if the use of opus craticium was initially dictated by economic reasons, later on, aware that it was easily flammable, it continued to be used only where its well known secondary features, lightness and elasticity, made it essential as a highly effective remedy against earthquakes. In Fig. 22.9 a house in opus craticium in Herculaneum, Naples, Italy is shown.

**Fig. 22.9** A house in opus craticium in Herculaneum, Naples, Italy



## 22.5 Seismic Isolators

As paradoxical as it may seem, some large buildings of antiquity built on sand or other unstable materials instead of stone, were more suited to withstand seismic activity. A test bench for this revolutionary criterion was, at least initially, Doric temples, a confirmation of resistance and validity. The technique, which will become well established during the Hellenic Era, has been rediscovered in recent decades and adopted with increasing frequency in our buildings to increase resistance to earthquakes. As for the implementing role played by the Doric Temple this is attributable to its simple assembly. Contrary to Roman constructions transformed

into monoliths by the use of concrete (*calcis structio*), those religious buildings of unsurpassed elegance always remained a mere superimposition of blocks of shaped stones, held together only by their weight. To eliminate any harmful lateral thrust all their contact surfaces were levelled and installed perfectly horizontal. Such a structure was statically stable but, at the same time, dynamically precarious even to the less violent seismic stress. In such case the absence of solidarity between its many parts and the level manner in which they were installed, caused each stone to slide over the one beneath. Thus the building would quickly disintegrate but without becoming rubble, as confirmed by the piles of the drums of columns, capitals, plinths and architraves piled on an almost completely intact base, such that in some cases they could even be re-assembled.

Repeated observations of similar destructions that devastated the most densely populated regions of antiquity with deadly frequency, began to suggest, in addition to theories on the nature of earthquakes, also the first expedients to deal with their fury. They began with the obvious observation that alluvial soils, composed of thick layers of silt, that at times were partially marshy, suffered rarer and less violent quakes, such as in all of Egypt, near the Nile. On the other hand where the soil was more solid, with outcropping rocks as in Anatolia, the devastation was not only greater but was also characterized by sinister faults and deep chasms in the soil that were interpreted as the result of the sudden caving in of large subterranean cavities. They therefore concluded that where the soil cracked and caved in, in order to prevent the same things from happening to buildings these had to be isolated. In other words, to make it as similar as possible to a ship that, although it is subject to the motion of the waves, suffered less effects because of the ship's autonomous cohesion. A foundation therefore that was unquestionably solid but that was not affixed to the soil like the roots of trees, but rather that could float above it like a large raft upon which to build the temple.

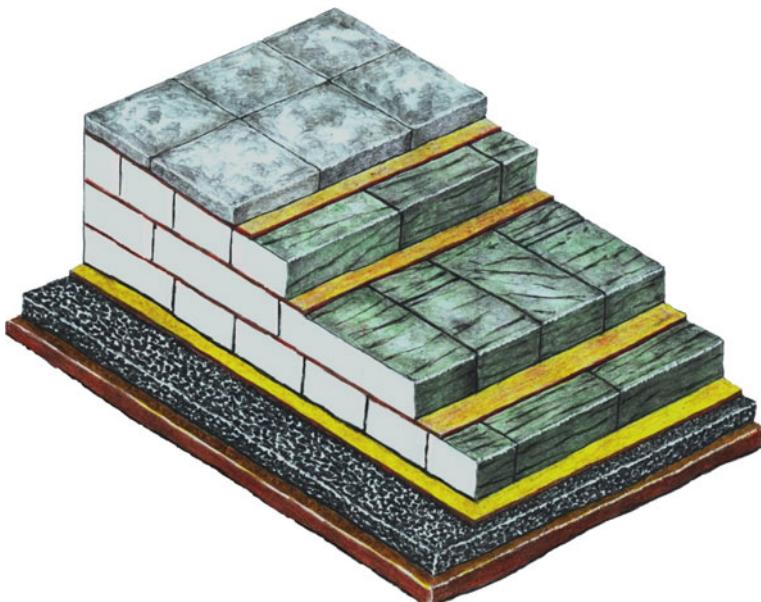
Recourse to an isolator that decouples—a terrible but effective technical neologism—the foundations from the soil seems to have been adopted already underneath the mythical walls of Troy, not incidentally reputed to be indestructible because of divine creation, constructed on a layer of arid land acting as a buffer. From those remote days the idea matured and was well tested by the time the major temples were constructed. Of all these temples the Temple of Artemis in Ephesus, one of the seven wonders of the ancient world, stands out for colossal dimensions and immense cost, both more than enough reason to try to immunize it from earthquakes, especially in a particularly menacing zone because of the frequency and magnitude of seismic activity. They began to build it at the foot of the hill of Ayassoluk, where the tiny city of Selcuk, Anatolia is currently located, around the middle of the VI c. B.C. The ruins, which jut out in some sections, indicate a temple that was 103 m long and over 60 m wide, with columns 18 m high and 1.8 m in diameter at the base, surmounted by stone architraves whose weight fluctuated between 24 and 40 tons! This grandiose work, designed and directed by Chersiphron, remained standing for more than two centuries before it was torched by a mythomaniac: the roof was destroyed but certainly not the stones, thereby leaving us to suppose that they were restored and re-used in the new temple,

