History of Mechanism and Machine Science 8

Cesare Rossi
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Ancient Engineers' Inventions

Precursors of the Present

Springer

Ancient Engineers' Inventions

HISTORY OF MECHANISM AND MACHINE SCIENCE

Volume 8

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Preface

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 whatever field, consists in 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 B.C. to A.D. 1600 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 constructions) accomplished by scientists and engineers.

Although many of these inventions are extremely old, the ones presented in this book are precursors of the knowledge and inventions of our era. In addition, many of them 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 six parts.

The first four parts pertain to specific fields and present inventions conceived up to the late Roman Empire. These are 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 part, consisting of Chapter 16, 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 was a society of great accomplishments (probably even today not yet completely understood) in many fields of science, technology and law; they started from the Italian peninsula but they do not belong just to the Italians. First of all, most of the inventions and the technology of the Roman Empire were not invented by Latin inventors; in fact, one of the merits of the Romans consisted in recognizing, appreciating and using the intellectual abilities of other peoples. In addition, the quality of organization and the "sense of a State" has been retained more by the German and Anglo-Saxon peoples than by the Latin ones; hence the heritage of the Roman Empire, today, belongs to people who 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.

As a point of reference, the authors think that the first industrial revolution started during the Roman Empire. Many aspects suggest this hypothesis: the Romans had a strong incentive to make great progress towards unification and standardization in the production of goods. At certain periods, the Roman Armed Forces had up to 500,000 men, all of whom had to be equipped with everything they needed to live, clothe and shelter themselves and fight. The army needed unified and interchangeable equipment because its military units had to be able to go anywhere in various sized units; this meant that unified industrial production systems were crucial to fulfil the army's needs.

The resulting standardization, that probably was devised for those military uses, was subsequently extended to civil applications: many of the components used in the various systems, such as hydraulic valves and pipes (see Chapter 8), cart wheels and gauges (see Chapter 10) and so on, had standardized dimensions and were interchangeable throughout the Empire. This history was clearly delineated by Vitruvius, the most famous Roman engineer.

Finally, the authors did not write this book for engineers only; hence they describe the devices in details that do not assume wide technical knowledge. The authors' main aim is to try to communicate their enthusiasm for the inventions and the inventors of the past and, possibly, to make their contribution to the fascinating study of the History of Engineering.

Napoli, X 2008

Part I – MEASURING THE ENVIRONMENT

Introduction

The first part of this book is divided into four chapters and mainly pertains to 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 computing machines.

The first step towards the establishment of scientific standards was to build a foundation for measuring of the environment. Toward this end, the first step was to define a system of units; the demand for such a system was certainly generated by people in the trades, but units of measure were obviously perceived as indispensable for any scientist, inventor or engineer to study a chosen science and to describe designs of experiments and constructions.

To the best of our knowledge, the first measure unit systems were probably established in the East in Mesopotamia, Persia and India, then in Egypt and Greece and later in Rome.

Most of the oldest inventions reported in this book were made by Greek–Roman inventors who, in their original writings, described their devices using Greek or Roman units; furthermore, at that time, the latter of these units were used all over the Roman Empire. For this reason the authors considered it useful to report both these systems of units in the tables that follow.

Ancient Greek units

Length units

In Tables I.1 and I.2, the ancient Greek length units are reported. For small lengths the unit was the dactylos (pl. dactyloi) meaning finger; for longer lengths the unit was the pous (pl. podes) meaning foot.

Table I.1 Greek length units.

Greek name	Latin alphabet	English name	Value (dactyloi)	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 hemipodion	Half foot	8	
λιχάς	lichàs	Span of thumb	10	
ὀρθόδωρον	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	

Table I.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
ἁπλοῦν βῆμα	aploun bema	Single pace	2.5	≈0.75 m
διπλοῦν βῆμα	diploun bema	Double pace	5	≈1.5 m
ὀργυιά	orguià	F or stretch of both arms	6	≈1.8 m
ἄκαινα	àkaina		10	≈3 m
πλέθρον	plèthron	Breadth of Greek acre	100	≈30 m
στάδιον	Stàdion	Stadium	600	Attic ≈ 177.6 m Olympic ≈ 192.27 Walking ≈ 157.5m
δίαυλος	Diàulos		2 stadia	≈355.2 m
ἱππικόν	hippikòn		4 stadia	≈710.4 m
δόλιχος	dòlichos		12 stadia	≈2.131 km
παρασάγγες	parasànghes		30 stadia	
σχοινός	schoinòs		40 stadia	

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 1 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 I.3 and I.4, the ancient Greek volume units are reported, for liquid and solid respectively.

Table I.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
οξυναφον	oxynafon		1/4	
ημίκοτύλη	emìkotýle		1/2	
κοτύλη	cotýla	Cup	1	≈0.275
ημίχους	emìchous	Half jug	6	
χοῦς	choùs	Jug	12	≈3.3
μετρητής	metretès		144 ≈1 amphora wine	≈39.4

Table I.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	
ἑκτεύς	hecteùs		8	
μέδιμνος	mèdimnos		6	

Weight/mass units

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

Table I.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	tàlanton	Talent	60 mina	25.86 kg	37.8 kg

Roman units

Length units

In Table I.6 the roman length units are reported.

Table I.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	5,000 ft = 1,000 pace	1.48 km
leuga	league	7,500	2.22 km

Area units

In Table I.7 the roman area units are reported.

Table I.7 Roman area units.

Latin name	English name	Value (acres)	S.I. Equivalence
pes quadratus	Square foot	1/14,400	~876 cm²
scripulum	Square perch	1/144	~8.76 m²
actus minimus	Aune of furrows	1⁄30	~42 m²
slima	Rood	1⁄4	~315 m²
actus quadratus(acnua)	Acre	1	~1,260 m²
iugerum	Yoke	2	~2,520 m²
heredium	Morn	4	~5,040 m²
centurium	Centurie	400	~504,000 m²

Volume units

The roman volume units are reported in Tables I.8 (liquid) and I.9 (solid).

Table I.8 Roman volume units, liquid.

Latin name	English name	Value (sesters)	S.I. equivalence $m^3 \times 10^{-3}$ (=litre)
ligula	Spoonful	1⁄48	~0.01125
cyathus	Dose	1⁄12	~0.045
sextans	Sixth-sester	1⁄6	~0.09
triens	Third-sester	1⁄3	~0.18
hemina	Half-sester	1⁄2	~0.27
choenix	Double third-sester	2⁄3	~0.36
sextarius	Sester	1	~0.54
congius	Congius	6	~3.25
urna	Urn	24	~13
amphora	Jar	48	~26
culleus	Hose	960	~520

Table I.9 Roman volume units, solid.

Latin name	English name	Value (pecks)	S.I. equivalence $m^3 \times 10^{-3}$ (=litre)
acetabulum	Drawing-spoon	1⁄128	~0.0675
quartarius	Quarter-sester	1⁄64	~0.0135
hemina	Half-sester	1⁄32	~0.27
sextarius	Sester	1⁄16	~0.54
semodius	Gallon	1⁄2	~4.33
modius	Peck	1	~8.66
quadrantal	Bushel	3	~26

Weight/mass units

In Table I.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.

Table I.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

Chapter 1 – MEASURING MASS

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 developing science and technology. Examples of balance scales from Mesopotamia and Egypt are dated to the 5th millennium B.C. but their use became common in nearly all populations of that time.

With respect to devices, the first ones were probably those designed to measure mass, since a yarn with some knots to measure a length can not be considered a real device. The impetus for the design of mass measuring devices quite certainly came from the trades.

It is interesting to consider that, according to the Egyptians, the balance scale was already considered a symbol of justice, even for the life after death. 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. Figure 1.1 is a picture of an Egyptian painting showing the god Anubis and a balance scale.

Fig. 1.1 Balance scale and god Anubis.

C. Rossi et al., *Ancient Engineers' Inventions: Precursors of the Present*,
History of Mechanism and Machine Science 8, 7–12.

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

1.1 The balance scale

The word balance (which is similar in many languages) comes from the Latin "bi lanx", meaning double pan. The balance scale essentially consists of a couple of pans suspended from a yoke; the latter is suspended at the middle point between the points at which the dishes are suspended. The use is very easy and well-known: the object that is to be weighed is located on one pan while on the other pan are placed 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 Figure 1.2 are pictured 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.

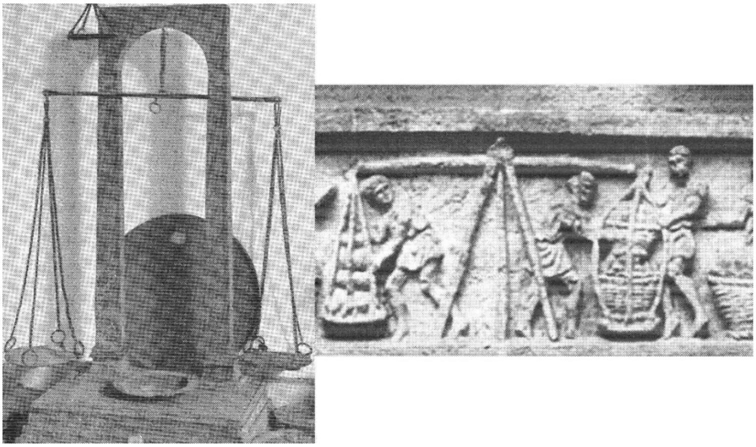

Fig. 1.2 Roman balance scales.

The mathematical theory of the balance scale is not very simple (and certainly was formulated thousands years after the first one 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 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.

1.2 The steelyard balance

The steelyard is also known as a 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 the 3rd century B.C., similar devices appeared in China. The working principle is shown in Figure 1.3.

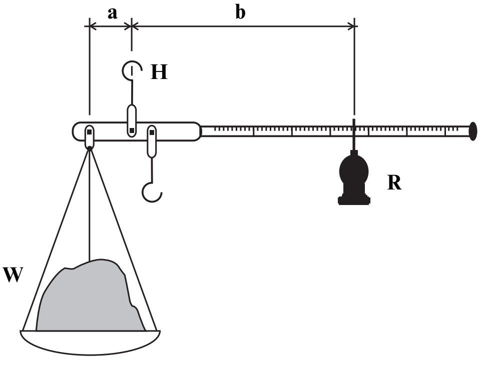

Fig. 1.3 Scheme of a steelyard balance.

The steelyard has two arms of different lengths; to the shorter one is linked a pan on which is located the unknown mass W, a known (and calibrated) counterweight 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 with respect to the pivot of the suspension hook H:

$$W \cdot a = R \cdot b \ \Rightarrow \ W = a \cdot R/b. \tag{1.1}$$

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 who will be widely mentioned in the following chapters of this book, in particular his famous treatise “De Achitectura”. It is interesting that Vitruvius, in his description, uses the term “momentum” with the same meaning of the English word in mechanics.

In Figure 1.4 is depicted an ancient steelyard found at Hercolaneum.

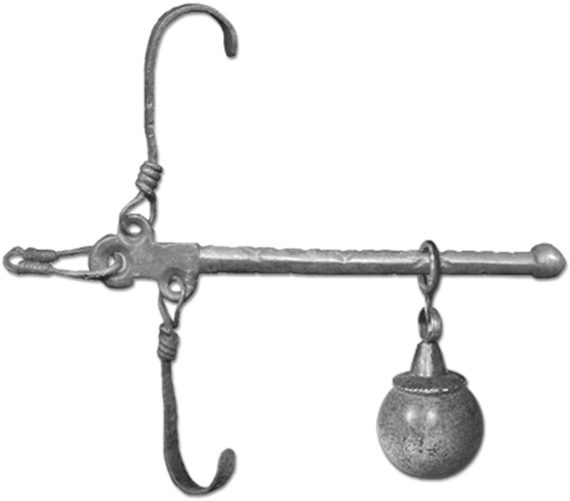

Fig. 1.4 Steelyard found at Hercolaneum.

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 men of that age; he wrote about liberal arts, law, medicine, natural science, and theology. In his treatise “De ponderibus et mensuris” (On the weights and measures), he calls the scale balance a statera 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 later publications.

Observations

Balance scales having, substantially, the same shape as those built thousands of years ago, have been enhanced until the present day and were 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 steelyards were used to measure 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 appeared in most country markets. Some modern steelyards are still built in small sizes to weigh the gunpowder charge needed to load cartridges; these devices generally have a sensibility of 0.1 grain (=0.0065 g).

An interesting legend, told by Vitruvius, demonstrates that, in ancient times, 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 suspicious that the goldsmith could have made the crown by substituting some of the 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 with 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 immerged 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 basis of the described procedure, the computation is very easy:

$$\frac{Gold\ mass}{Silver\ mass} = \frac{Silver\ volume - Crown\ volume}{Crown\ volume - Gold\ volume}\,. \tag{1.2}$$

This is a very simple equation that a mathematician such as Archimedes would probably have 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 of pure gold but contained silver.

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

Chapter 2 – MEASURING DISTANCE

Introduction

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

It is also well known that in building temples and towns, accurate measuring of distances is essential. A powerful impulse in this field of knowledge was experienced during the Roman Empire.

As everybody knows, the Roman Empire was one of the most widely distributed powers ever to exist in human history. On the other hand, most people believe that technology and science were quite primitive during that era, and the study of them mostly neglected. Our study of the History of Engineering, however, has been of great help in recognizing that, contrary to science in general, mechanical knowledge was rather advanced, and we have been able to discover the function and the meaning of many archaeological finds and to analyze their ways of working. In particular, through the common efforts of archaeologists and engineers it was possible to demonstrate that many devices of present day common use were actually invented and built about 20 centuries ago.

In such a far-flung empire as that of the Roman, measurements of distances, both on land and at sea, played a crucially important role in governance and trade. One of the most important constructions the Romans built in Europe was, in fact, a widely dispersed system of roads. Most of those roadbeds are still in use today. In addition, since the sextant and the marine chronograph had not yet been invented, the only way to determine a distance on the sea was to measure the length of a ship's run.

C. Rossi et al., *Ancient Engineers' Inventions: Precursors of the Present*,
History of Mechanism and Machine Science 8, 13–25.

2.1 Jacob's staff, Astrolabe

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 rudimentary. 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 its principle lies 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 Figure 2.1 a schematic reconstruction of a roman era staff or baculum is shown, with a medieval print illustrating the use of a staff or baculum.

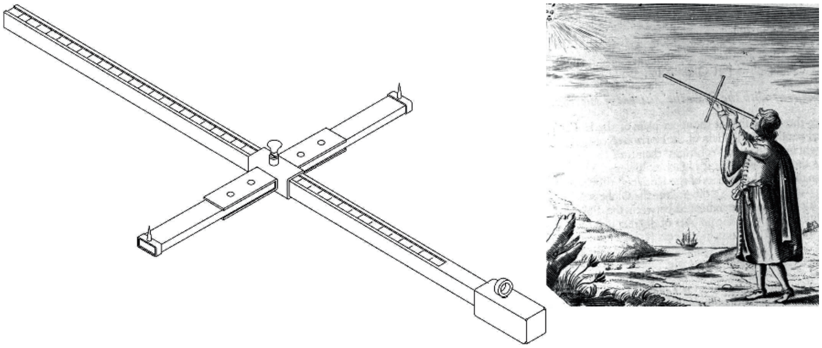

Fig. 2.1 Jacob's staff.

2.2 Range finders

In this section we discuss those ancient devices which made possible the development of topography.

2.2.1 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 taken from the Greeks around the 4th century B.C., and renamed 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.

Figure 2.2 shows a virtual reconstruction of a groma and a bas-relief from the Roman imperial era representing a groma.

Fig. 2.2 Groma.

2.2.2 Surveyor's cross

This little deficiency of the groma was overcome with the surveyor's cross, either the drum or case version. In Figure 2.3 is shown a find and an authors' virtual reconstruction of this device.

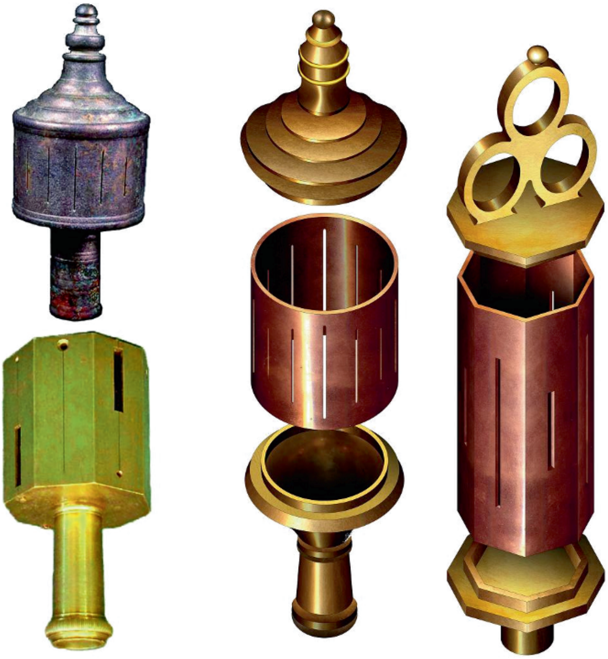

Fig. 2.3 Surveyor's cross: find and virtual reconstruction.

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° intervals, decreasing to 45° in the more accurate ones. For more important uses requiring more than simple squaring, the distance was further decreased as low as 22°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°, he could identify the direction orthogonal to the preceding one. Finally, looking through the slit at 45° he would determine the diagonal and its bisecting line from the line placed at 22°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°. Lost during the Second World War, 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°30′, each one a half millimetre wide. Perfectly identical to the models of the 1800s, 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′.

2.2.3 Chorobate

The need to contain the maximum inclination of roads within 3% and within 0.1/1,000 for aqueducts, spurred the invention of effective precision leveling 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 metres. 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 1.5 m 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 Figure 2.4 a virtual reconstruction of Heron's level, using communicating pipes and optical sights is shown with the Table XXXIX from Giovanni Branca "Macchine", Rome 1629, showing a similar device.

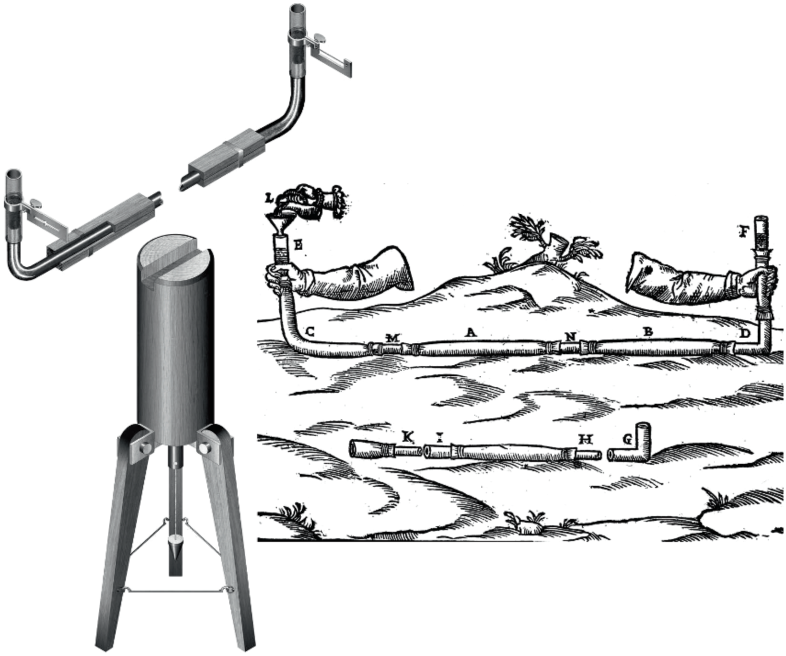

Fig. 2.4 Virtual reconstruction of Heron's level and Table XXXIX from G. Branca.

2.3 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 dioptre, 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 dioptre 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 leveling rods that completed the dioptre. 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 Figure 2.5 are shown reconstructions of Heron’s dioptre and of a roman era stadia, according to Heron’s description.

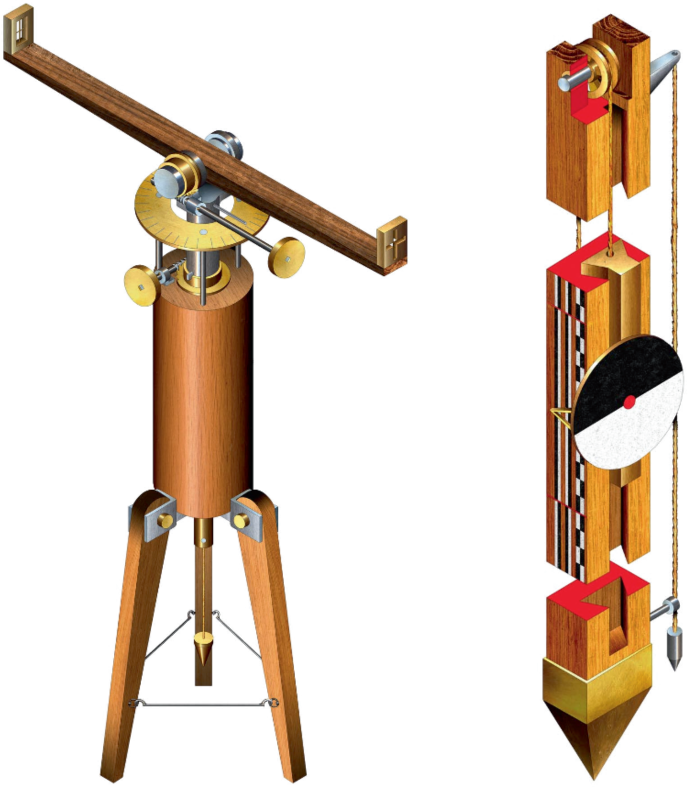

Fig. 2.5 Virtual reconstructions of Heron’s dioptre (*left*) and of a Stadia (*right*).

In 1907, the relic of a Roman ship was found off the coast of Mahadia. 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 dioptre.

2.4 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 on land and at sea.

2.4.1 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 a 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 Figure 2.6. A paddle wheel was installed at each of the sides of the ship; the paddle wheel was rotated by the movement of the ship. Both the paddle wheels were fitted on an axle that moved the mechanism of the odometer.