promptly rebuilt on the same foundation, and swallowed up centuries later by a Christian church before disappearing forever.

Even during its greatest splendor the particular aspect of the Artemision that most interests us was invisible, that is its strange foundation which Pliny describes as: “Graecae magnificentiae vera admiratio exstat templum Ephesiae Dianaee CXX annis factum a tota Asia. In solo id palustri fecere, ne terrae motus sentiret aut hiatus timeret, rursus ne in lubrico atque instabili fundamenta tantae molis locarentur, calcatis ea substravere carbonicus, dein velleribus lanae.” [XXXVI, 21, 95] in English: “The most wonderful monument of Graecian magnificence, and one that merits our genuine admiration, is the Temple of Diana at Ephesus, which took 120 years in building, a work in which all Asia joined. A marshy soil was selected for its site, in order that it might not suffer from earthquakes, or the chasms which they produce. On the other hand, again, that the foundations of so vast a pile might not have to rest upon a loose and shifting bed, layers of trodden charcoal were placed beneath, with fleece s2 covered with wool upon the top of them”.

Figure 22.10 shows a graphic reconstruction by the authors of the isolating sub-foundation of the great temple of Artemis.

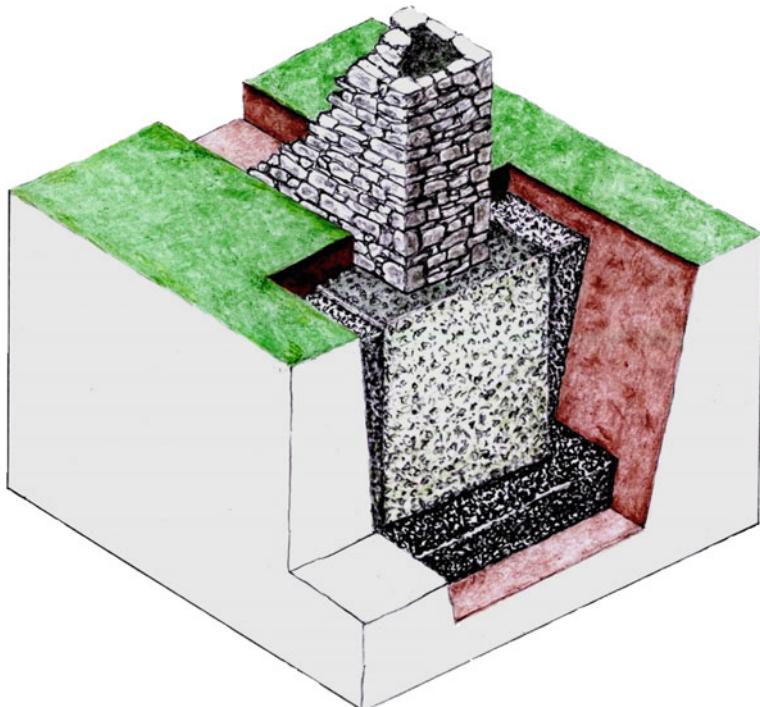
In this brief description there is already the first hint of the decoupling of a large building from the soil, achieved by means of isolators, in this case a conspicuous layer of charcoal, topped by a second and thinner layer of skins, underneath a complex foundation. Archeologists have discovered a rather singular composition



**Fig. 22.10** Graphic reconstruction by authors of the isolating sub-foundation of the great Temple of Artemis

of this foundation: a triple row of thick plates of gneiss placed one above the other, each about 30 cm thick, separated by a thin coating of clay, above which rested the stylobate measuring another 20 cm thick. Between that imposing multi-layer of stone and the soil was yet another layer of crushed charcoal, installed in such a manner that it could in no way be confused with the remains of a great fire. This was confirmation of the anti-seismic remedy described by Pliny, without the sheepskins that if they had been used for waterproofing had by now dissolved.

The concept of decoupling the foundation, which later sources attribute to the famous architect Theodorus of Samos, was not limited to the Artemision but soon spread to the construction of other major temples whose foundations rested on thick beds of sand, an economical alternative to charcoal, layered upon the underlying stones, as in Paestum and Metapontum. And even when they began to use a continuous foundation, that is one running only under load bearing walls poured into special ditches larger than the walls, it was placed, for the reasons mentioned, on abundant layers of charcoal, sand or pebbles. Figure 22.11 shows a schematic graphic reconstruction by the authors of a continuous foundation isolated according to the standards of the classical era.



**Fig. 22.11** Schematic reconstruction by the authors of a continuous isolated foundation according to the standards of the Classical Age

The basic concept remained unchanged: to make a flexible sub-foundation that separated the foundation from the soil, leaving it free to oscillate at a speed much less, and thus less destructive, than that of a seismic event. And since the cohesion with the surrounding soil was not limited only to the supporting surface but extended to the lateral contact, even the interstices between the trenches and the foundation walls were filled with scraps from the stone elements of the building, forming a sort of pliable cavity that isolated it from seismic stress and from humidity.

In the past century this ancient expedient was initially implemented in the construction of the Imperial Hotel of Tokyo, an enormous hotel designed around 1919 by the celebrated architect Frank Lloyd Wright. Preliminary surveys revealed the existence of a couple of meters of compact soil, over a 20 m layer of muddy silt underneath what was to be the site of the structure. The architect therefore decided to use this thick layer as an enormous buffer that would transform the building into a ‘floating carapace’. A few months after its completion, on April 26, 1922, one of the most violent seismic events of the past decades took place, followed on September 1, 1923 by another much more catastrophic one with a magnitude of 7.9 and a frightening duration of over 4–5 min, an earthquake that razed a good part of Tokyo to the ground. Wright’s Hotel survived both intact!

## 22.6 Consideration on Ancient Concrete

The Romans called the mixture of lime and pozzolana opus caementicium, a definition whose phonetic assonance reveals an affinity with our universally used cement. In practice, however, the mixture in question did not possess significant analogies except for its initial fluidity and subsequent setting to a stone consistency. It should be noted also that the definition of opus caementicium was not specific as in the past it also designated any mixture containing inert substances, that is any mixture of gravel and mortar. But none of these mixtures was even remotely close to having the same resistance as opus caementicium that in less than one century completely replaced all others.

The Roman conglomerate cannot be defined as either cement in the modern sense nor as concrete. The: “...word concrete is very generic: it means a mixture of solid substances, or aggregates, and cement matter such as hydraulic lime and Portland cement. The differences between mortar and concrete are purely arbitrary...” (Davey 1965). In spite of this, not having a better definition, we will continue to call it ‘concrete’.