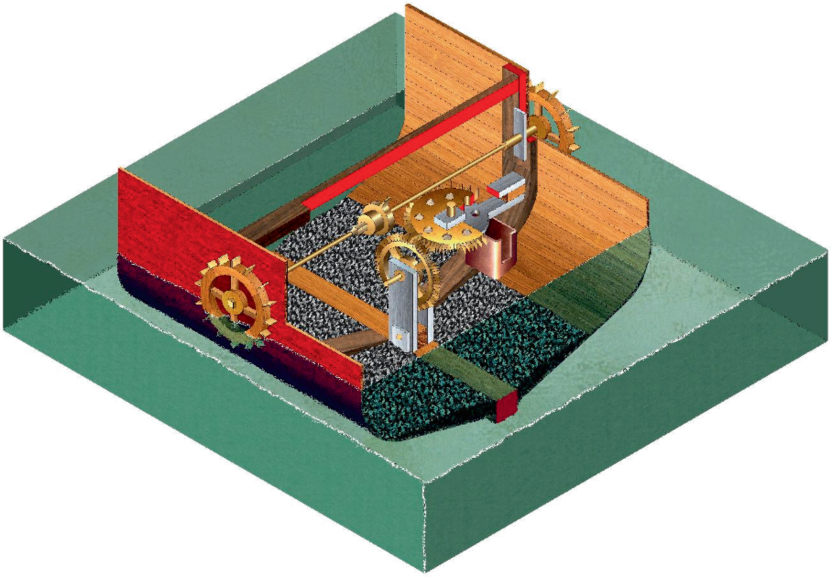

Fig. 2.6 Perspective reconstruction of the naval odometer by Vitruvius.

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 shown in Figure 2.7; the axle 1 is that of the paddle wheels.

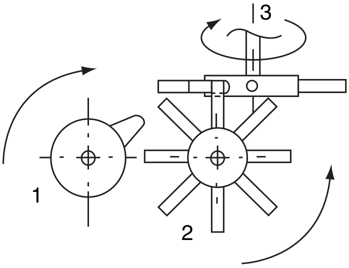

Fig. 2.7 Scheme of the first three axles of the mechanism.

This device, 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 a nautical mile. By means of an hourglass, the number of knots passed in the unit of time was 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, coastal navigation, both sporting and professional, was effected by log and compass till the present day. At the time of the Roman Empire, navigation was mainly coastal as ships were helped by a wide system of long-range lighthouses.

2.4.2 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, A.D. 62 that he described; so, he was probably born in 10 B.C. and died in about A.D. 70. He studied the work of Ctesibius, Philon, Euclid and Archimedes; a lot of inventions are attributed to him, mainly in the fields of 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 tripmeters.

This device was of great importance during the Roman Empire since it was used to locate milestones; this permitted planning of movements of 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 by Vitruvius it is possible to propose the perspective reconstruction in Figure 2.8.

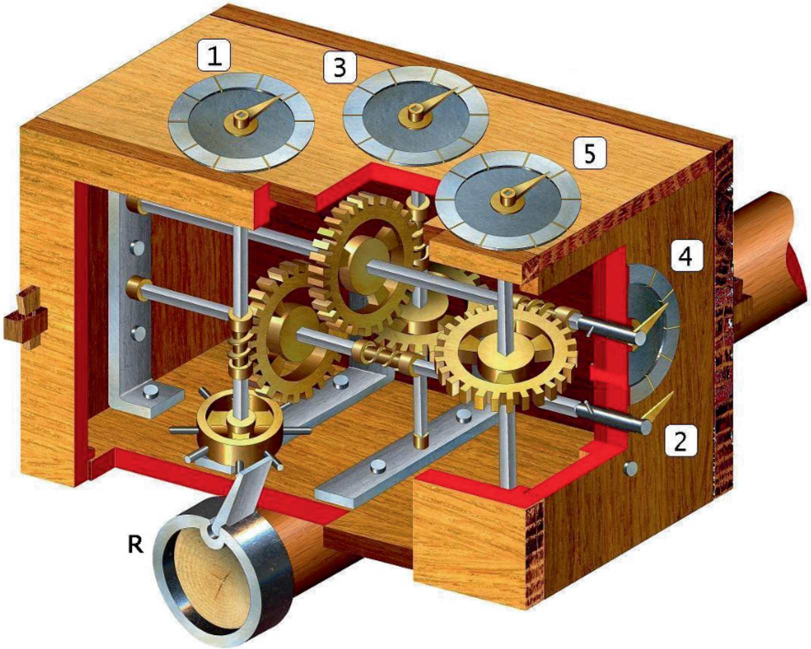

Fig. 2.8 Perspective reconstruction of the odometer by Heron.

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 Figure 2.8) 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 Figure 2.8) moved a third axle again with a worm gear and so on.

A cinematic scheme is shown in Figure 2.9. 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 two principles and, consequently the wheels had 20 teeth.

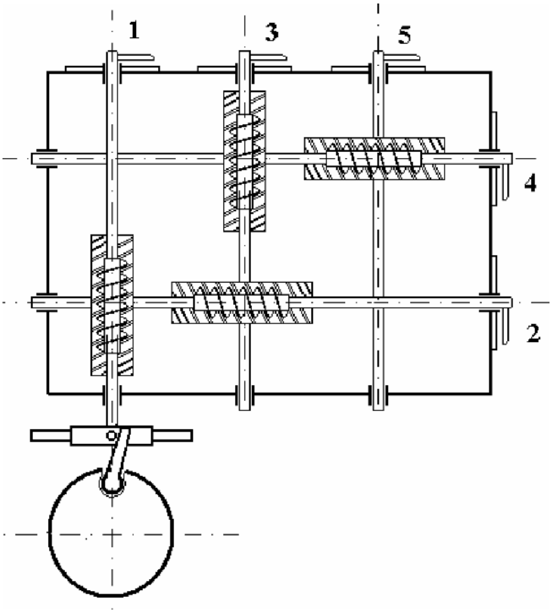

Fig. 2.9 Gears scheme.

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 eight pins; measurements can be computed as:

$$8 \text{ carriage wheel revolutions} = 10 \text{ roman steps} = 14.785 \text{ m} \qquad (2.1)$$

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

$$14.785 / (8\cdot\pi) = 0.588 \text{ m} \cong 2 \text{ roman feet} \tag{2.2}$$

which 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.

Chapter 3 – MEASURING TIME

Introduction

Speaking about time measurement we must, first of all, consider how the length of the day 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, 12 for the day and 12 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, Tables 3.1 and 3.2 identify the length of the daylight hours at the winter solstice and at the summer solstice, respectively.

Because of the different duration of hours it was rather complex to build a clock, much more than for 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 idor = water and suggests something that works by the removal of water. Such clocks probably existed around the 1st century B.C., as during Augustus' time there was a competition

C. Rossi et al., *Ancient Engineers' Inventions: Precursors of the Present*,
History of Mechanism and Machine Science 8, 27–39.

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.

Table 3.1 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.
VI	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 3.2 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.
VI	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.

The oldest types of devices for measuring time are represented by sundials and water clocks, hence we will present some examples of these.

3.1 The sundial

The sundial was the first device used to measure (or to visualize) the hours of the day. It was based on the apparent motion of the sun and served its purpose for thousands of years. The device essentially consists of a thin rod or a sharp and straight edge, called the gnomon or the 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's shadow 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 dates back to ancient times and one of them still exists in the Forbidden City, Beijing.

The development of sundials based on scientific principles was probably due to the Greek scientists who formulated those principles and used them to build very precise solar clocks having dial surfaces that were not all horizontal, some of them being also nonplanar.

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 the 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 parts 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's axis with the point of its style 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 centuries 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 part of a broader evolution within society. In Figure 3.1 are shown some sundials found at Pompei.

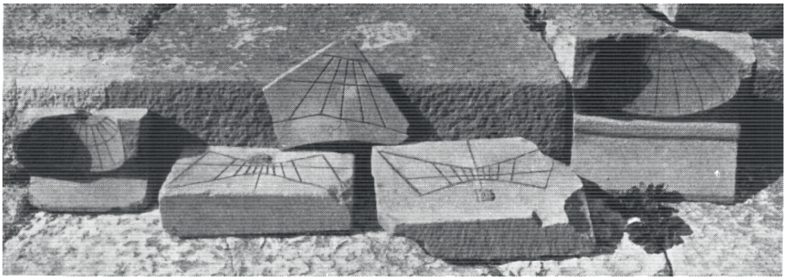

Fig. 3.1 Sundials found at Pompei.

Description of the working principle of the sundial requires astronomical knowledge that is beyond the scope of this book, hence we will confine ourselves to simple descriptions of the fundamental types of sundials.

3.1.1 Fixed sundials

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

3.1.1.1 Equatorial sundials

The simplest type of sundial consists of a plane parallel to the equator of the earth and oriented toward the north and a gnomon that is parallel to the earth's axis. A scheme of an equatorial sundial is shown in Figure 3.2.

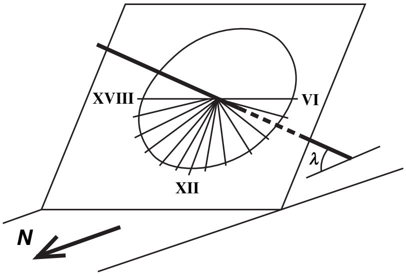

Fig. 3.2 Scheme of an equatorial sundial.

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°. 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.

3.1.1.2 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 α is given by:

$$\alpha = 90° - \lambda \qquad (3.1)$$

where λ 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 γ given by:

$$\gamma = \sin\lambda \cdot \tan(15° \cdot t) \qquad (3.2)$$

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

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

3.1.1.3 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 (3.2):

$$\gamma = \cos\lambda \cdot \tan(15° \cdot t) \qquad (3.3)$$

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

3.1.1.4 Non-planar sundials

Nonplanar 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 Figure 3.3 is shown a meridian found at Hercolaneum, Italy.

Fig. 3.3 Roman sundial found at Hercolaneum.

3.1.2 Portable sundials

The portable sundial is a very ancient device; probably the Egyptian one shown in Figure 3.4 is the oldest one known.

Fig. 3.4 Egyptian portable sundial.

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.

Diptych sundials are made by a pair of tablets joined by a hinge; a tin cord is located between both the tablets' ends, hence the cord 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 Figure 3.5 is shown a portable diptych sundial including a compass to correctly orientate it; such devices are still being built and sold as curiosities.

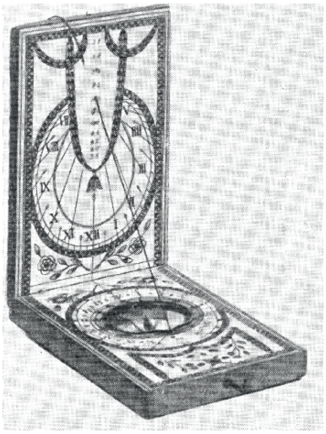

Fig. 3.5 Diptych sundial.

Ring dials essentially consist of a ring held by a cord. 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 Figure 3.6 is shown a ring sundial.

Fig. 3.6 Ring sundial.

3.2 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 κλεπτω = I thieve and υδωρ = 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.

3.2.1 Early water clocks

Water clocks, or clepsydras, were quite common 2,000 years ago but generally they were very simple and not very accurate. Essentially they consisted of 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 to 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 12, 1 for each month.

Water clocks as old as the Egyptian ones were built in Babylon 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 of 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 Chapter 15.

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 it 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 Figure 3.7 a scheme of the working principle of this clock is demonstrated.

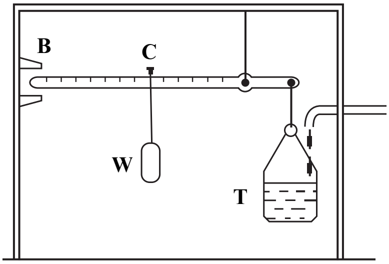

Fig. 3.7 Working principle of a Chinese water clock.

A tank T is filled by a constant water flow and its weight is measured by a stadera (see Chapter 1) 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 permit one to measure the time with different units of measure.

Most Roman 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 Figure 3.8. This type of water clock was quite commonly used by Roman patricians. 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 flows out through the vent V. From this tank, a constant flow of water fills the tank Tb 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.

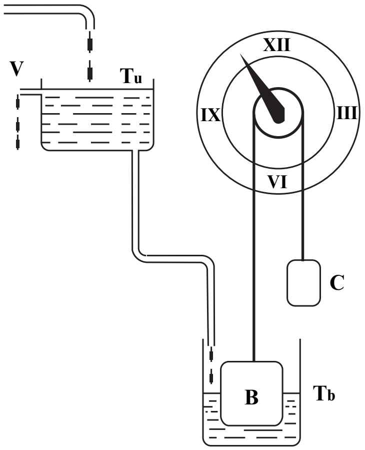

Fig. 3.8 Working principle of a water clock.

3.2.2 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 1 h 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 Figure 3.9 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 cord was connected to the ball clock and to a counter weight and was wrapped in a 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 Figure 3.8.

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 Figures 3.9, 3.10 and 3.11.

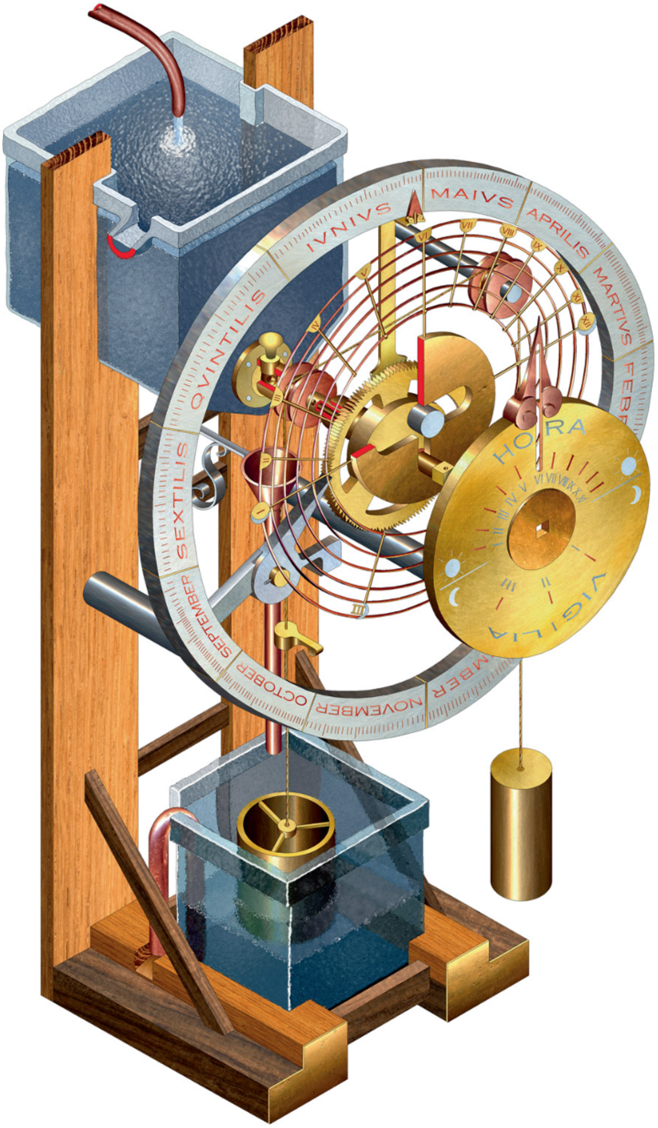

Fig. 3.9 Virtual reconstruction of the water clock by Ctesibius.

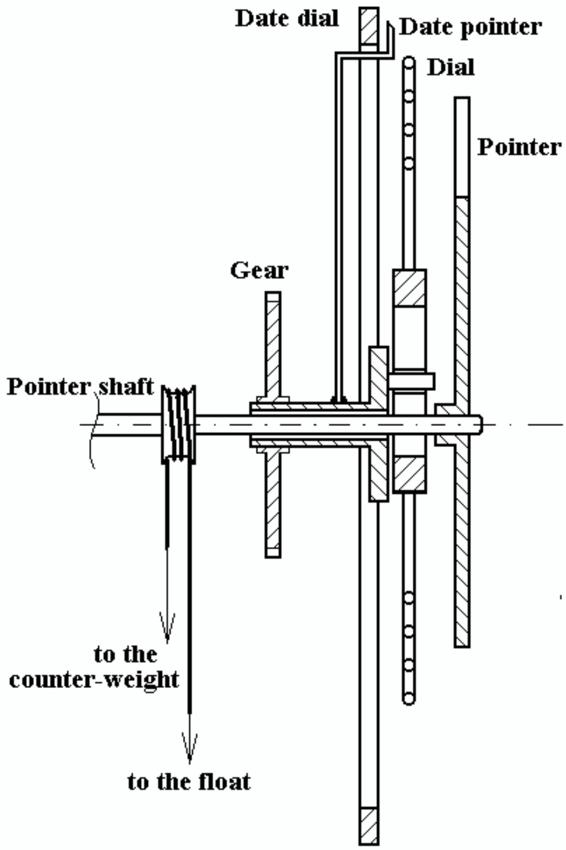

Fig. 3.10 Kinematic scheme of the clock by Ctesibius.

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 1 year, and was fitted on a hollow shaft coaxial to the pointer shaft and connected to a rod, as shown in Figures 3.10 and 3.11.

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 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.

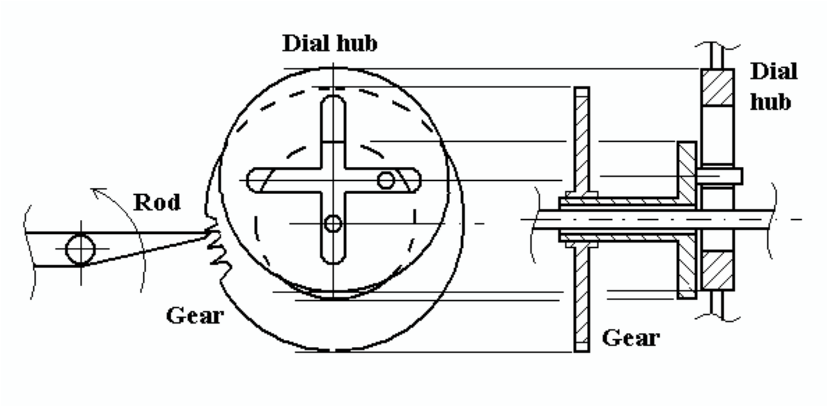

Fig. 3.11 Scheme of the mechanism for the dial motion.

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 (which is described in Chapter 15 since it is mainly an automaton) and Taqi al Din, who will be widely mentioned in Chapter 7 for his six cylinder water pump. Taqui 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 4 – ANCIENT COMPUTATION DEVICES

Introduction

In the previous chapters the most important devices for environment measuring have been discussed. But a measure has little use if no computation devices are available. For this reason in the present chapter we will look at those that were available in ancient times.

What we call today "computing machines" were invented and developed after the 16th century but, as will become clear in the following sections, older devices are, without any doubt, legitimate precursors in the art of computation. Some of them show a surprising skill and modernity on the part of their ancient inventors.

4.1 The abacus

The abacus is the oldest computation device and is found in almost any population in every part of the planet. Incidentally, the authors have observed that it was still used in the 1960s in shops in Russia. The word abacus comes from the ancient Greek αβαξ (=tablet), possibly derived from the Hebraic abaq (=sand) as thousands of years ago tablets spread with sand were used for writing.

The pre-Columbian civilizations (e.g., the Incas' talking knots) and many others, all over the world, used and still use yarn and knots to count. These devices cannot be considered as abaci or computing tools but, more properly, as data storage facilities.

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 housed at the National Museum of Epigraphy, Athens. It is a marble slab approximatively 1,490 mm in length, 750 mm in width and 45 mm thick, with five groups of markings.

C. Rossi et al., *Ancient Engineers' Inventions: Precursors of the Present*,
History of Mechanism and Machine Science 8, 41–59.

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 × 90 mm with nine long slots and eight short slots. A layout of it is shown in Figure 4.1.

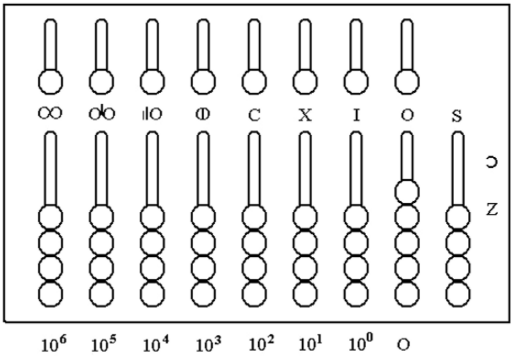

Fig. 4.1 Layout of a Roman hand abacus.

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 (⊃ 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 which word we derive calculus, calculations etc.

The Chinese abacus (swanpan) is similar and quite as old as the roman one. It is composed by 20 bamboo sticks (10 in the upper part and 10 in the lower) and the buttons are generally made of ivory. Each of the upper sticks have two buttons as does 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 one to compute additions and subtractions easily, and with a little training also multiplications and even divisions.

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

4.2 The mesolabio

This device is also known for its solution of 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.

4.2.1 The mesolabio of Heratosthenes

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 Mesolabio.

This device is shown in Figure 4.2. 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 tablets is drawn a right triangle. A piece of twine t is 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 are moved till the hypotenuse of the second triangle intersects the cathetus of the first triangle at the point where the twine intersects the same cathetus; the same is made moving the third triangle. Now we have:

$$\frac{a}{x} = \frac{x}{y} = \frac{y}{b} \tag{4.1}$$

From the previous equations, three couples of equations can be written; let us consider the following:

$$\begin{cases} x^2 = a \cdot y \\ x \cdot y = a \cdot b \Rightarrow y = \dfrac{a \cdot b}{x} \end{cases} \tag{4.2}$$

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

$$b = 2a \tag{4.3}$$

hence, from the second of Equation (4.2) comes:

$$y = \frac{2}{x}a^2 \tag{4.4}$$

and, by substituting in the first of Equation (4.2):

$$x^3 = 2 \cdot a^3 \tag{4.5}$$

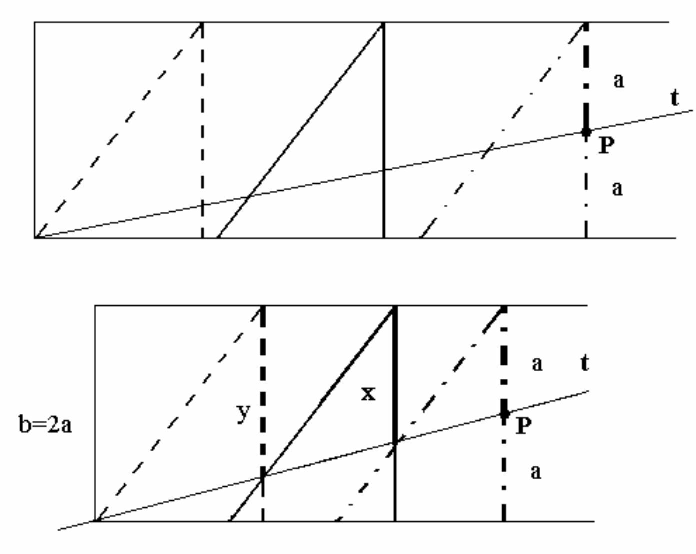

Fig. 4.2 The mesolabio of Heratosthenes.