Strangely enough for the Romans caementa meant inert items, the smaller stones that were held together by a bonding agent, a mixture to which they never gave a name although it was very similar to mortar, whose knowledge and availability by means of calcination of the calcareous stone goes back many, many eras. The first information of its use goes back to the time of Nebuchadnezzar when they began to replace asphaltic mortar with hydraulic lime in Babylon, a practice that spread

rapidly, especially where there was no easily obtainable bitumen but an abundance of calcareous rock and wood. Further study of the archaeological artefacts reveals that calcination of the limestone was practiced in Mesopotamia since 2450 B.C... [and] since [its] production... has always been relatively expensive, in order to economise, the custom emerged of diluting it with less expensive materials, such as sand, round stones, tile powder and ashes. The types of sand that can be used are many, some having the same effects as pozzolana and contributing to increasing the resistance of the mortar..." (Davey 1965).

Pozzolana, although currently considered to be a sort of sand is in reality a volcanic detritus composed of ashes and minute lapilli, altered and homogenised by atmospheric agents, rich in silicium oxide, aluminium and iron, as well as a variable percentage of calcium and magnesium oxide. With lime and water it provides an extraordinary mortar that has with the same properties as cement, and if inert substances are added, such as sand and gravel of different size, when mixed with more water it produces a fluid concrete, perfectly suited to be poured into formwork that, once set, has the consistency of stone.

In more detail, while the sand is no more than stone mechanically reduced to the smallest of fragments by the erosion of wind and water, the Pozzuoli powder is a volcanic sediment with a powerful siliceous component. And if the former is mixed with lime, obtained from the dehydration of calcareous stone, it produces a sort of artificial limestone. The same process applied to the latter produces a mixture that once hardened is much more resistant and cohesive, suitable to sustain highly significant compressive stress and, a peculiar feature, moderate traction, a characteristic that is not shared even by modern non reinforced concrete. The most obvious difference between pozzolana mixtures and sand mixtures is their stupefying capacity to set underwater. For the same reason they require less lime, a detail that is very influential in large constructions because of its high cost. All these features are summarised under the term pozzolana effect. Obviously this definition belongs to our culture while its discovery is attributed to the Roman era: in spite of this undeniable ignorance it was this chemical-physical process that led to the mentioned revolution. Wrote Vitruvius: "There is also a kind of powder which, by nature, produces wonderful results. It is found in the neighbourhood of Baiae and in the lands of the municipalities round Mount Vesuvius. This being mixed with lime and rubble, not only furnishes strength to other buildings, but also, when piers are built in the sea, they set under water. Now this seems to happen for this reason: that under these mountainous regions there are both hot earth and many springs. And these would not be unless deep down they had huge blazing fires of sulphur, alum or pitch. Therefore the fire and the vapour of flame within, flowing through the cracks, makes that earth light. And the tufa which is found to come up there is free from moisture. Therefore, when three substances formed in like manner by the violence of fire come into one mixture, they suddenly take up water and cohere together. They are quickly hardened by the moisture and made solid, and can be dissolved neither by the waves nor the power of water." (Mondini 1973)

Without entering into the merits of the chemical reaction that lead to the hardening of the pozzolana-lime cement, it should be noted that pozzolana contains

siliceous oxide ( $\text{SiO}_2$ ) and aluminium oxide ( $\text{Al}_2\text{O}_3$ ) in physical conditions such that, in the presence of water, they may react even at room temperature with calcium hydroxide ( $\text{Ca}(\text{OH})_2$ ), leading to the formation of silicates and aluminates hydrates, similar to those that originate during the hydration of Portland cement.

Obviously the hardening reaction of pozzolana-lime cement is completely different from the one just mentioned and requires many years to reach maximum solidity, although it attains significant resistance even in just a few days.

From the historical perspective, yet again it is highly probable that Roman technology co-opted the discovery of mortar from Magna Grecia around the 3rd century B.C. A convincing testimony to this may be found in the walls of Cosa, built in 273 B.C., whose base is in polygonal work while the raised structure is of cement mixture. In 273, therefore, not only were they in possession of the revolutionary procedure but they had such confidence in it as to use it in fortifications, a symbolic detail in promoting its widespread use.

But in the initial decades in order for cement work to be actually usable they had to be able to secure the famous pozzolana that is the sediment that was erroneously supposed to be found only in some areas around Mt. Vesuvius. This became possible to the Roman technicians only after the conquest of Campania, which occurred during the same period. For a long time they collected this material even for works to be constructed hundreds of kilometres distant and it was only when they realised that the entire Lazio region and thus a good part of central Italy were rich in this very precious harena fossica that they began to make liberal use of concrete.

In spite of the lack of understanding of how the pozzolana mixture actually set, there was no uncertainty on its exact dosage and, in a very brief time, they realised its very vast field of application. Roman engineers, however, only took advantage of this gradually, pushing, decade after decade, toward increasingly complex and daring constructions, as they had to first overcome the psychological resistance of using this poor material as an alternative to the traditional stones. In effect, the: “first part of the history of Roman concrete is the history of the accidental discovery and slow empirical exploration of the properties of pozzolana as an ingredient of a mortar much more resistant than the one heretofore known. At the end of the Republic, the hydraulic properties of pulvis puteolanus were well known and they had understood that the most valuable types of Roman harena fossica had the same properties...”

What were the consequences of the use of this new material in the architecture of the late Republic? The first and most obvious was its affirmation as an economical and often more effective alternative to traditional materials...” (Ward-Perkins 1974).

And where if not for perimeter fortifications was the concept of economy and ease of use most desired? To be able to assemble enormous structures using minute pieces, fluid to boot, soon revealed itself to be the solution of the many problems associated with the city walls, without considering the structural result provided by the mixture. Since the mixture initially had a fluid consistency, and at least in this it was exactly similar to our cement, it had to be poured, or tamped, into special

formwork. But very rarely were these made of wood planks and they systematically preferred to use two masonry facings that, according to their principal nature, gave the name to the particular technique. Not incidentally the definition of this masonry is also: "sack work", because the formless material is poured, as in a sack, into a formwork that can be of wood, stone or brick" (Mondini 1973).

Thus it had different names: when the facings were made with small blocks of stone of irregular shape it was called *opus incertum*, if square *opus reticulatum*; with facings in brick it was called *opus latericum*. But apart from the exterior image, often concealed by the plaster, it was always the same very solid concrete. The function of the facing was not reduced simply to that of a simple formwork as it provided static support for the entire time required to set, a period of time that, as mentioned, could also be extremely long, especially if it involved thick stones. It was for this reason that the pourings were not performed all at once but in layers, inside of which: "the stones were installed by hand, in courses that were more or less horizontal and with an abundant mixture of mortar; and it was the fusion of the mortar into a monolithic block and binding the different courses that made up the strength of the finished product. The time required to put up wood scaffolds between phases of the work created a difficulty that the constructors of the late Republic still had difficulty in solving... It was only with the general use of tiles as material for the facings that the problem was satisfactorily resolved, thanks to the introduction of courses of "bipedal" (brick 2 foot in length) that had the double function of concluding each phase of the work and providing the constructors with a substructure and levelling for the subsequent phase..." (Ward-Perkins 1974).

Concerning the sectors in which it is used, one of the first great applications of *opus latericum* was military construction. In fact: "another aspect of this initial use of Roman concrete was its selective application. As already noted, from a social point of view, the abandonment of traditional materials was more acceptable in certain branches of architecture than in others. And this is a very common phenomenon... The premises were there: it was only a matter of developing them; and one wonders what extraordinary innovations would have permitted the reconstruction of Rome under Augustus if it had taken place under different political circumstances. In reality, public authority emphasised the restoration of traditional Roman values, which in architectural terms translated into the extravagant exteriors of traditional classicism with a layer of neo-Atticism that had no relation to the latent possibilities of Roman cement work. The only important innovation that these produced in the Augustan era was the widespread use of brick as a surface covering. A material already so common in Rome that Tiberius used it for the exterior walls of the Castro Pretorio (21–23 AD)... " (Ward-Perkins 1974).