4.2.2 The solution by Hippocrates and the mesolabio by Dürer

The solution by Hippocrates is based on Euclid's theorem: 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 Figure 4.3 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:

$$\frac{a}{x} = \frac{x}{y} \tag{4.6}$$

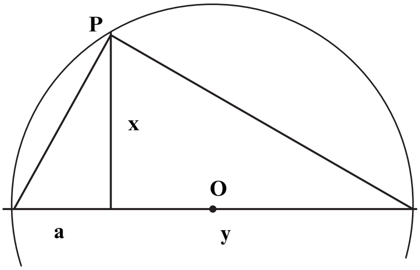

Fig. 4.3 A right-angled triangle.

In Figure 4.4 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 pair 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' lengths, while the relations among them did not change. Further details on the working principle are given in the observations.

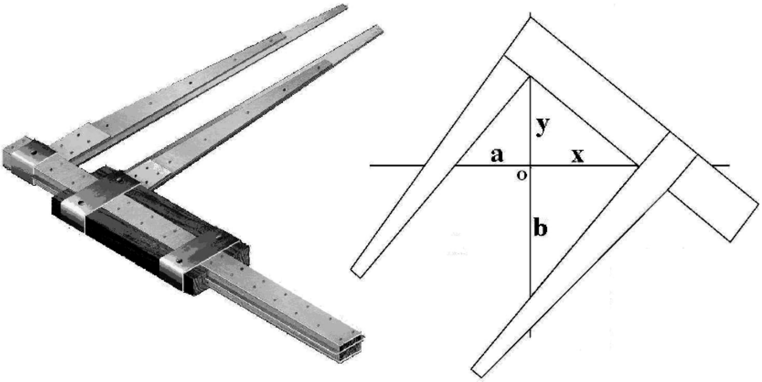

Fig. 4.4 The mesolabio by Dürer.

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 Renaissance also to divide in two equal parts any musical interval.

Both devices were described by Vitruvius (Marcus Vitruvius 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 reproduced in Figure 4.5.

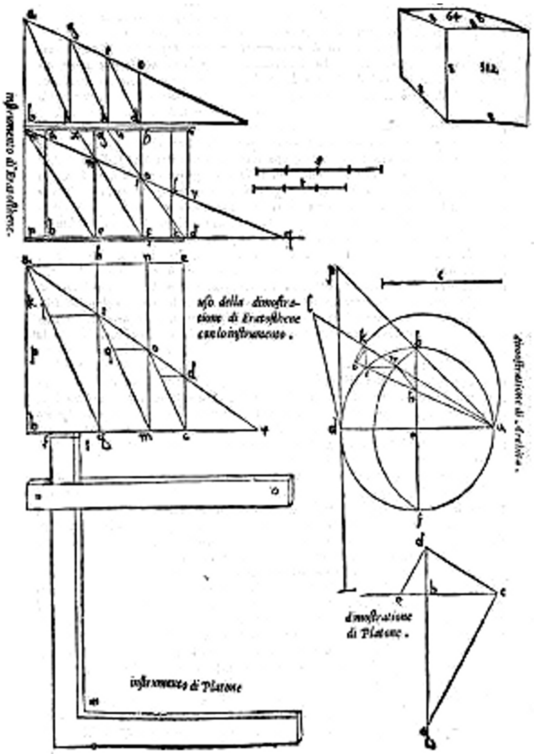

Fig. 4.5 Mesolabia, from D. Barbaro's translation of Vitruvius' treatise.

4.3 The mechanism of Antikythera

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 Antikythera is a very brilliant work of its era; together with other devices presented in this book, it shows, once again, that 20 centuries ago scientific knowledge was much more advanced than one commonly supposes.

4.3.1 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 on in the first paper from Professor Derek de Solla Price (1922–1983), Professor of History of Science at Yale who was the first to deeply study 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 Antikythera 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 from all countries and is ill famed because of many shipwrecks. The spongefisher's cutter dropped anchor near a little bay called Port Potamo (lat. 35°52′30″ N, long. 23°10′35″ E) where Elias Stadiatis, 42 m deep, found a large ship that 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 was estimated that the ship had sunk between 80 to 60 B.C.; it was also concluded that it was a Roman or Greek cargo ship headed for Rome that was carrying more than 100 statues similar to others the Romans had brought to Italy after they had conquered Greece.

Later the find was brought to the Athens' Museum where it was not seriously studied until 1928, when the Greek admiral Jean Theophanidis mentioned the find in some articles. Theophanidis described some visible gears in the mechanism and proposed a reconstruction with stereographic projection suggesting that the device was an astrolabe. In Figure 4.6 is a picture of the find at the Athens' National Archaeological Museum.

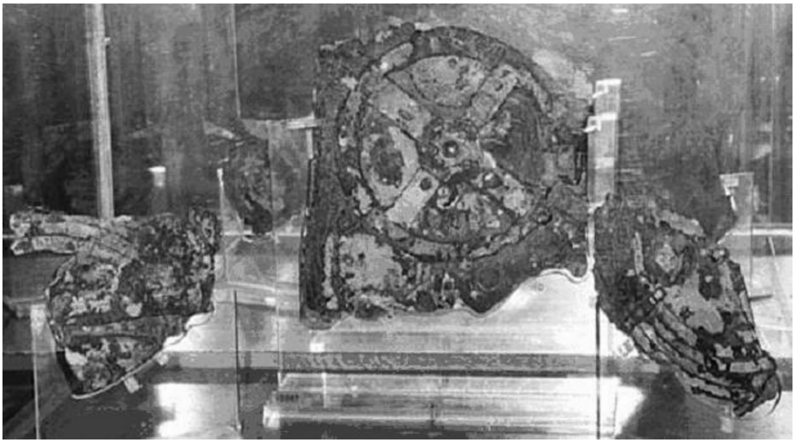

Fig. 4.6 The find (Athens' National Archaeological Museum).

In 1951, De Solla Price, with the cooperation of the director of the Athens' National Archaeological Museum, Christos Karouzos, started a deep investigation of the mechanism. During his studies De Solla Price was also helped by several other scientists with radiographic and chemical analyses. In the following years researchers such as Allan George Bromley, Michael Wright and others who participated in the recently constituted Antikythera Mechanism Research Project, continued investigations of the mechanism, discovering new possibilities in the interpretation and reconstruction of the mechanism. Among the scientists presently investigating the mechanism, Giovanni Pastore must be mentioned; he devoted an entire chapter of his book on slide rules to the Antikythera mechanism.

4.3.2 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 × 15 × 7.5 cm. Outside the box was located a crank handle that was used to create motion. In Figure 4.7, on the left, a working model of the mechanism made by John Gleavè, based on the studies by De Solla Price is depicted; on the right of the same figure, is a possible pictorial reconstruction of the device with a wooden box, hypothesized by the authors.

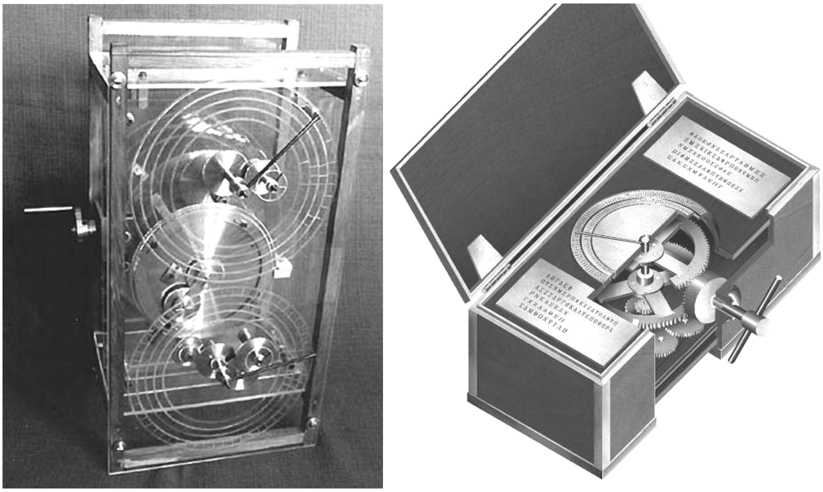

Fig. 4.7 Reconstructions of the mechanism of Antikythera.

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 to 100 B.C. In Figure 4.8 the reconstructions of the three dials are depicted.

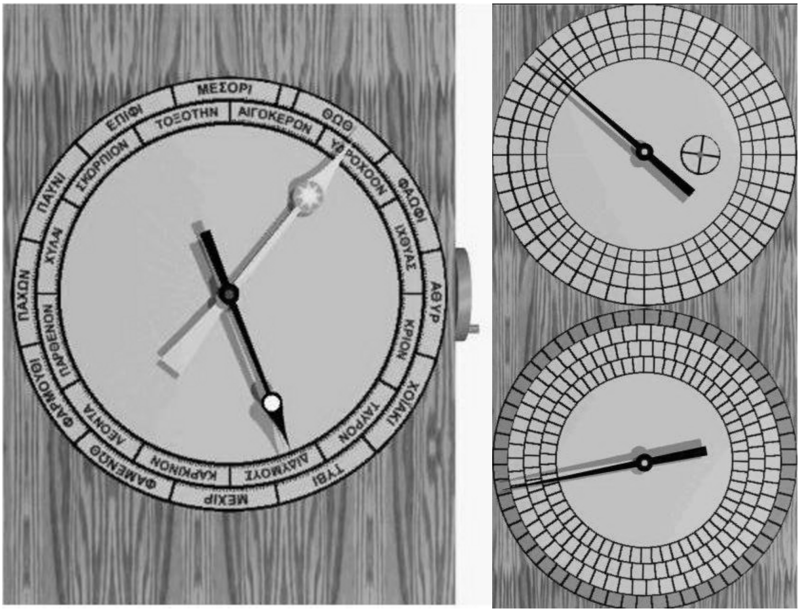

Fig. 4.8 Reconstruction of the dials.

The only dial that is clearly understandable is the one located on the front panel. Its reconstruction is based on a fragment as big as about one fourth of the entire circle; on it there is a circular scale about 45° wide. This dial contains two annuli as shown in Figure 4.9. On the external scale the months are recorded while on the inner the constellations of the zodiac.

The marks are not precisely spaced: the mean error is about 1/3°. The front dial clearly shows the motions of the sun and of the moon with respect to the constellations of the zodiac; it also shows the rising and setting 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 during 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's orbit around the earth, observed from the earth. The other dial is not intelligible.

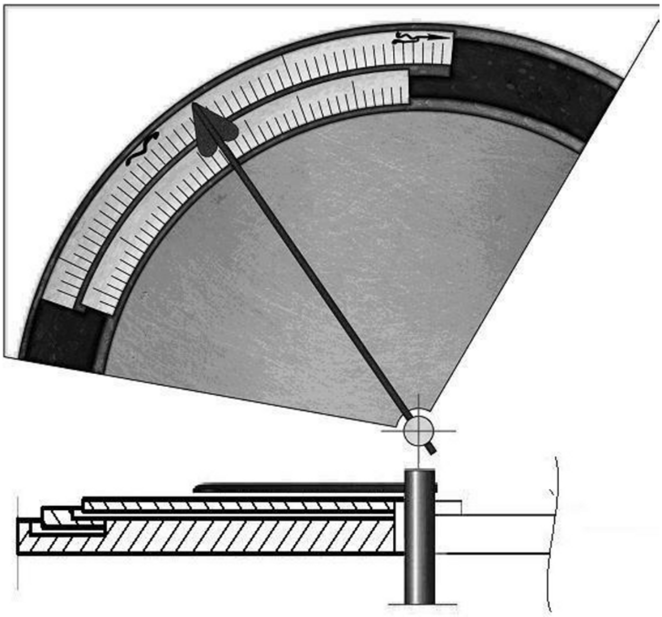

Fig. 4.9 Front dial, detail.

In Figure 4.10 is shown the scheme of the gear trains as drawn by De Solla Price.

The motion is given by the crank handle on whose shaft is fitted a first wheel A1 having 45 teeth. This wheel's gears mesh with the wheel B1 that has 225 teeth; the latter gives 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 recognized 27 wheels; the main part of the gear train is constituted of 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 with respect to the sun. The differential gear aim was also to show the lunations that were obtained by subtracting the motion of the sun from the sidereal motion of the moon.

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

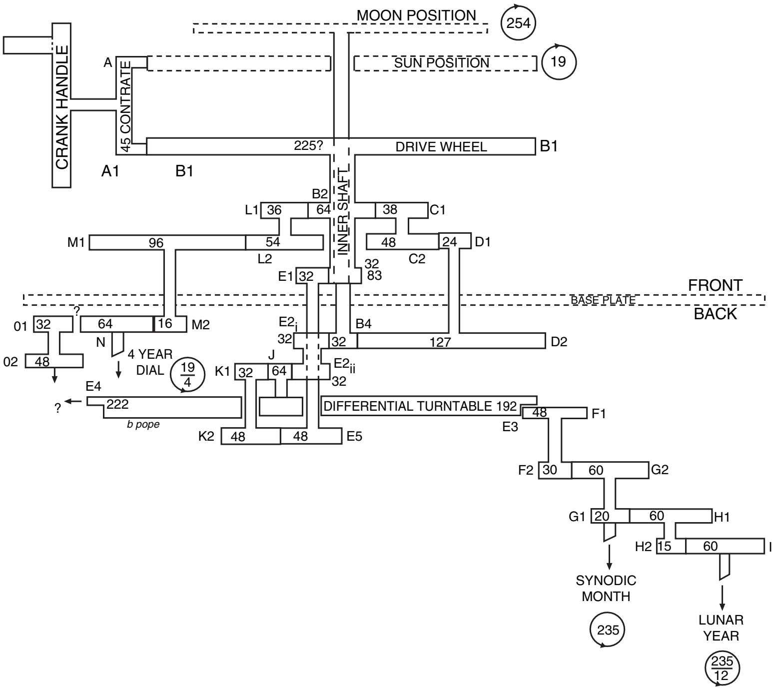

Fig. 4.10 Scheme of the gear trains by De Solla Price.

Figure 4.11 shows a frame from the animations of the mechanism by Dr. M. Roumeliotis, University of Macedonia.

After De Solla Price, many other scientists studied the mechanism; among them we can mention Allan George Bromley (University of Sydney) and Frank Percival, a clockmaker who collaborated with him and Michael Wright (London Science Museum). 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 model, 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.

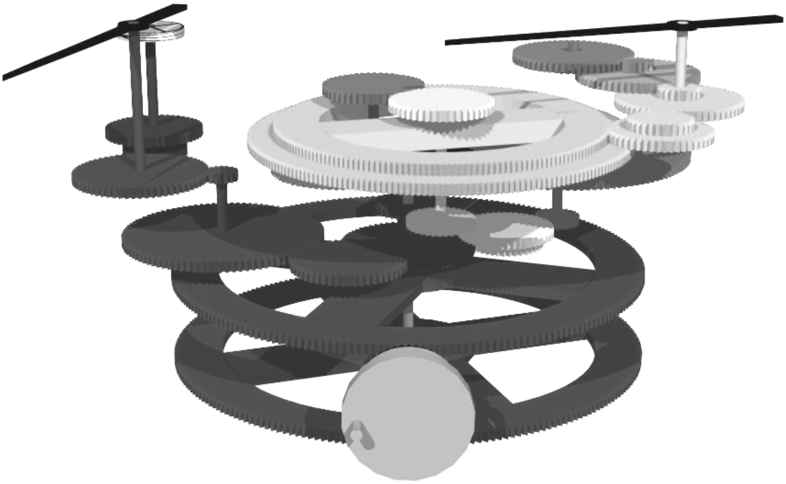

Fig. 4.11 A frame of an animation of the mechanism.

The number of recognized gears rose to 31. In addition, Wright proposed also that the scale of the dials on the rear panel had five 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 eclipses.

According to Wright, no epicyclic gear train is present in the mechanism.

Presently the mechanism is being studied by a team of scientists of the "Antikythera Mechanism Research Project" that is comprised of universities, museums, and some private companies' research centers, and has the financial support of the Greek National Bank.

The most recent 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 were two more pointers that showed two more important astronomical cycles: the Callippic cycle and the Hipparchus cycle.

4.3.3 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.

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 of material. The analysis results are contained 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 were probably adsorbed by salt water; no zinc was found. In conclusion, the alloy and the impurities were perfectly compatible with the technology of 2,000 years ago.

The gear teeth are very simple and inaccurate. The tooth profile is represented by a simple triangle; that the mechanism worked was possible only because the backlashes were very wide as is shown in Figure 4.12.

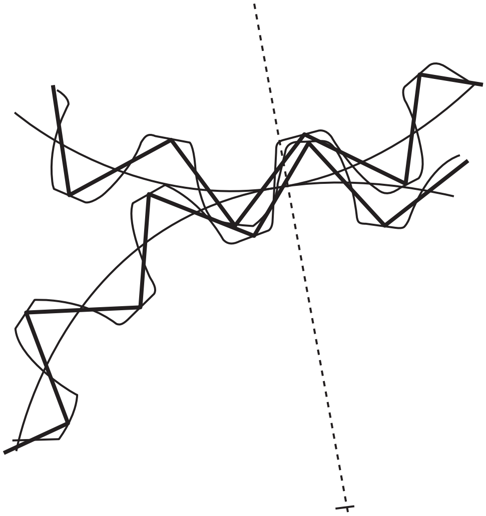

Fig. 4.12 Teeth profile compared with modern involute.

Also the diametral pitch is quite inaccurate: in Figure 4.13 is a graph of the number of gear teeth versus the wheel radius that was estimated by De Solla Price for some of the gears.

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 Antikythera certainly represents one of the most brilliant pieces of the Hellenistic age but it is perfectly compatible with the technology of those centuries.

The necessary astronomic knowledge also was available to the astronomers of that age.

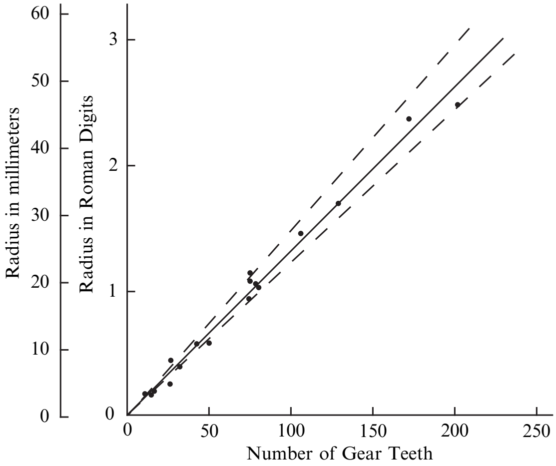

Fig. 4.13 Diametral pitch of the wheels.

4.3.4 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 excogitasset 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 found the way to reproduce, with a single rotation, stars' motions that cannot 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 subsequent sheets of this section of "De Republica" have been lost.

From Cicero's description we can deduce that:

- Similar devices existed in Rome about 50 years after the shipwreck at Antikythera and, probably, 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 of 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 comprehensive as the one by Cicero.

4.3.5 A recent interesting finding

Recently (2006) on the sea bed close to Olbia (Sardinia, Italy) an interesting fragment of a gear was found. The gear diameter is 43 mm and the number of teeth is 55, hence, the dimensions are comparable to the ones of the gears in the mechanism of Antikythera. The find was dated to the 3rd century B.C. and the teeth seems to be much more advanced than the rough triangular shaped teeth of the gears in the mechanism of Antikythera; their profile, in fact, seems to be similar to the one of modern gears. This could suggest that mechanisms like the one of Antikythera were built, with even more accuracy, 2 centuries before the shipwreck at Antikythera.

Observations

The devices presented in this chapter 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, however, a figure's value depends on the position it has 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 also be 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 × 31 = 465; in Roman notation it becomes: XV × XXXI = CCCCXLV. The computing was carried out, using the abacus, by means of the procedure described as follows.

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 2 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 it is not considered.

In Table 4.1 an example for the multiplication 33 × 15 = 495 is reported; in brackets the corresponding numbers in Arabic notation are written.

Table 4.1 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)

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 4.2:

Table 4.2 Example of multiplication with Roman numbers.

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

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 design 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 had been considered as the one that had given the best performances. In other terms, many ancient engineers generally thought that, once a satisfactory prototype had been fashioned, to make another one, bigger or smaller, the same good performances could be expected if only the dimensional ratios were respected. Obviously this was a mistake: for instance if a ball having doubled weight is to be thrown the same distance by a ballista as the single weight was thrown, this does not mean that a ballista having all its dimensions doubled is required.

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

The possibility of computing the cubic root of a given number by using the mesolabio by Hippocrates (or by Dürer) is shown in Figure 4.14.

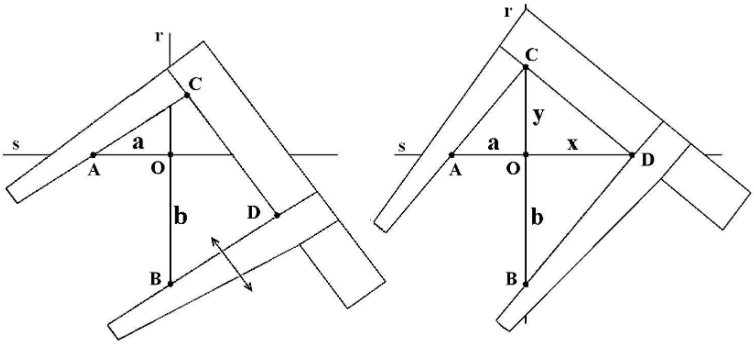

Fig. 4.14 The working principle of the mesolabio by Hippocrates.

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 we have:

$$\overline{OB} = b = R/a^2 \tag{4.7}$$

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 Euclid's theorem shown in Figure 4.4, it is:

$$\frac{a}{y} = \frac{y}{x} = \frac{x}{b} \tag{4.8}$$

From the first two ratios it is possible to obtain:

$$x = \frac{y^2}{a} \tag{4.9}$$

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

$$y = \frac{a \cdot b}{x} \tag{4.10}$$

Now, by substituting (4.9) in (4.10), we get:

$$y = \frac{a^2 \cdot b}{y^2} \Rightarrow y = \sqrt[3]{a^2 \cdot b} \tag{4.11}$$

And, by substituting (4.7) in (4.11), the cubic root of R is obtained:

$$y = \sqrt[3]{R} \tag{4.12}$$

Moreover, if in the given scale the point A was fixed then we have:

$$a = 1 \tag{4.13}$$

From Equation (4.11) it comes directly:

$$y = \sqrt[3]{b} \tag{4.14}$$

As for the presence of epicyclic gear trains in the mechanism of Antikythera, the authors think that probably De Solla Price was right. In fact epicyclic gear trains can be 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 Figure 4.15, on the left, is depicted the reconstruction of the mechanism made by John Gleavè based on the studies by De Solla Price; on the right is a drawing of an epicyclic gear train by Leonardo da Vinci.