This enormous rectangular enclosure was a sort of fortified encampment, of which there were many examples throughout the Empire, though constructed in *opus incertum* or *opus reticulatum*. Similar ones are also found in central and southern Italy, now reduced to miserly segments, such as in Albano, near Rome, with the exception of an enclosure that is still whole, in Alife, in the province of Caserta. The exceptional constructive innovation, which came into general use starting from the II cen. B.C., is the tangible geographic proof of the expansion of imperial

hegemony. Thanks to its unquestionable convenience and ease of use, it was ideal for all constructions, civilian or military, from the modest villa to the grandiose amphitheatre, from the extremely long aqueducts to the numerous city walls. Significantly this was considered the principal contribution of Rome to the history of European architecture. Certainly, the appearance of concrete in the sector of building construction was a true revolution due to its immense range of consequences and implications, comparable to modern day reinforced concrete. Because of the facility of setting, the availability of its components, its rapid construction, flexibility of use and structural longevity this permitted the construction of a great number of works that were otherwise sporadic, homogenising city planning starting with the fortifications. Roman pragmatism thus succeeded within the contest of static defence in conciliating two otherwise insurmountable limitations.

On the one hand, the relative economy of cement work easily permitted all the new cities to be encircled by walls, without causing any prohibitive concerns to suspicious Rome. In other words, the circles of walls provided the mandatory social safety without transforming the city centre into a powerful stronghold that, as the experience acquired during the 17 years of war against Hannibal had tragically demonstrated (Tassinbee 1981), in the event of defection would have been difficult to reconquer. The defensive standards, of excellent average level, were modest if compared to those of the Greeks of the same era, but absolutely congruous to the presumable threats that were by now issuing solely from brigands, as the powerful military apparatus handled any improbable enemy invasions.

What made this extraordinary discovery perfectly suited to the construction of fortifications was a characteristic that may be considered one of the principal causes of the laboriousness of traditional defence structures, however they may have been built. From time immemorial it had been perfectly understood that the passive resistance of a work depended on the size of its composing elements and their cohesion. A fortification would have been more indestructible the larger were its hewn stones and the greater their cohesion. This was understood by the Italics who used giant boulders, fitting them one into the other in a very complicated manner, but also by the Greeks who developed a horizontal variant, using stones of enormous size. In both cases, however, upon receiving the impact of the battering rams the structures disconnected. It would have been desirable at that point to further increase the size of the stones to increase inertia, a solution that was often impracticable. The greatest difficulty, in fact, was not in moving the large blocks, certainly laborious but not impossible, but in extracting a sufficient number. Very few quarries could provide them in the thousands because of the non homogeneity of the rocky layers. The true and ideal solution would have been to construct works tending to the monolithic, assembling them with the smallest component possible.

Thus having a technique that allowed for achieving a monolithic structure ‘*a posteriori*’ provided the solution to this millenary problem. In effect, fortifications built with concrete, though constructed by means of numerous small pourings, once the mixture set became one immense block that reacted solidly to individual stresses, exactly as will occur with reinforced concrete millenniums later. Even the cupola of the Pantheon from this aspect is no more than a gigantic cover, statically

similar to the stone that covers the Mausoleum of Theodoric in Ravenna and completely different from Michelangelo's St. Peter, almost equivalent only in size.

The only difference with reinforced concrete is the absence of an interior support structure to increase cohesion, but as there was no threat even remotely comparable to high explosive projectiles, the resistance available was amply sufficient even for modestly thick structures to resist the impact of medium size battering rams. It must however be noted that in rare cases bars of metal, mostly iron, were found in the mass of concrete, installed in a manner to resist traction stress.

As experience increased they were able to find the different components required for the mixture in many areas and the legions propagated its use throughout the empire. Adapting the technology of concrete to the advanced criteria of Italic fortifications became a process of synthesis typical of the Roman mentality: there resulted a specific military architecture that cost little and provided good protection, optimal requirements for a quantitative rather than qualitative production and one perfectly congruous with the urban concept of the Empire.

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