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

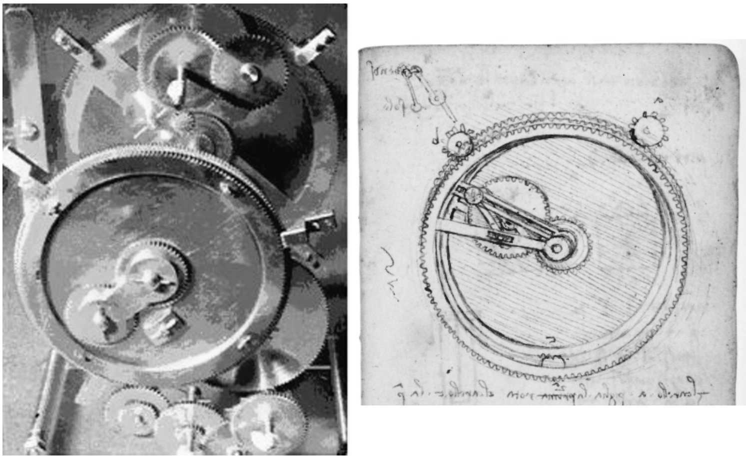

Fig. 4.15 Epicyclic gear trains.

Finally, it is possible that the mechanism of Antikythera has been used also for sailing applications: knowledge of the moon's 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 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.

Part II – USING NATURAL ENERGY

In this part we discuss some early motors that used natural energy like wind and water long before this became a crucial societal issue.

Although we speak in this part about motors with rotating shafts, we hasten to point out that the ancient engineers, e.g., the Greek and Roman ones, had a concept of a motor that was sometimes rather different from ours. For us, when we think of a motor, it is common to imagine a device that transmits mechanical energy by a rotating shaft. For an ancient Greek or Roman engineer, a motor was anything that was capable of generating a motion. From this point of view, many of the delayed or automatic action devices, invented first by the Greeks and then by the Romans, presuppose the use of a motor; nevertheless rarely did these have any rotation mechanism.

Since this book is not written for engineers only, let us talk briefly about the concepts of: force, energy-work, power and motors.

According to physics, a force is something that can cause an object with mass to accelerate, that is to say a force changes the velocity of an object: it starts its motion if it is stationary and changes its speed during the motion. This concept was not clearly understood in antiquity: Aristotle, for instance, in order to explain why bodies fall to earth, believed that objects had an innate tendency of finding their "natural place" that lead them to "natural motion"; he spoke also about an unnatural or forced motion, which required continued application of a force.

The first to propose an alternative (and substantially correct) model was the well-known Galileo Galilei (Pisa, 15 February 1564–Arcetri, 8 January 1642).

If a force is applied at a certain distance from an axis, as in the case of the crank shown in Figure II.1, the axis will be acted upon by a moment of a force (torque) the amount of which depends on the nature of the force and its distance from the point of action.

In Figure II.1 it is supposed that the force F is orthogonal to the plane that contains the axis a and the distance r, hence the moment M is simply given by $M = F \cdot r$.

In the same figure is shown a (constant) force F that acts on a body moving it from a position A to a position B along a distance d; in this case the force transfers energy, a process called mechanical work, that depends on the force and the distance.

In the figure, since force and displacement are parallel, the mechanical work W is simply given by W = F·d.

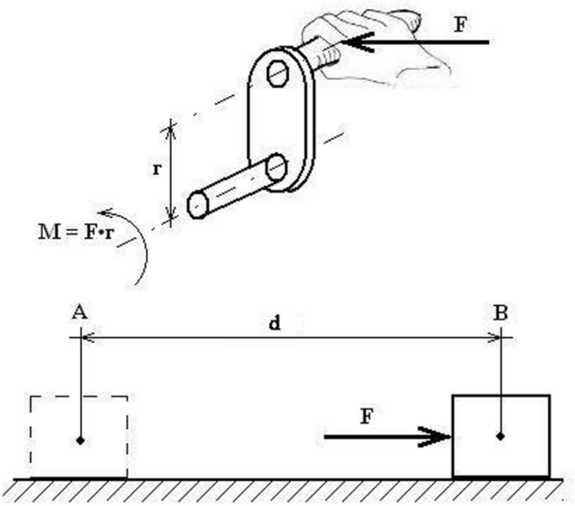

Fig. II.1 Moment and mechanical work of a force.

In the figure the displacement is horizontal, hence no work against gravity is done; so, if the body's velocity is constant (no acceleration), the force F equals the friction forces (due to air, soil, etc.) acting on the body.

Since the moment of a force and the mechanical work are both given from the product of a force and a length, they both have the dimension of energy.

A motor can be linear or rotating; in the first case the output is represented by a moving element that exerts a force, in the second case the output is a rotating shaft that exerts a torque.

Power is the work done in a given unit of time. In the case of linear motors, power is the product of the force times its velocity; in the case of rotating motors, power is the product of the torque times the angular speed.

Hence two machines can produce the same power but one of them can give great torques at a low angular speed while the other one can give low torque at a high angular speed.

Chapter 5 – WIND MOTORS

Introduction

The first non-muscular source of energy used by man was wind energy; examples of wind motors, in fact, are very old. By wind motors we mean all the devices that create 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 in which it exists. 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 wind pushing or pulling an object to construction of a device that could capture and use this force, its achievement coinciding with what historians call the end of prehistory.

C. Rossi et al., *Ancient Engineers' Inventions: Precursors of the Present*,
History of Mechanism and Machine Science 8, 63–79.

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 a paddle wheel or, in respect of its primary use, a mill. Regarding this latter meaning, specifically indicating the motor of a machine used for grinding, the definition soon had to specify whether by wind or by water, the two natural currents. It is only in very recent times that these natural sources of energy have been replaced by physical or chemical reactions of liquid or gaseous fluids, an extreme separation from the root word and thus requiring a clearer definition.

In the following sections, we will examine some examples of ancient wind motors in operation both on the earth and at sea.

5.1 The wind mills

Wind mills can be considered as ancient ancestors of modern aeolic generators, the use of which saw 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 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.

5.1.1 The Afghan mill

For approximately 1,000 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 2nd millennium B.C. in Mesopotamia, as seems to be suggested by some allusions in the Code of the great Hammurabi. Figure 5.1 shows a pictorial reconstruction of an Afghan mill and in Figure 5.2 orthogonal views of the same mill are drawn.

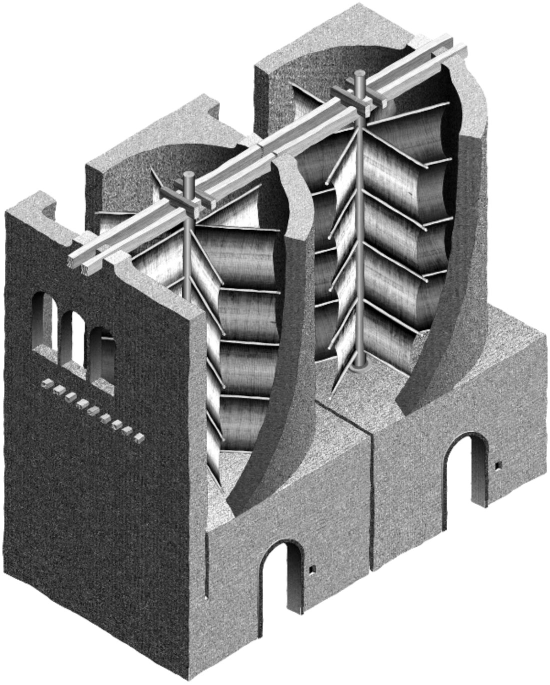

Fig. 5.1 Virtual reconstruction of an Afghan mill.

Upon Hammurabi's 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: they probably did not greatly differ 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 grindstone that rotates above an underlying one”.

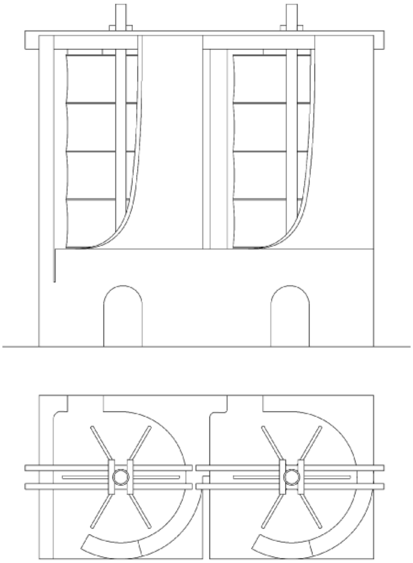

Fig. 5.2 Orthogonal views of the Afghan mill.

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.

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 its 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 1st 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 can be seen in a drawing dated 1595 by Fausto Veranzio (1551–1617); this eminent scientist will be more widely cited in Section 6.4 for his water wheel. Its true novelty, and perhaps its greatest contribution, consisted 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.

5.1.2 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" (ανεμουριον) 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 ανεμουριον, 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, maneuvering 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 4 to 12 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° 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 maneuver 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 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 maneuvers, relegating rotors with a greater number of sails to more difficult tasks or to less windy locations.

Figure 5.3 shows a reconstruction of the rotor of the Cretan mill.

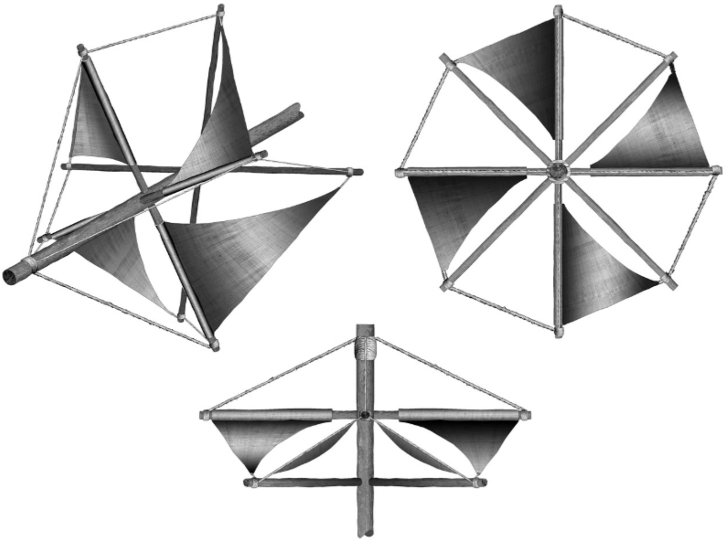

Fig. 5.3 Virtual reconstruction of the rotor of the Cretan mill.

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. Figure 5.4 shows pictures of a Cretan mill in Greece and a Dutch one.

Fig. 5.4 Cretan windmill from Greece and Dutch windmill.

5.2 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 rudimental mat used to push pirogues on the tranquil lagoons, accomplished in accordance with complex calculations around the 4th 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 6,000 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 were, 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 maneuver: 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 2650 B.C. the pharaoh Snefru sent 40 vessels to Biblios (near the modern Beirut) to bring cedar tree trunks to Egypt that had to be used to built boat hulls.

Figure 5.5 depicts a bas-relief and a painting showing an Egyptian ship dating about 5,000 years ago. It can be observed that the mast is made of two poles and has many backstays, just one forestay and no shrouds. This permitted one to put down the mast easily and to move on by oars.

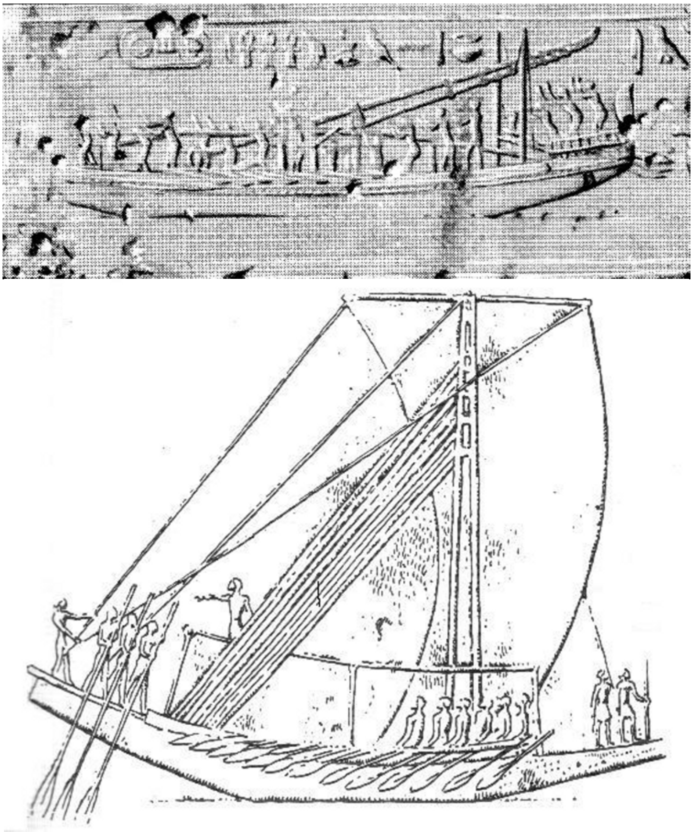

Fig. 5.5 Egyptian ships.

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 maneuvers.

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 Figure 5.6 a reconstruction of a Roman liburna galley is shown. From the figure it is also possible to note the pair of rudders, one installed on each side of the ship. Lateral rudders were used on European ships till the Middle Ages with very few exceptions.

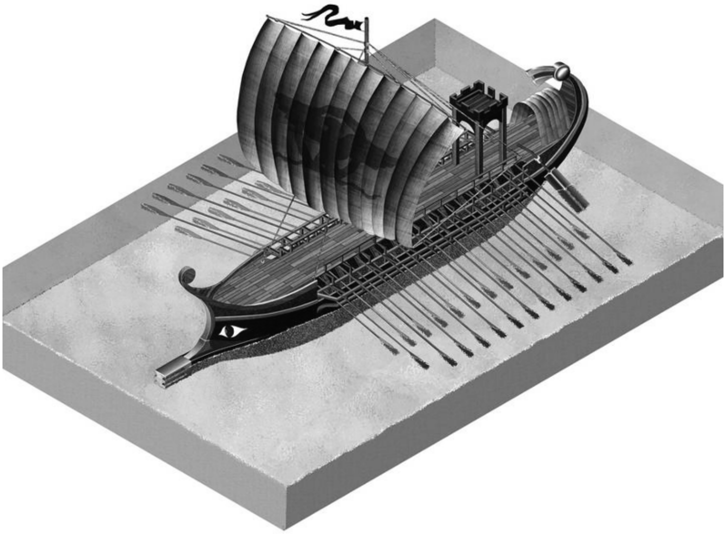

Fig. 5.6 Virtual reconstruction of a Roman liburna.

Development of the square sail went on till the second half of the 19th century when advances in naval architecture made it possible to design and build the fabulous clippers that represent a masterpiece of the sail ship construction. The clippers were very fast, more so than the steam ships of that age: it is believed that some of them 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 1920s.

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 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 direction and the ship's longitudinal axis is lower than 90°. In this case the vessel will run over a zigzag route going up the wind as schematized in Figure 5.7; this method of sailing is called tacking.

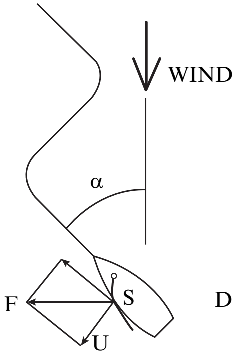

Fig. 5.7 Tacking.

This method can be applied 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 α 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's 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's 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 α not lower than, say, 75–80°, adopting particular lines (bow lines) to stretch the forward edge of the sail (luff); the ancient vessels with square sails, till the 16th century, could not sail with angles lower than 135–160°; only the Scandinavian drakkars could reach about 90°. 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.

5.2.1 Evolution of the sail rig

The first sail that permitted sailing with lower angles than 90° as the lateen sail. In Figure 5.8 is schematically shown the evolution of sails that permitted sailing closer to the wind.

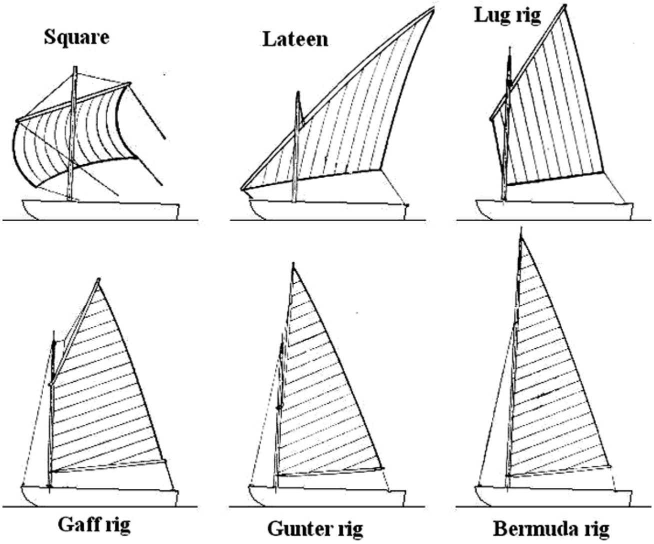

Fig. 5.8 Evolution of the sail.

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 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 battle, were powered only by oars. In Figure 5.9 is shown 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.

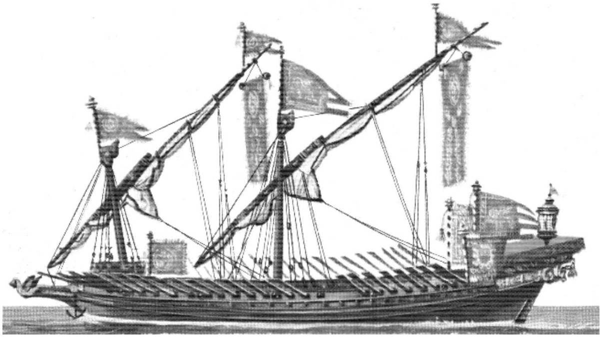

Fig. 5.9 Venetian galley of the 16th century.

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

The lug rig appeared later and as of today is still used on the Atlantic coasts of Europe and in the Adriatic Sea.

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

5.2.2 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 a unique central rudder that is more efficient than the pairs 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 of masts without any forestay, backstay or shroud; the sail was made by a mat, with many battens disposed horizontally and as wide as the sail. Most of the battens are 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 (Figure 5.10).

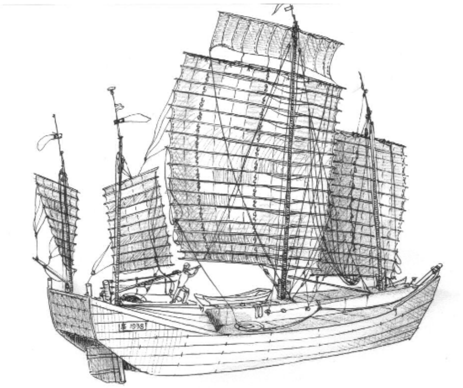

Fig. 5.10 Chinese junk (Courtesy by Dr. A. Cherini).

5.2.3 The Flettner rotor

An interesting evolution of sails is represented by the Flettner rotor; actually it does not represent an ancient invention and probably is not a precursor but it does represent the last evolution of wind motors and for this reason merits a short description. The working principle is based on the Magnus effect, discovered by Heinrich Gustav Magnus (1802–1870) and schematically presented in Figure 5.11.

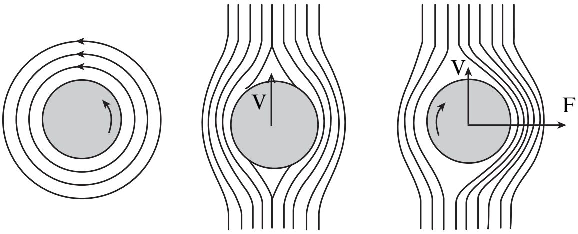

Fig. 5.11 Scheme of the Magnus effect.

In the figure 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 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 as 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, with respect to the direction of motion, the fluid particles' velocity 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 arises, orthogonal to the direction of the velocity.

In 1924 Anton Flettner (1885–1961) applied the Magnus effect to the propulsion of the ship "Buckau", shown in Figure 5.12. 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 angle values of as low as 20–30° while the original sail rig permitted tacking only with angles not narrower than 45° to the wind; moreover, the rig made it possible 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.

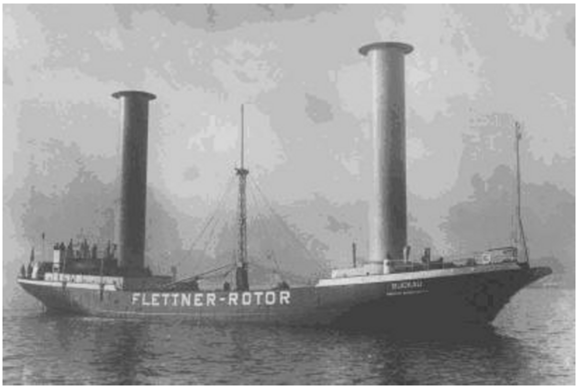

Fig. 5.12 The rotor ship Buckau.

The continued use of Flettner 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 aeolic generators.

Observations

Aeolian energy presents the following interesting aspects:

1. Aeolian motors are the first examples of a non-animal driven motor having a rotating shaft.
2. The development of sails permitted navigation on the sea and hence the diffusion of ideas, devices and knowledge.
3. Nowadays aeolian motors have a second childhood: modern wind motors are used in some applications in the field of renewable energy.

Chapter 6 – HYDRAULIC MOTORS

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.

6.1 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

C. Rossi et al., *Ancient Engineers’ Inventions: Precursors of the Present*,
History of Mechanism and Machine Science 8, 81–96.

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.

6.1.1 The Greek mill

In Figure 6.1 is represented a virtual reconstruction of a vertical axis mill whose rotor has vertical blades and mill grinders.

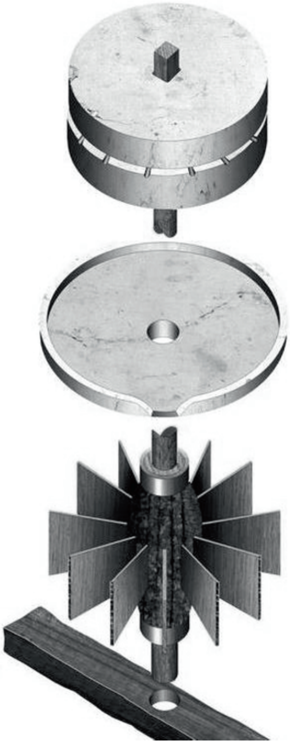

Fig. 6.1 Virtual reconstruction of a vertical axis mill.

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 8 or 12 very solid and thick planks, not longer than half a metre 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.

Figure 6.2 depicts an authors' virtual reconstruction of the rotor installed in its housing.

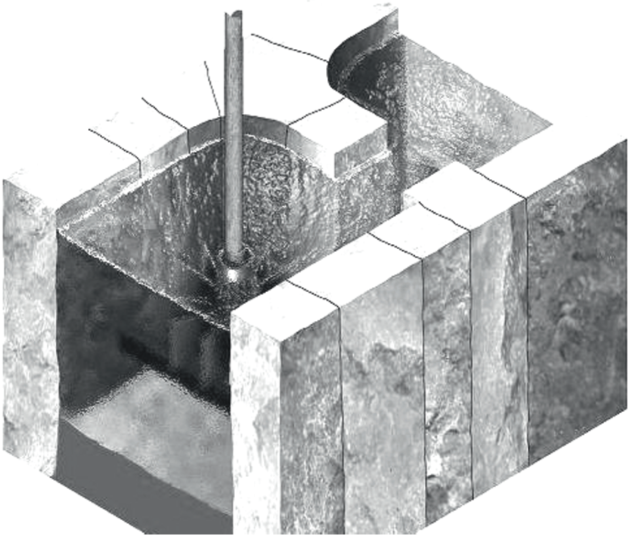

Fig. 6.2 Virtual reconstruction of the vertical axis rotor in its housing.

This vertically immersed rudimentary rotor opposed a strong resistance to the current: however, since its right and left blades 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. It is 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.

6.1.2 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 realty, 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 immerging 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, at which length it risked 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 that obstacle to be overcome, 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 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.

Figure 6.3 shows the virtual reconstruction of a vertical axis rotor with oblique blades and in Figure 6.4 the same rotor in its housing.

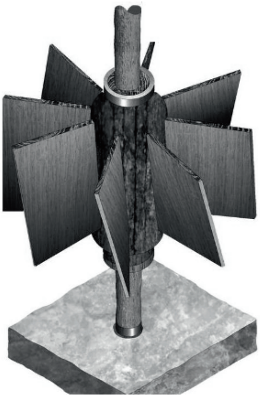

Fig. 6.3 Virtual reconstruction of a vertical axis rotor with oblique blades.

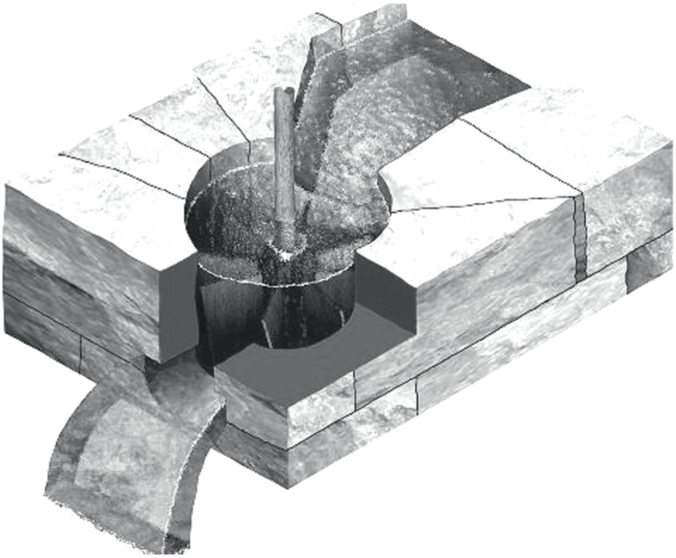

Fig. 6.4 Virtual reconstruction of the rotor in its housing.

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 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.

6.2 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 one represented in Figure 6.1 but was partially immersed in the stream. This type of water wheel is the undershot water wheel. At a later date appeared the overshot water wheel that, instead, receives water from above.

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 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 1st 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.

6.2.1 Undershot water wheels

An interesting device moved by an undershot water wheel is the saw represented on the bas-relief shown in Figure 6.5.

Fig. 6.5 Bas-relief showing a saw powered by a water wheel.

In the upper part of the picture, on the right, the channeling to feed the water wheel from below is clearly distinguishable.

A reconstruction by P. Klaus Grewe and Paul Kessner (from A Stone Relief of a Water-powered Stone Saw at Hierapolis, Phrygia in Energie Hydraulique et Machines Elevatrices d'Eau Durant l'Antiquitè, 2007, Centre Jean Berard, Napoli) is shown in Figure 6.6. In this device it is possible to observe one of the first realizations of a crank and slider mechanism.

For almost 2 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 pump used to raise water. In the 4th century Decimus Magnus Ausonius (Burdigala, today Bordeaux, ca. 310–395) wrote in his Mosella, vv. 362–364:

> "Praecipiti torquens cerealia saxa rotatu
> Stridentesque trahens per levia marmora serras
> Audit perpetuos 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.

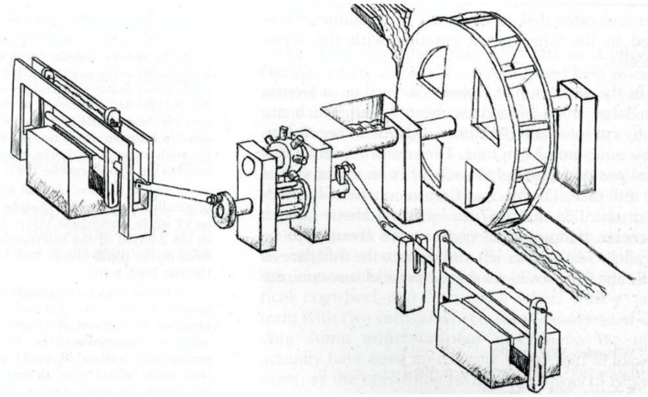

Fig. 6.6 Reconstruction by Grewe and Kessner.

6.2.2 Overshot water wheels

A further increase in efficiency was obtained by feeding the water wheel from above. Figure 6.7 shows an orthogonal drawing of a mill powered by a horizontal axis water wheel and Figure 6.8 a virtual reconstruction.

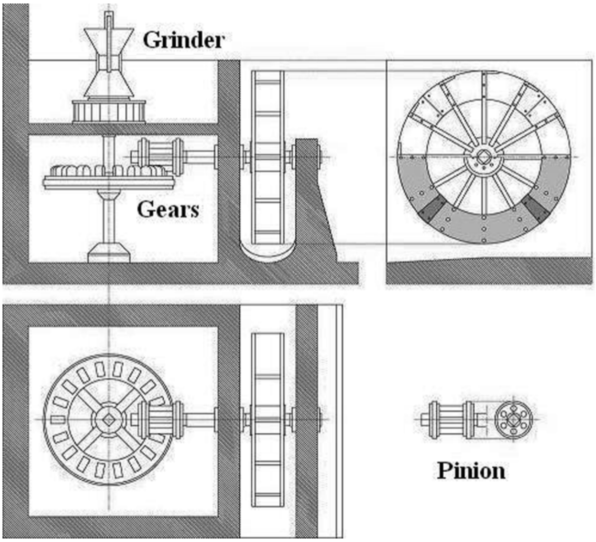

Fig. 6.7 Orthogonal drawing of a mill powered by a horizontal axis water wheel.

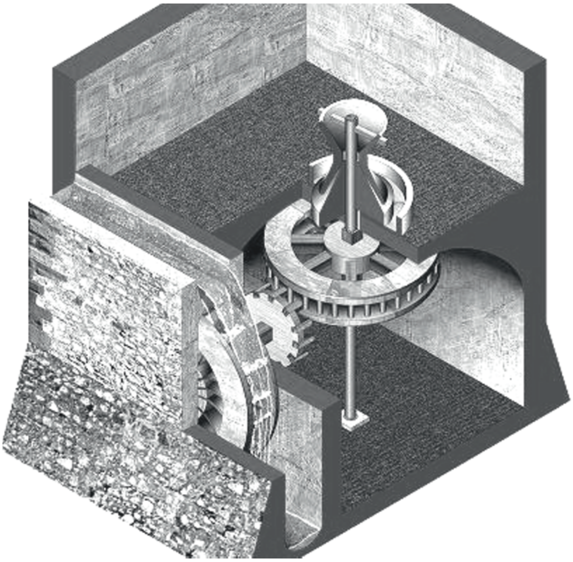

Fig. 6.8 Virtual reconstruction of a mill with horizontal axis water wheel.

6.2.2.1 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 cm wide and about 15 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; the article 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 …”.

Figures 6.9 to 6.11 show some drawings of the “Ruota di Venafro”; respectively: an orthogonal drawing, a virtual reconstruction and some details of the axis and of the system to embed the blades.

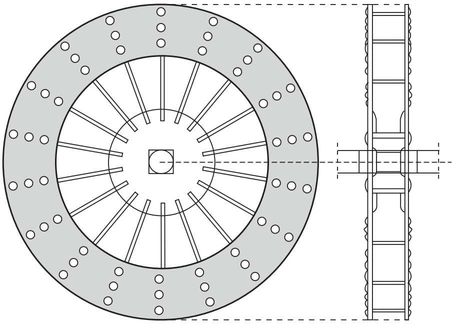

Fig. 6.9 Orthogonal drawing of the “Ruota di Venafro”.

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 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 t 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.

Fig. 6.10 Virtual reconstruction of the “Ruota di Venafro”.

Fig. 6.11 Details of shaft, hub and blades assembly of the rotor.

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 Figure 6.12 are shown some pictures of the rotor as it is installed on a channeling of the river 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.

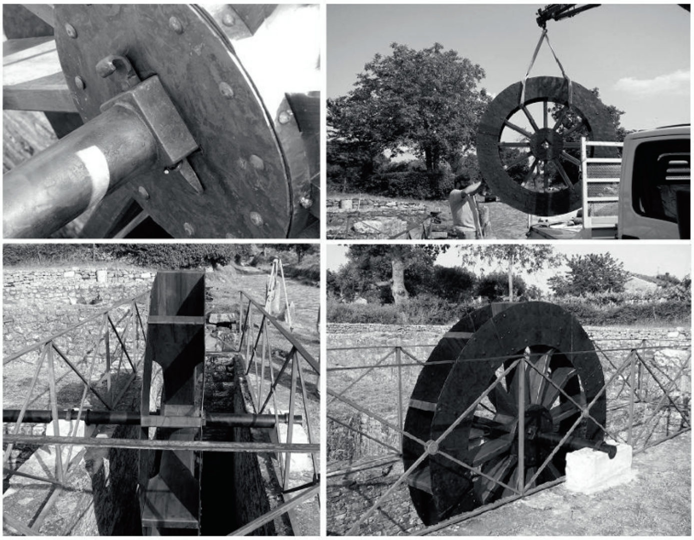

Fig. 6.12 The reconstruction and installation of the Ruota di Venafro.

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

6.3 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. Figure 6.13 shows both 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).

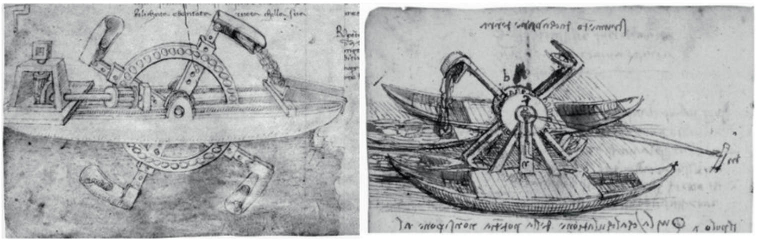

Fig. 6.13 Draggers by di Giorgio Martini and by da Vinci.

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 nonsense.

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 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 m 0.3 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.

6.4 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 was carried out by Arab engineers. A famous example of Arab water wheels are the hydraulic motors of the noria at Hama that are discussed in Chapter 7. 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 Chapters 7 and 15.

In Europe, water wheels, derived from the Roman ones, were built during the Middle Ages and the Renaissance and were used until a 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 design in the Renaissance is shown in Figure 6.14.

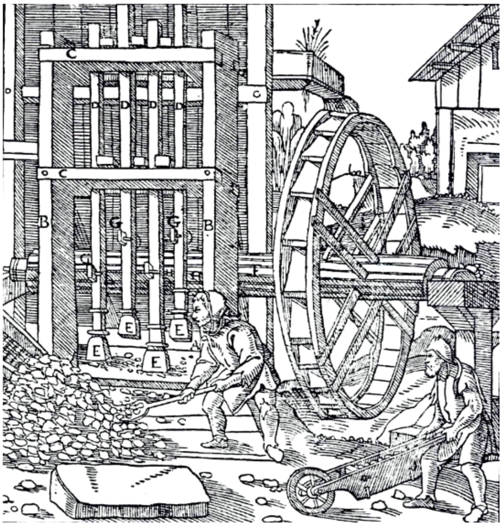

Fig. 6.14 Water wheel from “De Re Metallica” by Georgius Agricola.

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 Pawer or Bauer (1494–1555) in his treatise “De Re Metallica” (=About the metals) in 12 books on metals and mining, published in 1556 but finished almost 6 years before. The author was a German scientist better known as Geogius Agricola which 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, shown in Figure 6.15.

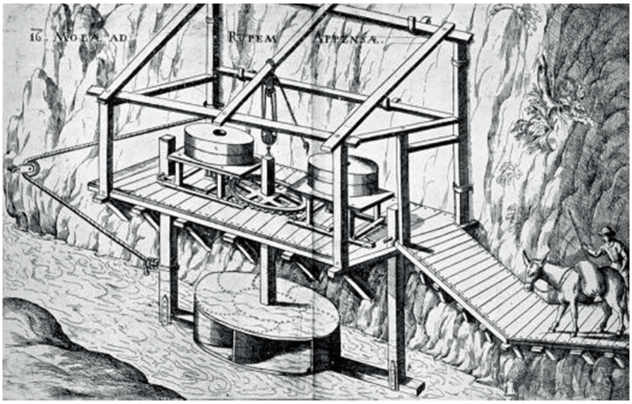

Fig. 6.15 Water wheel powered mill by Fausto Veranzio.

Veranzio (Sebenico 1551–Venice 1617) had many fields of interest: he was a glottologist, historiographer, politician, literary man and engineering 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 ca. 1595, 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 of particular interest. The water wheel powered mill shown in Figure 6.15 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.

Part III – USING WATER

In this part some early inventions that concern the use of water are presented. Many of them are still used today in the same form that was conceived by ancient engineers; furthermore, some of the devices that were built about 2,000 years ago are still used or are in such good condition that they could be easily put to use.

Certainly, water is the most important element for life and is indispensable for domestic animals and agriculture. For thousands of years, man founded his villages near rivers and lakes because of the need of water or just moved from one source of water to another. In those times, agriculture, when it existed, was a continuous effort to maximise the use of water sources in the locations where they could be found. It is impossible to conceive of non-nomadic livestock holdings or agriculture by using water only where it naturally flows. For this reason one of the most important steps in leaving prehistory was the knowledge of the control of water sources; any civilization starts from this ability.

This part is divided into three chapters in order to distinguish among the devices that were conceived to raise water or increase its pressure, the devices that were invented to distribute it and the early underwater activities. In Chapter 8, an interesting mining technique that made use of pressurized water is also presented. This technique, whose effects are still clearly visible today, changed the shape of an entire region (in Spain, at Huelva Valverde) and can be considered as one of the first examples of an ecologic disaster.

Chapter 7 – LIFTING WATER

Introduction

Water is without doubt the most necessary element for the existence of life; for this reason, 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 1 t 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 1 m^3 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

C. Rossi et al., *Ancient Engineers' Inventions: Precursors of the Present*,
History of Mechanism and Machine Science 8, 99–118.

dating to the 18th century B.C. made explicit reference to irrigation machines operated by windmills. The very opposite of those used almost 3 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.

7.1 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. Figure 7.1 shows an Egyptian painting of the 1st millennium B.C. showing a shaduf and a pictorial reconstruction of it. Over the centuries it was perfected and became highly diversified and is still used in many non-industrialized countries. This device was also used for the medieval trebuchet a (kind of catapult, see Chapter 12), 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. 7.1 The shaduf.

7.2 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 Pompei 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 Pompei, 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 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. Figure 7.2 shows a scheme of the Archimedes' screw used to lift water.

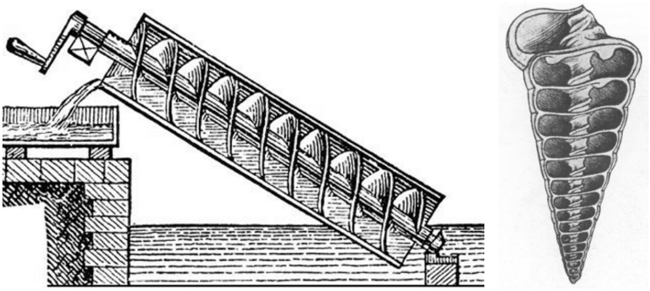

Fig. 7.2 Archimedes' screw.

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

7.3 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.

7.3.1 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. Figure 7.3 depicts 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.

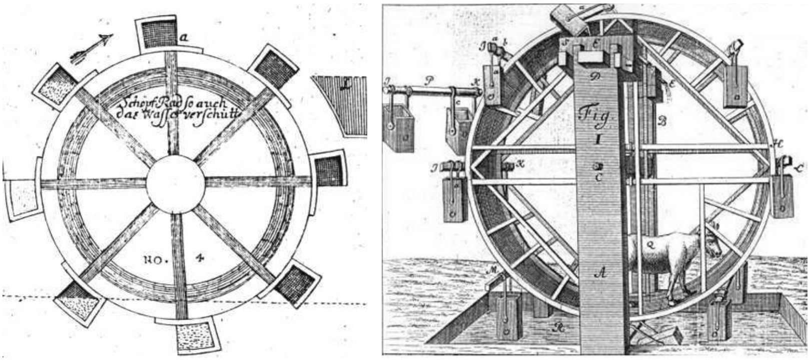

Fig. 7.3 Scoop wheels by Leupold.

From classic sources the water lift devices of the city of Ostia are widely mentioned. According to historical 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 but 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 metres. 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. Figure 7.4 shows a pair of these, still existing, devices.

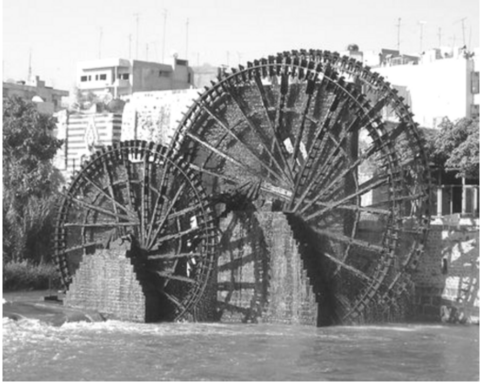

Fig. 7.4 Noria at Hama.

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.

7.3.2 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. Figure 7.5 shows a scheme of a chain noria.

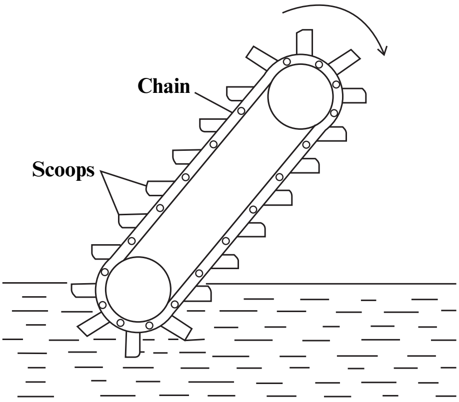

Fig. 7.5 Scheme of a chain noria.

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 of 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 (Chapter 3) and his automaton (Chapter 15). Among other water lifting machines, probably the most interesting is the one shown in Figure 7.6.

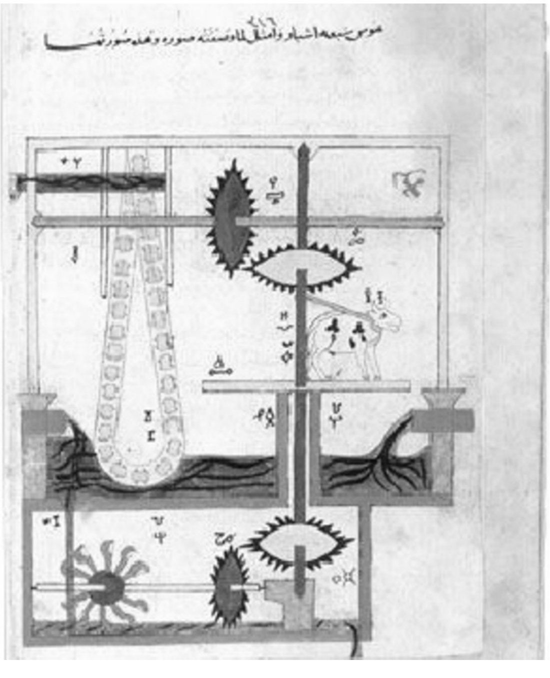

Fig. 7.6 Chain noria by al Jazari.

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 Figure 7.7 is shown a picture of one of these “modern” norias.

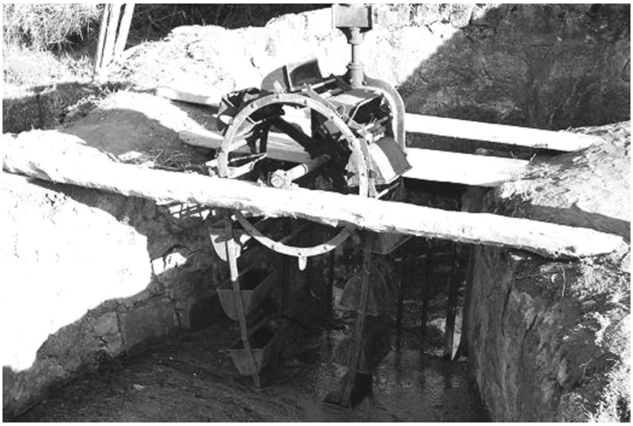

Fig. 7.7 A “modern” chain noria.

7.4 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.

The chain-pump was conceived to remove excess water from on board ships and so, being essential for safety, it was 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. The chain-pump is still used today in thermal engines, hydraulic cylinders and even the very common medical syringe.

7.4.1 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 metres 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 Figure 7.8 are depicted the finds of a chain pump found at the St. Gervais relict and a virtual reconstruction of it.

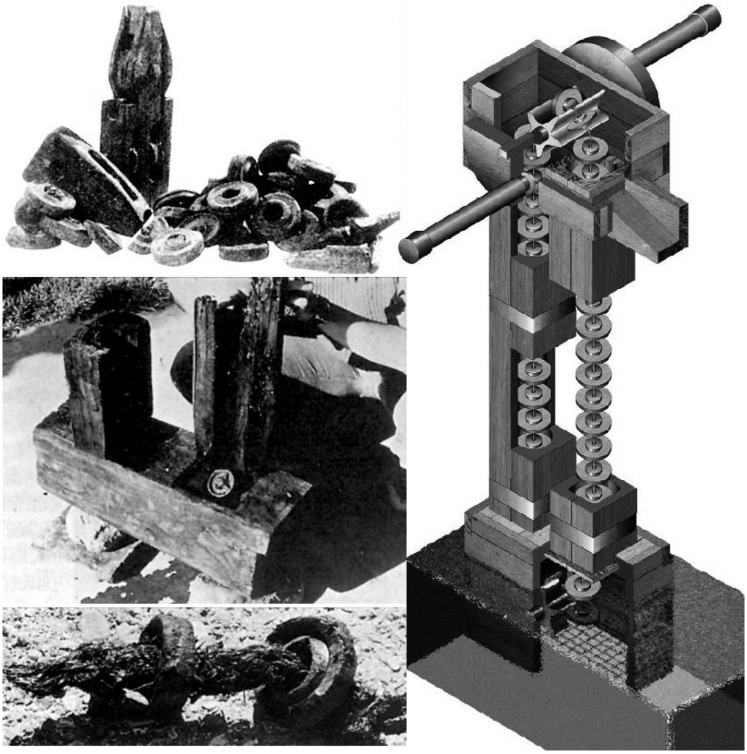

Fig. 7.8 Chain pump: finds and authors' virtual reconstruction.

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: Figure 7.9 is a drawing from a treatise on architecture, engineering and military art by Francesco di Giorgio Martini (1439–1501); some further biographical information is given in the last section of this chapter.

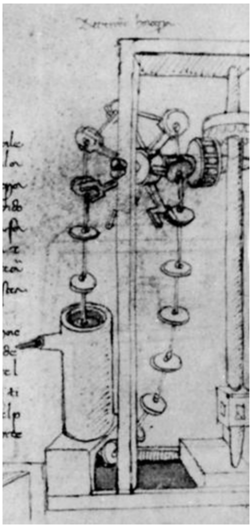

Fig. 7.9 Chain pump by Francesco di Giorgio Martini.

7.4.2 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 spurts. 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 fire fighters 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.

Figure 7.10 shows 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.

Fig. 7.10 A two cylinder reciprocating pump; finds and authors' reconstruction.

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 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 omni-directional 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 1 m 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 was 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. Figure 7.11 shows the finds, a virtual reconstruction of the pump acting as a flamethrower and some orthogonal views.

It is a 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 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 use the term siphon to mean 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.

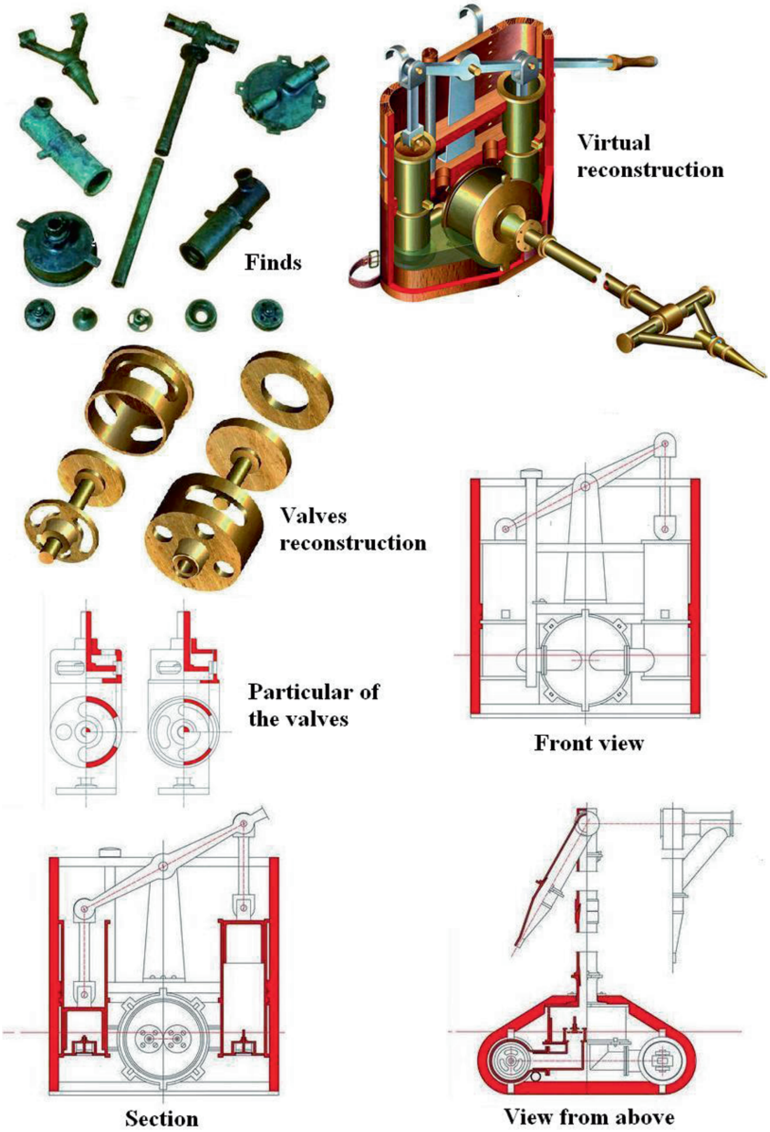

Fig. 7.11 Pump of Valverde; finds and author's reconstruction.

Another interesting ancient application of the reciprocating pump is the water organ by Ctesibius, a virtual reconstruction of which is shown in Figure 7.12; in the figure, a particular of a mosaic showing the organ is included.

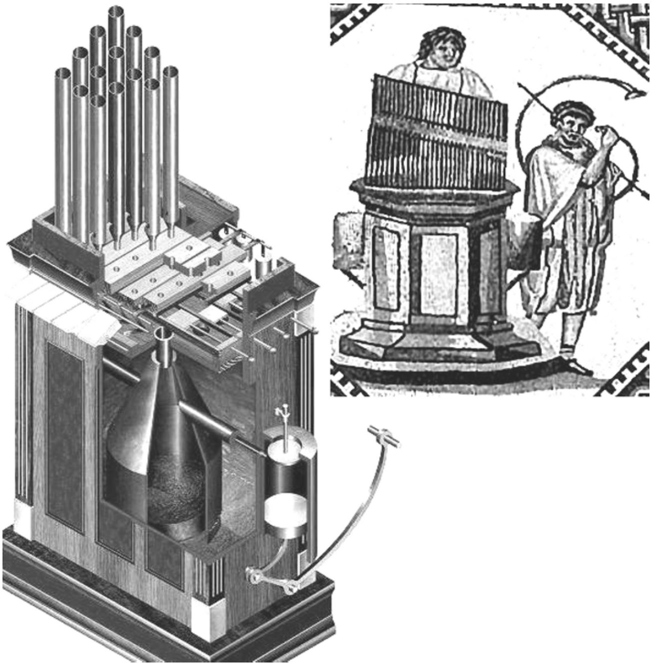

Fig. 7.12 Water organ; authors' virtual reconstruction and particular of a mosaic.

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 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 inventions of water pumps were carried on by Arab engineers; among these, once again, the machines designed by Al Jazari are particularly interesting. One of them consists of a pair of copper cylinders horizontally opposed; the pistons are moved by a water wheel through a gear train and a quick return mechanism. Figure 7.13 shows a drawing of Al Jazari's reciprocating pump.

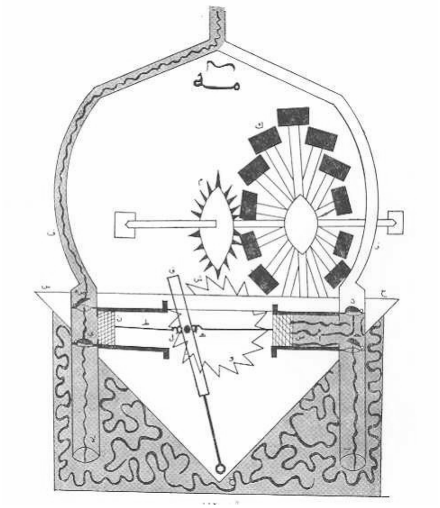

Fig. 7.13 The two-cylinders water pump by Al Jazari.

An even more interesting pump was designed much later by Taqi al Din (Damascus, Syria 1526–1585) who has already been mentioned in Chapter 3 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 shown in Figure 7.14; on the left is shown an original drawing and on the right a schematic reconstruction of the working principle.

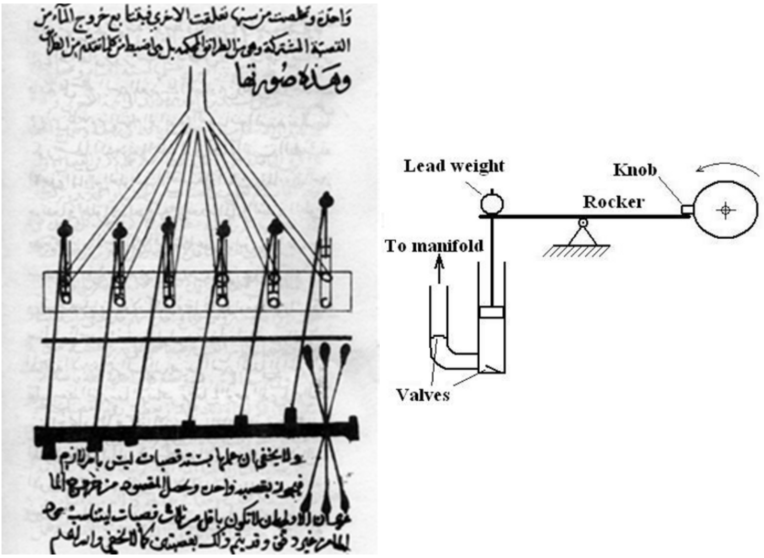

Fig. 7.14 Six cylinder pump by Taqi al Din.

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 piston rods. The unique manifold probably gives the benefit of regularizing the pressure.

During the Renaissance an interesting study on water pumps was carried on by Francesco di Giorgio Martini (Siena, 1439–1501) an Italian sculptor, architect, painter and most of all military engineer who worked mainly at the court of the Dukedom of Urbino. His main work was a treatise on architecture where he stated the main principles of the art of building fortifications called “modern fortification”, an 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 on by the latter. Francesco di Giorgio is mentioned in this book also in Chapter 10 for his self-propelled carts.

As for the water pumps by Francesco di Giorgio Martini, Figure 7.15 reproduces a page of his treatise on architecture and machines.

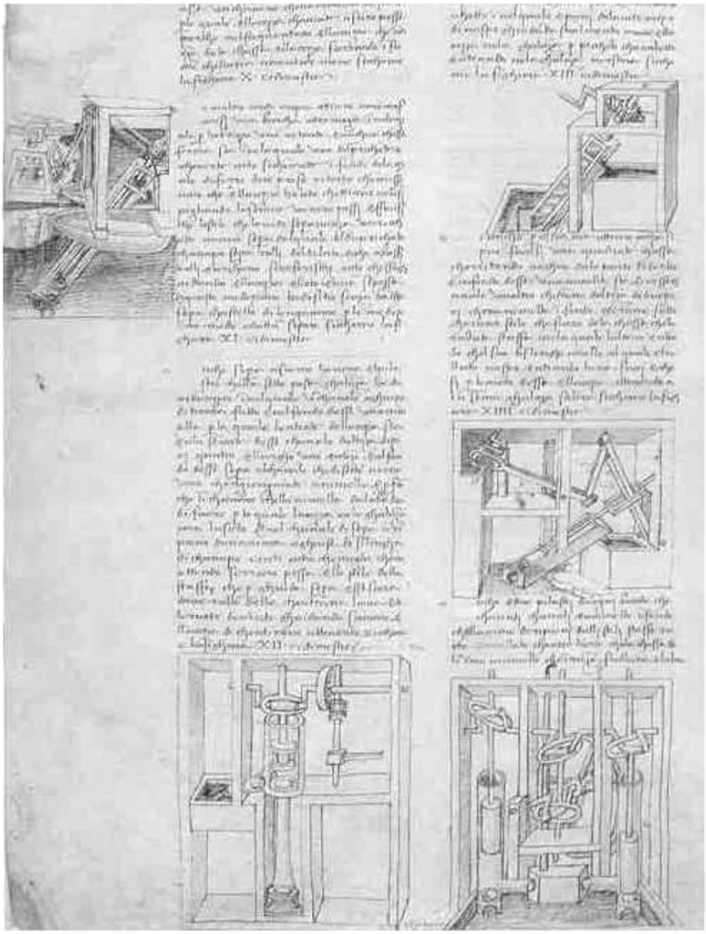

Fig. 7.15 Pumps by Francesco di Giorgio Martini.

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 enlarged in Figure 7.16; a crank, through a quick return mechanism moves a four bar mechanism and the rocker of the latter moves the piston.

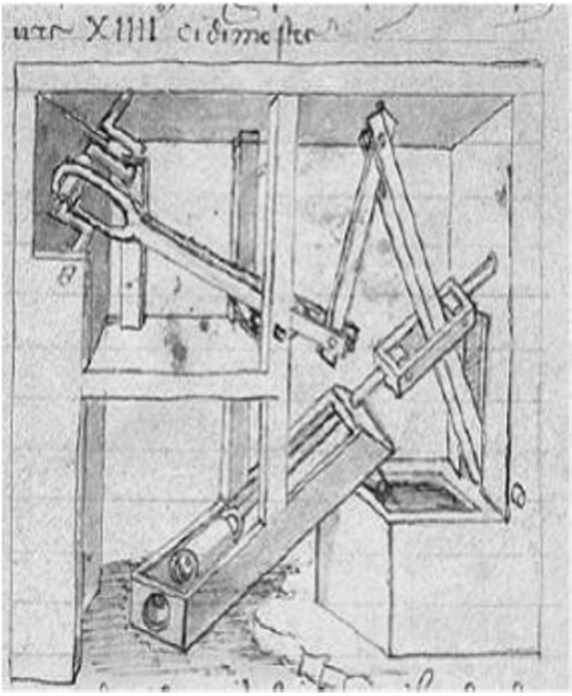

Fig. 7.16 Reciprocating pump by Francesco di Giorgio Martini.

Observations

The working principle of most of the pumps that have been described here, conceptually, is still used. In addition, the reciprocating pumps are the first reciprocating machines and the first machines that required components machined with close tolerance.

Chapter 8 – ADDUCTION AND DISTRIBUTION OF WATER

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 this 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.

8.1 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.

C. Rossi et al., *Ancient Engineers' Inventions: Precursors of the Present*,
History of Mechanism and Machine Science 8, 119–141.

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 transporting 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. These were all difficulties that increased exponentially as the distances to reach the water increased.

Figure 8.1 depicts some examples of Roman aqueducts.

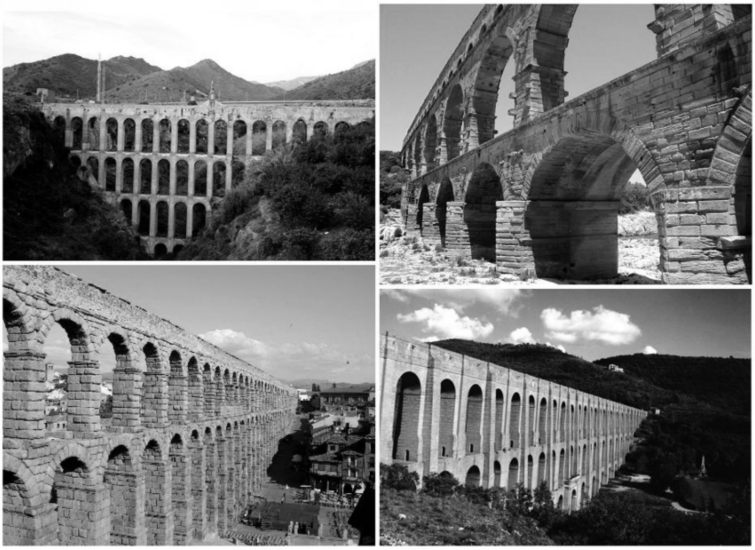

Fig. 8.1 Examples of Roman aqueducts.

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 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).

8.2 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 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.

Figure 8.2 illustrates some examples of Roman penstocks made of stone. It is believed that this type of conduit could resist an internal pressure of up to 2 GPa.

Fig. 8.2 Roman stone pipes.

8.3 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 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 stress.

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 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. Figure 8.3 shows some examples of Roman cisterns.

Fig. 8.3 Roman cisterns.

The figure includes: the large cistern of Jerusalem (top right), the large cistern of Constantinople (modern day Instanbul, Turkey) and, on the left the Piscina Mirabilis at Miseno, Naples, Italy.

8.3.1 The Piscina Mirabilis at Miseno

One of the largest and best examples of a Roman cistern is in Miseno: the Piscina Mirabilis, shown in Figure 8.3, 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 metres 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 rises 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 supply the city of Pompeii and the villas of Herculaneum en route, and a colossal cistern. Estimating the daily individual requirements as 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^3 were required, plus an amount for the fleet, bringing the total volume of water to 12,000 m^3. 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.

8.4 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 Pompei, 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 Frontino. In Figure 8.4 are shown some pictures of the three-way water 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-off 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.

Fig. 8.4 The three-way distribution system at Pompei.

8.4.1 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 1 m^3 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. Figure 8.5 shows a picture of a piezometric turret at Pompei 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.

Fig. 8.5 Piezometric Turret.

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 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.

8.5 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 Chapter 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 10 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 1800s 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 10 m 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 metre, 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 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 Figure 8.6 are shown some lead pipes found at Pompei 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.

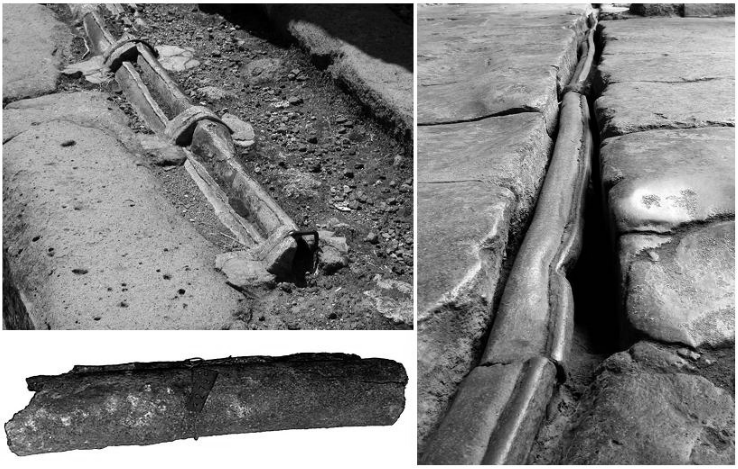

Fig. 8.6 Lead pipes.

Figure 8.7 shows pictures of clay pipes (on the left) and oak pipes on the right.

Fig. 8.7 Clay pipes (*left*) and oak pipes (*right*).

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.

8.5.1 Dimensions of the lead pipes

According to Chapter 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 Frontino 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. Table 8.1 provides the dimensions of the Roman lead pipes, expressed in Roman digita (fingers) and in millimetres.

Table 8.1 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 15 finger pipe	55 69
Fistula vicenaria	20 finger pipe 25 finger pipe	92 115

8.6 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.

8.6.1 Shut-off valves

Figure 8.8 shows some shut-off valves found at Hercolaneum and an authors' virtual reconstruction of them.

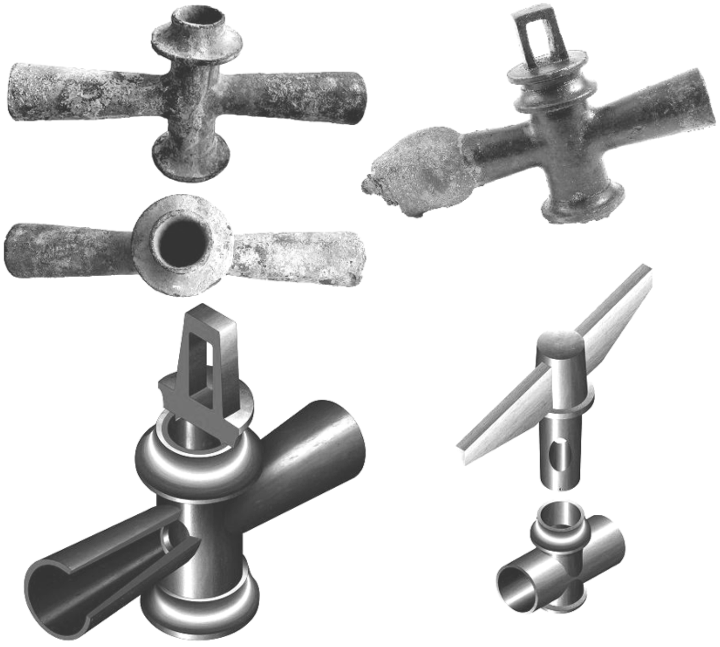

Fig. 8.8 Roman shut-off valves.

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° and at 90°, 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.

8.6.2 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 shown in Figure 8.9 with a virtual reconstruction and a scheme of the working principle.

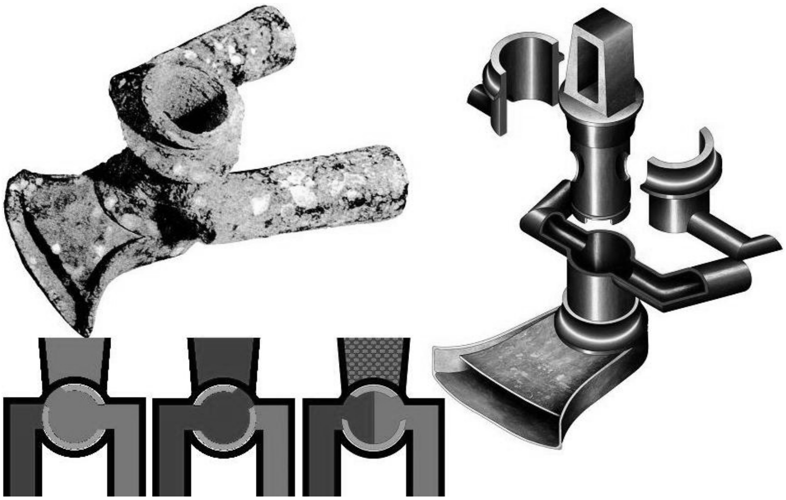

Fig. 8.9 Single control Roman mixer.

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.

8.7 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/t). This means bringing to light 1 m^3 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 women receive 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 five 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.

8.7.1 The technique of "*ruina montium*"

The principle is known as Pascal's barrel, schematized in Figure 8.10; 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 × d × 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.

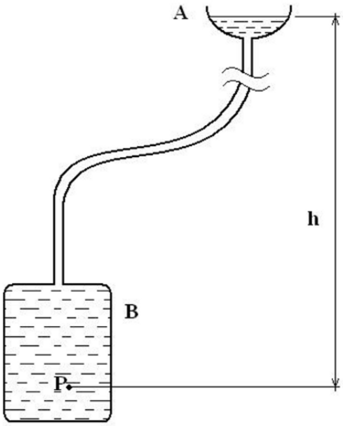

Fig. 8.10 Pascal's barrel.

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^2 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 kilometres.

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 10^5 Pa; that is, every square metre of the surface of the cavity would have had a force of approximately 10^5 N. Considering for ease of calculation a cubic cavity of 10 m per side equal to a surface of 600 m^2, the total thrust would have been 60 MN (6,000 t 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.

8.7.2 Historical references

Pliny the Elder (Gaius Plinius Secundus), 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 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 enhanced 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 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 on which, since they are much sharper near their peaks than on their 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 60x60] 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 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^2 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.

Figure 8.11 shows a landscape of Las Medulas where the effects of the ruina montium technique are clearly visible.

Fig. 8.11 Landscape of Las Medulas (Spain) showing the effects of the “ruina montium” mining technique.

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 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 t 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 metre, 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 9 – UNDERWATER ACTIVITIES

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.

9.1 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 showing men swimming in water, breathing from large leather bags filled with air. Figure 9.1 depicts 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. Figure 9.2 shows 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 system to remain underwater: a helmet equipped with a tube, through which one could breathe, as the extremity

C. Rossi et al., *Ancient Engineers' Inventions: Precursors of the Present*,
History of Mechanism and Machine Science 8, 143–148.

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.

Fig. 9.1 Assyrian bas-relief showing scuba divers.

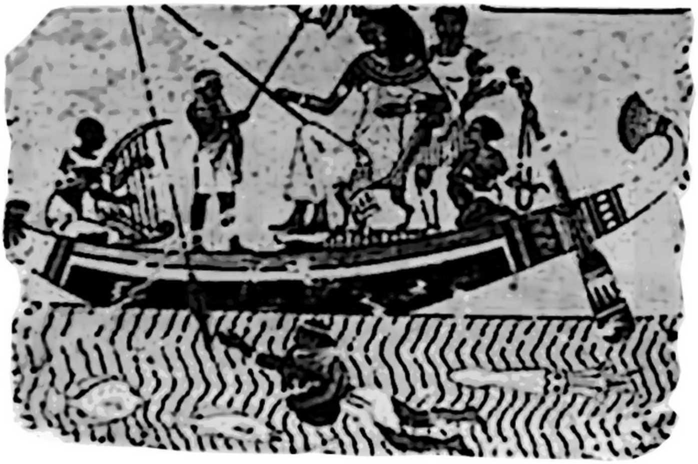

Fig. 9.2 Egyptian illustration of the fishing episode related to Mark Antony.

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 immerge. Testifying to its existence, Pliny mentions their curious habit of 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. Figure 9.3 shows an imperial era funeral stone commemorating the military divers called urinatores.

Fig. 9.3 Imperial era funeral stone commemorating the military divers.

In Figure 9.4 is drawn 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.

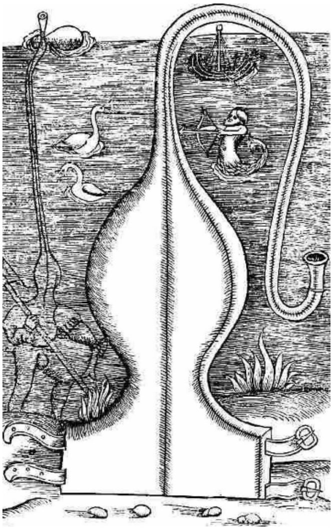

Fig. 9.4 A diving helmet.

9.2 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 Figure 9.5 are two depictions of the immersion of Alexander the great, found in medieval codes.

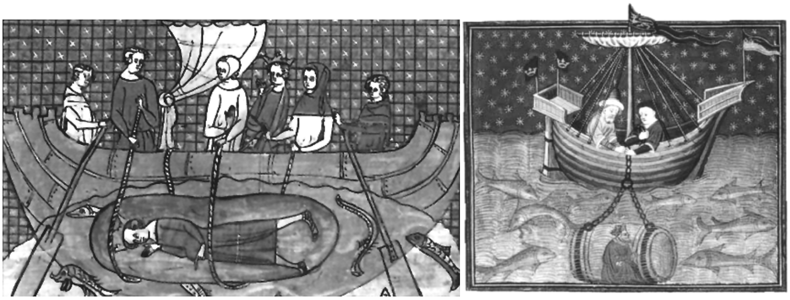

Fig. 9.5 Depiction of the immersion of Alexander the great.

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 shortly after the sinking of the Swedish galleon Wasa in 1628 (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 Figure 9.6.

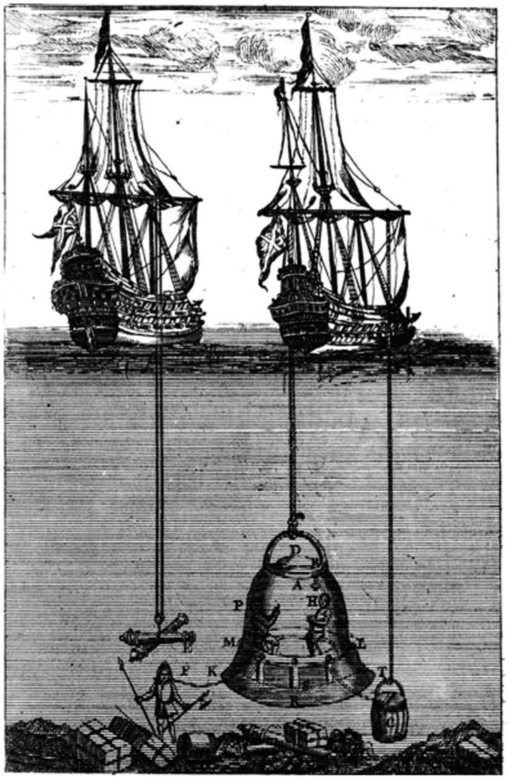

Fig. 9.6 Diving Bell designed by Edmond Halley.

From this last figure the working principle of a diving bell is clear: when the bell is immerged, 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 diver who operates outside the bell, compressed air will be supplied to breathe at that depth simply by connecting his diving helmet to the diving bell.

Part IV – COMMUNICATION AND TELECOMMUNICATION

Introduction

In this part, some ancient devices in the field of communication are presented; the word communication, here, is used in a wide sense, hence transport, both vertical and horizontal, and telecommunication devices are shown. Many of the devices are dated about 2,000 years ago and, nevertheless, show a surprising modernity either for their design or for their working principle or both.

As already mentioned, this book has not been conceived for engineers only, hence let us briefly present some basic concepts about the working principles of machines that were used to improve muscular work and that had been used in lifting devices and also as the "motor" for the ancestors of some self-propelled vehicles.

The capstan

In Figure IV.1 is shown the working principle of a capstan.

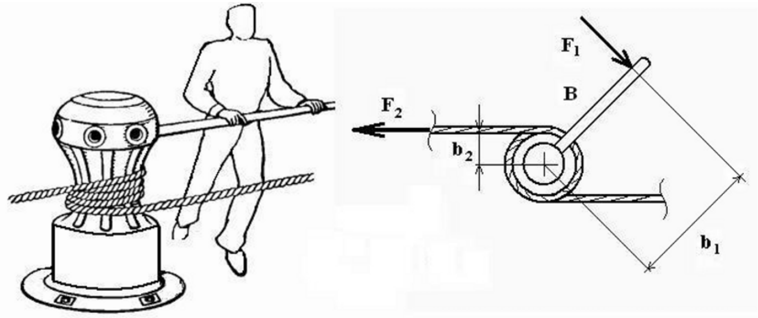

Fig. IV.1 Working principle of a capstan.

If a force F_1 is exerted (by 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. If only the first two forces are considered, the equilibrium of their moments, which are given (see Introduction to Part II) by the product of the force and the distance, then we have:

$$M = F_1 \cdot b_1 = F_2 \cdot b_2 . \tag{IV.1}$$

From Equation (IV.1) the force on the rope is:

$$F_2 = F_1 \cdot \frac{b_1}{b_2} . \tag{IV.2}$$

This means that a force exerted on the capstan bar is increased proportionately to the increase in the length of the bar with respect to the capstan radius.

For example, suppose that a man exerts on a bar 1 m long a force of 200 N ($\approx$20 kg_F) and that the capstan radius is 25 cm; this means that a force of 800 N will act on the rope (if the tightening force is neglected, as aforesaid). Now, on a medium sized capstan up to (say) five men can act; this means a considerable traction. An application of capstans to the propulsion of vehicles will be shown in Figure 10.18.

For higher traction efforts such as in cranes, the force of the men was applied by using a quite different device: the squirrel cage. This last term is not to be confused with the one that refers to the rotors of the induction (asynchronous) motors.

The squirrel cage is very similar to the one that is often fitted in the cages of squirrels and other rodents. Figure IV.2 is 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 who climb on the rotating steps; a capstan is linked to the shaft of the squirrel cage, which has 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 bond onto the capstan. The equilibrium of the moments is the same as 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.

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

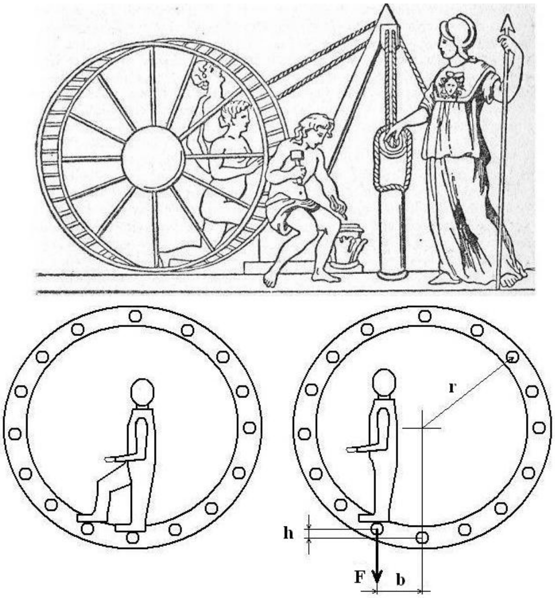

Fig. IV.2 Squirrel cage crane and its working principle.

Telecommunication devices

Telecommunication devices are discussed in this part since they can be considered, together with transportation systems, as the main facilitators of modern communication. The ancient devices, naturally, did not use any source of electric energy but, nevertheless, some of them were surprisingly modern in their conception. It must be considered, in fact, that, particularly during the reign of 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 (which is an island) or in other places a long way from Rome where they had their luxurious mansions. Since political affairs were not what one would consider 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 will be shown, such communication systems did exist in those ages.

Chapter 10 – LIFT AND TRANSPORTS

Introduction

The development of a transport system is another important step towards modernity. The concept of transport may mean both vertical and horizontal movement of things and people; in this chapter both aspects will be presented.

As for vertical transport, we must remember that wherever there is construction there is a need to lift items to the top of the structures being built, like water from a well. But in naval shipyards, often an entire ship had to be lifted. This led to the invention of huge cranes for port use, the largest cranes still used today. Another example of vertical transport is represented by counterweight operated lifters like elevators and other devices that were employed in large theaters to lift scenery and curtains, e.g., in the Coliseum.

Horizontal transport devices are represented by carts and ships, some of which show a design whose modernity is surprising. Probably it is also surprising that ancient engineers reduced the friction between hub and shaft using ancestors of ball bearings; they also conceived a rail system and they had some knowledge about the possibility even of flying.

10.1 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 with 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

C. Rossi et al., *Ancient Engineers' Inventions: Precursors of the Present*,
History of Mechanism and Machine Science 8, 153–188.

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 a stone quarry wheel, only a maximum of five men could be used to activate a traditional model. 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 30 men at a time. Figure 10.1 shows a funeral bas relief from the tomb of Hanerii showing a large crane with a squirrel cage wheel and an axonometric reconstruction of it.

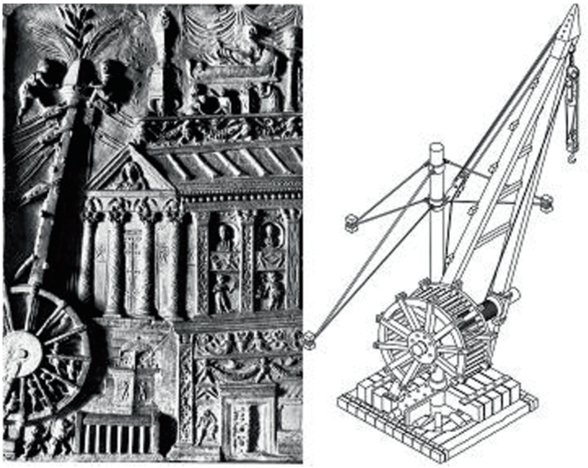

Fig. 10.1 Large crane.

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, consisting 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. Figure 10.2 shows 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.

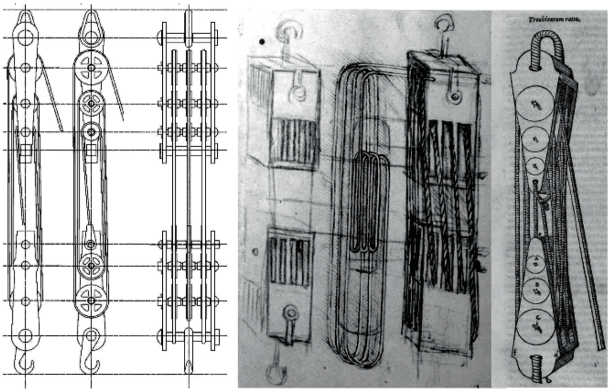

Fig. 10.2 Pentaspaston.

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 that are, in spite of their size, 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 taut by a counterweight electronically activated by a pentaspaston!

10.2 Gravity driven elevators

Gravity driven motors were used in ancient times for a number of devices, one of them was Heron's programmable moving robot described in Chapter 15. 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 10 t, 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 Figure 10.3 a virtual reconstruction of a device to move the curtains is represented.

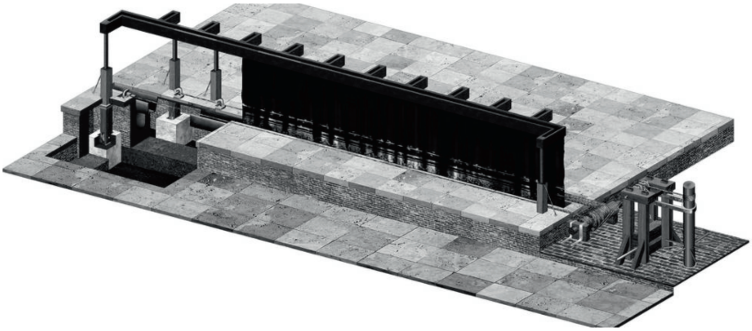

Fig. 10.3 Virtual reconstruction of the device to lift the curtains.

10.3 Roman carts

The Roman four-wheeled cart, 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 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 four or six cots.

Figures from 10.4 to 10.7 depict a variety of 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 is a bas relief showing the cart, an authors' virtual reconstruction and a technical drawing.

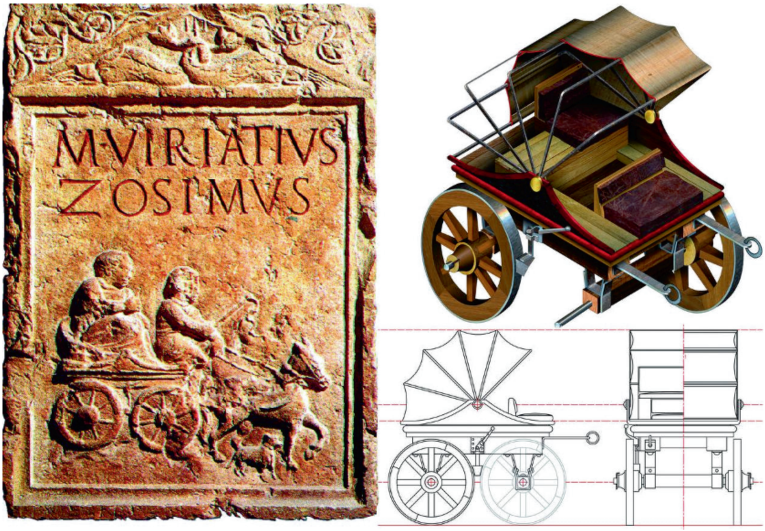

Fig. 10.4 Fast private cart with folding top.

Fig. 10.5 Barrel cart.

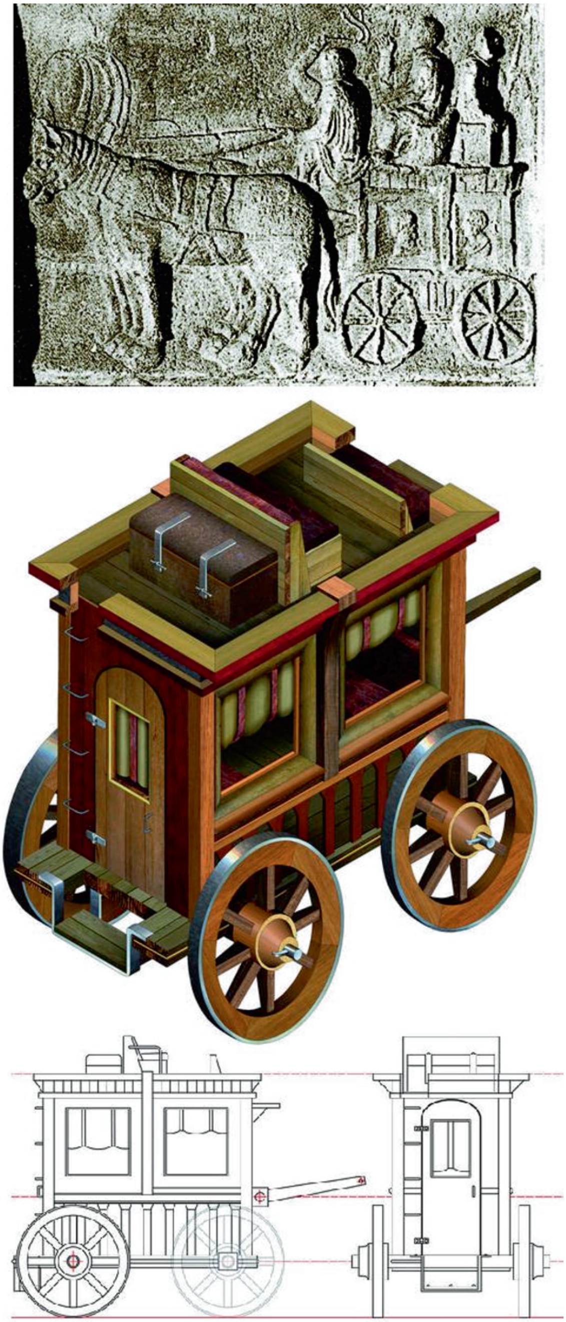

Fig. 10.6 Cart used to transport dignitaries.

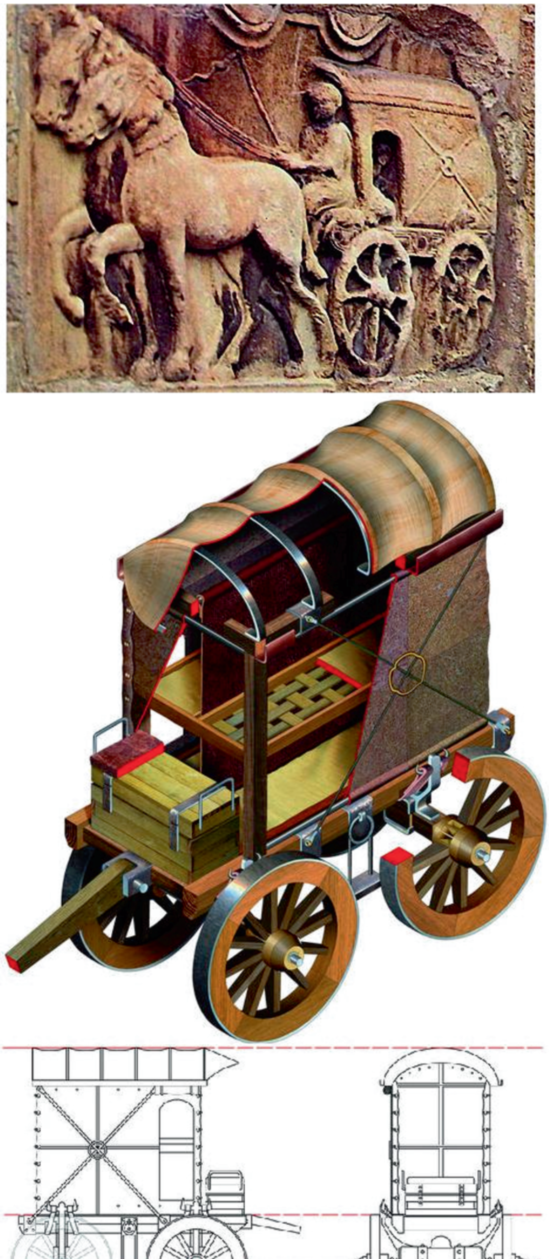

Fig. 10.7 Sleeping wagon.

From Figure 10.4 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, which is the reason why such freight wagons had fixed axles. In Figure 10.6 can be observed the seat on the top of the chart and in Figure 10.7 are represented some leather belts that have the function of suspension; these last two particulars are very similar to those of the stagecoach in the 19th century.

Figure 10.8 is a detail of a bas-relief showing the brake and Figure 10.9 is a detail showing the suspension.

Fig. 10.8 Detail of the brake.

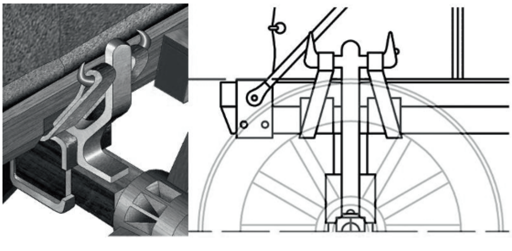

Fig. 10.9 Detail of the suspension.

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 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 Figure 10.10 are shown some supports for suspension belts on Roman sleeping wagons.

Fig. 10.10 Supports for suspension belts.

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.

10.4 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 100 km. In Figure 10.11 are shown pictures of those tracks at Malta.

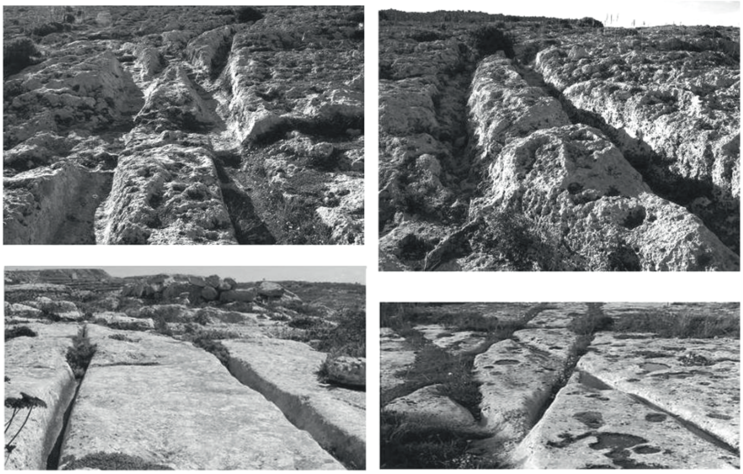

Fig. 10.11 Parallel cuts into rock in Malta.

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. Figure 10.12 shows a reconstruction of the railed cargo.

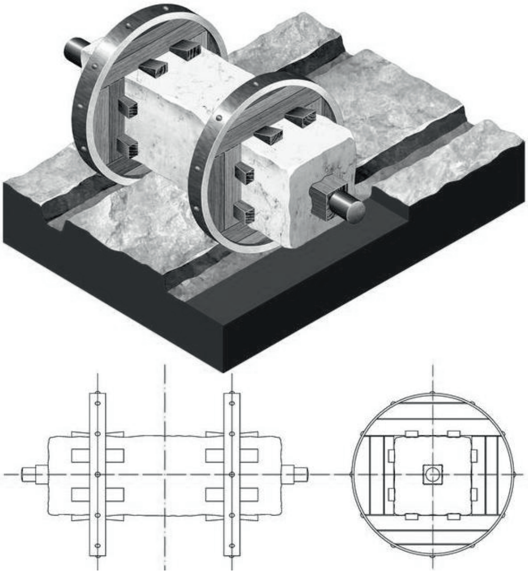

Fig. 10.12 Reconstruction of the railed cargo.

The false axle system was reserved for longer items to be transported and later became 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. Figure 10.13 shows a reconstruction of the system conceived at Eleusis to transport bulky cargo, according to Vitriuvus' 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 1,000 years.

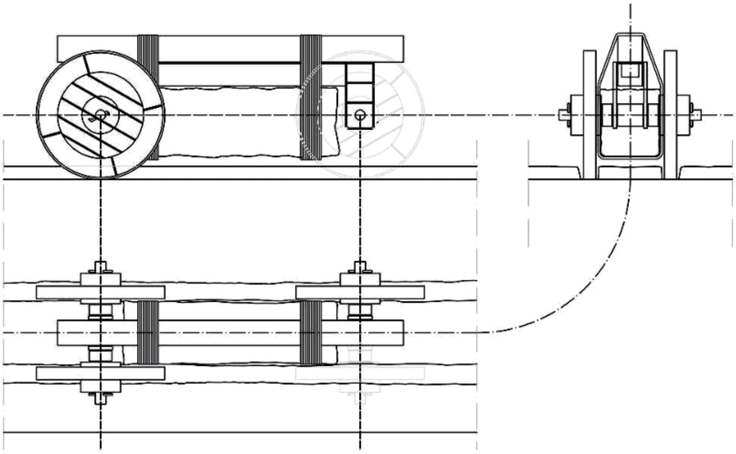

Fig. 10.13 False axle system.

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.

10.5 The rails of Pompei

Numerous systems similar to the Diolkos were made, some even for the streets of Pompei. 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 metres 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. Pictures of some tracks at Pompei are shown in Figure 10.14.

Fig. 10.14 Rail tracks at Pompei.

10.6 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 military officers were attempting to prevent the massacre of soldiers pushing siege towers underneath enemy walls. 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 Demetrius 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 t.

Figure 10.15 shows an author’s virtual reconstruction of the elepoli of Posidonius.

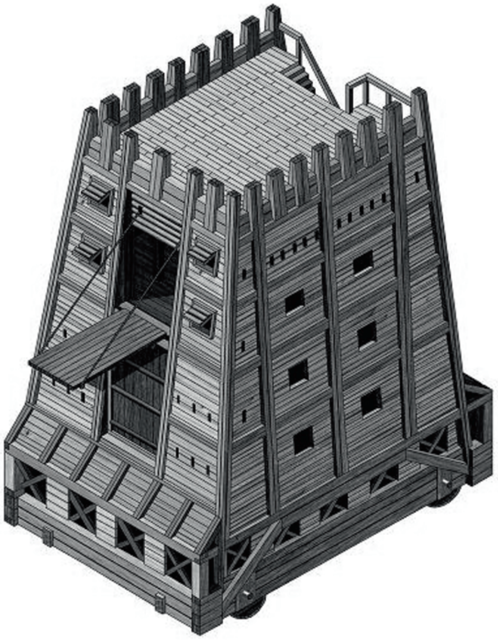

Fig. 10.15 Virtual reconstruction of the elepoli of Posidonius.

Figure 10.16 shows a virtual reconstruction of the great elepoli of Demetrios Poliorketes.

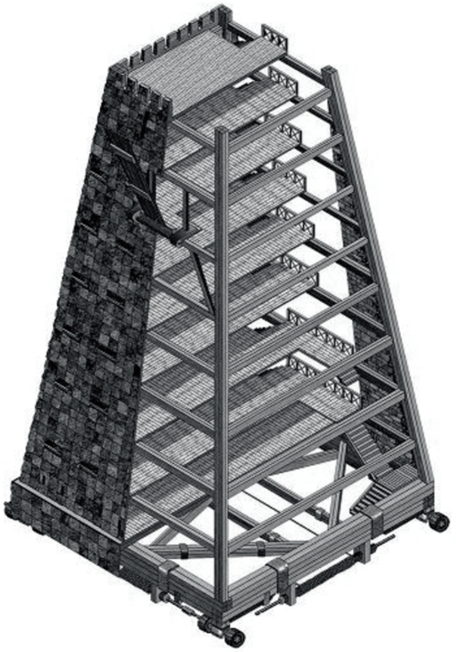

Fig. 10.16 Reconstruction of the elepoli of Demetrios Poliorchetes.

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 was able to move such a large machine”. Whatever the original concept, it is certain that motive power was supplied by humans, with the help of levers and pulleys. It is interesting to remember that Flavius Vegezius was the author of 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 derived.

We can also presume that they made use of a capstan or mooring swivel, as we gather from a very few written mentions, a device that was well known during that era. Maneuvering required about 100 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.

Figures 10.17 and 10.18 depict virtual reconstructions of possible motorization systems for the elepoli. In Figure 10.17 is shown a double squirrel cage motor with rope transmission on two axles and in Figure 10.18 a capstan with rope transmission and a detail of it.

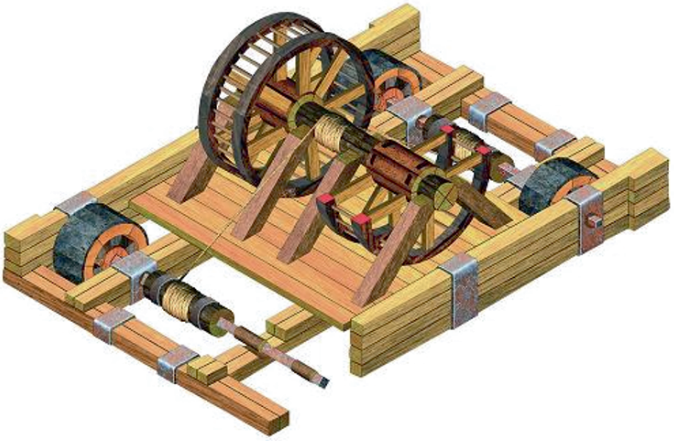

Fig. 10.17 Virtual reconstruction of a double squirrel cage motor.

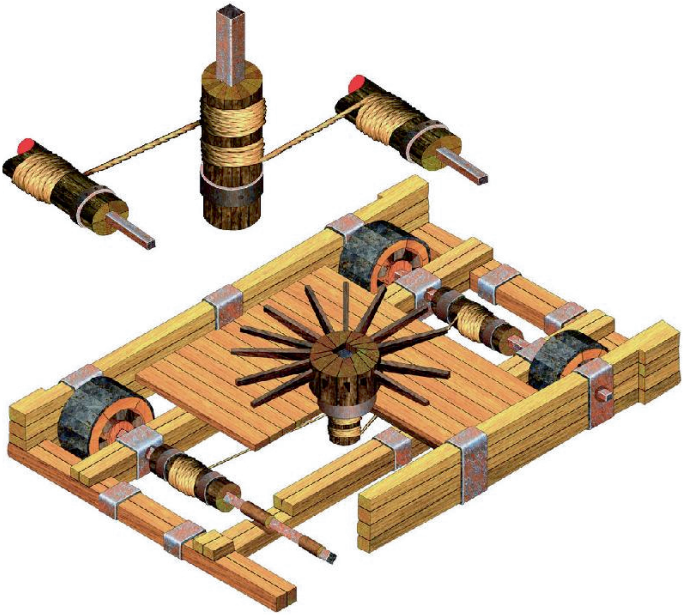

Fig. 10.18 Virtual reconstruction of a capstan with rope transmission.

These towers were still in use around the 1st century B.C., as confirmed by an interesting and even amusing episode recalled by Caesar:

> [the Aduatuci] had shut themselves in the city. When they saw that the Romans … had begun to construct a tower at a considerable distance, they began to mock them from the bastions and ask why they were assembling such a large machine so far away: how were they going to push it and with what strength could such small men … hope to move such a heavy tower? But when they realised that the tower moved and was approaching the walls, incredulous and frightened of this unknown object they sent ambassadors to Caesar to negotiate peace. The ambassadors said that they did not believe it possible for Romans to wage war without divine intervention since they could move such tall machines at great speed.

10.7 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. Figure 10.19 shows a virtual reconstruction of a roller bearing of the hub of a Celtic cart.

Fig. 10.19 Virtual reconstruction of a Celtic roller bearing.

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. Figure 10.20 is a drawing of the thrust ball bearing of the spherical platform installed in one of the Nemi ships; in the upper part of the figure a drawing of the find is shown and in the lower the reconstruction.

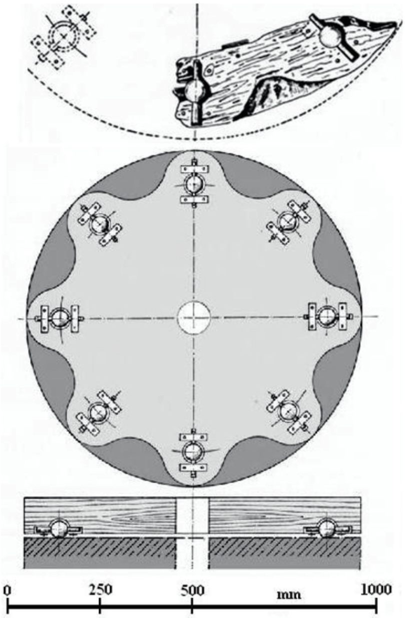

Fig. 10.20 Thrust ball bearing on a Nemi's ship.

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 shown: in Figure 10.21 antifriction hinges made of bone, for furniture, and in Figure 10.22 bearing hinges and rolling plates in bronze.

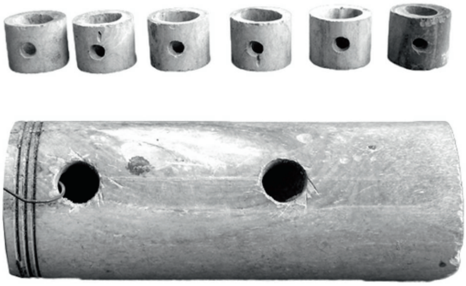

Fig. 10.21 Antifriction hinges.

Fig. 10.22 Bearing hinges and rolling plates.

10.8 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 was the art of making hulls discovered by assembling together some boards, and naval architecture began; this happened at the dawn of the historical age.

In Chapter 5 the evolution of sails was traced, while in this section we will present two examples of unusual ancient boats that were precursors of modern inventions.

10.8.1 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: it is highly likely that millers turning a wheel in the still waters of a mill course using levers, might also have managed to move the entire mill, even if slowly and only for a short distance.

In Figure 10.23 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 holes for the oars can be observed.

Fig. 10.23 Bas-relief of a Roman ship at Mainz.

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 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. Figure 10.24 is an illustration from the ancient Roman treatise “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.

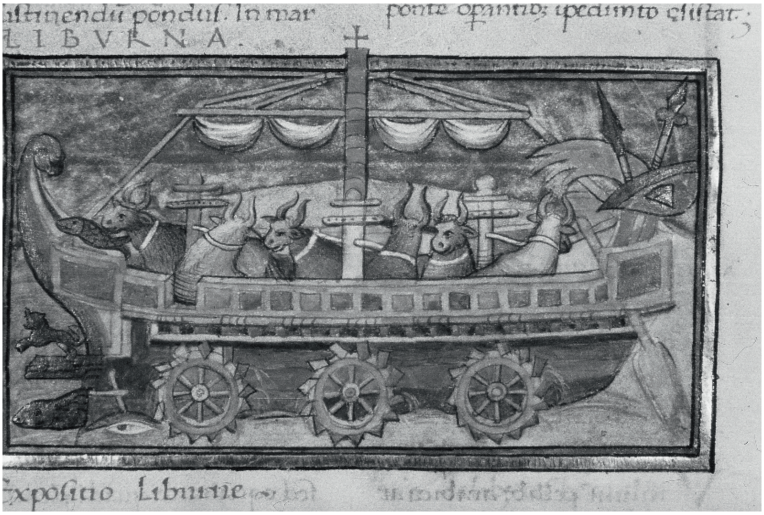

Fig. 10.24 Liburna with wheel propulsion.

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, activated the hoists for wells, moved the saws that cut the large blocks of stone, and 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 merely incidentally, defined as the iron age.

10.8.2 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 2nd 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. Figure 10.25 consists of two Assyrian bas-reliefs showing the use of inflatable hides (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. 10.25 Assyrian bas-relief showing inflatable hides.

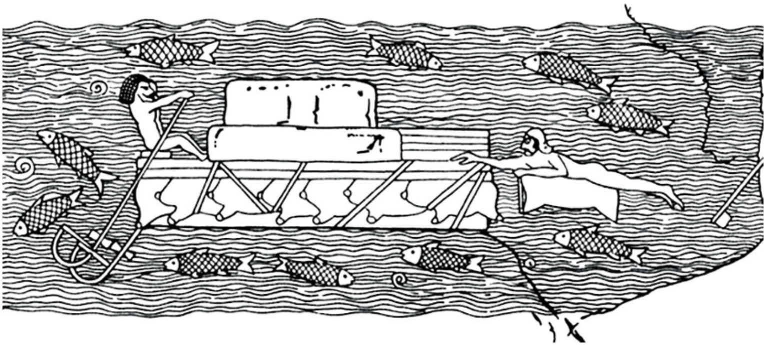

Fig. 10.26 Assyrian raft with inflatable hides.

Xenophon, who lived between the 5th 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, in these words:

> 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 Figure 10.27 is reproduced a picture from the "De Rebus Bellicis" showing a pneumatic bridge.

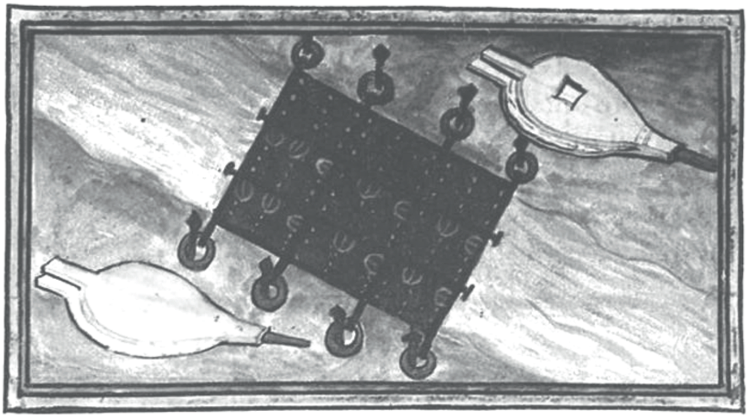

Fig. 10.27 Pneumatic bridge from "De Rebus Bellicis".

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 ingeniousness 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 … – 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 as shown in the pictures in Figure 10.27 (from V.L. Grottanelli “Etnologica l’uomo e le civiltà” Labor, Milano, 1966); the picture on the left is from the Sudan while the one on the right from Himalaya.

Fig. 10.28 Inflatable bags used in the 20th century.

10.9 Cableways

When two points were linked by a rope and to this last was hung something like a pulley holding a load, the first cableway had been invented. The load could run downhill because of 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 much older than the invention of the ropes themselves. This clearly appears in the suspension bridges made by the Incas and in similar structures in Asia; in fact, this kind of bridges are called Tibetan bridges.

Because of friction and the atmospheric agents, ropes made by vegetal fibres had a short life, hence it is very difficult to discover them among archaeological finds. Much more durable are the metallic ropes, especially those made by less oxidable 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 was quickly destroyed by corrosion. At Pompei was found a copper lanyard made of three strands each of which was composed of 19 wires.

For the reasons reported above, the authors believe that cableways were used in very ancient times but they could find no archaeological proof of it.

The first documented cableway is depicted in Figure 10.29 where a Chinese device of about 1250 was drawn by H. Dieter Schmoll (Weltseilbahngeschichte Band I: bis 1945, Ottmar F. Steidl Verlag, Eugendorf/Salzburg, 2000).

Fig. 10.29 Chinese cableway of about 1250.

In Europe, at the end of the Middle Ages, there appeared cableways designed by Johannes Hartlieb (around 1400–1468); a drawing of one of them is shown in Figure 10.30. In the same figure there appears a drawing of a device by Giovanni Fontana (A.D. 1395–after 1454), who will be more extensively cited in Chapter 15 concerning his automata; this last image is in Fontana's treatise "Bellicorum instrumentorum liber" (Book on the war devices, 1420) that can be read on line on the Munchener Digitale Bibliotek.

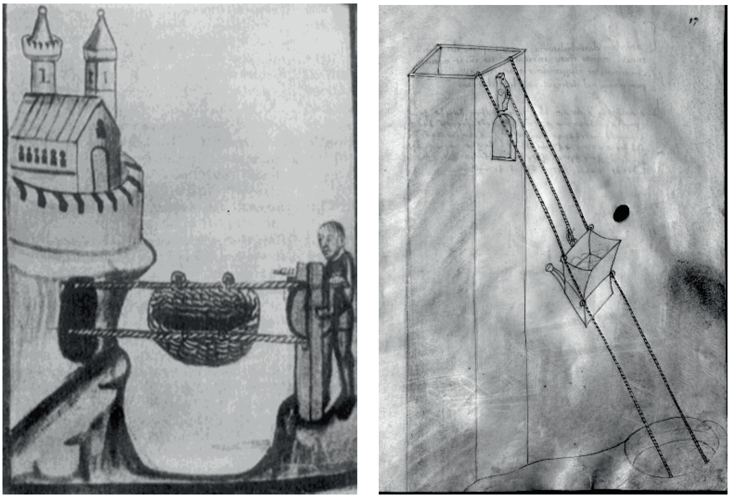

Fig. 10.30 Cableway by Johannes Hartlieb (*left*) and a device by Giovanni Fontana; Bellicorum instrumentorum liber, folio 17 recto, Munchener Digitale Bibliotek (*right*).

In 1615 Fausto Veranzio (1551–1617), already cited in Chapter 5 for his wind motor and more widely in Chapter 6 for his water wheel, designed the “Pons unius funis” (Bridge [made by] an only rope) that is depicted in Figure 10.31.

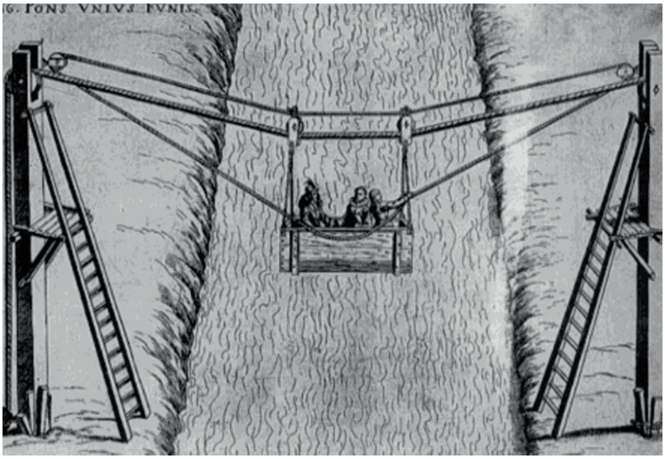

Fig. 10.31 The “Pons unius funis” by F. Veranzio.

Another interesting example of ancient cableway is depicted in Figure 10.32; 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.

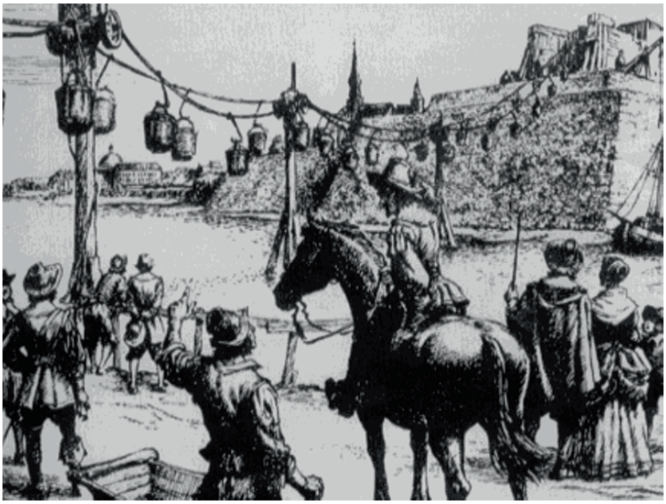

Fig. 10.32 Cableway by Adam Wybe.

10.10 The dawn of flight in antiquity

Most people know that the first aeroplane was built by the Wright brothers, Wilbur (1867–1912) and Orville (1871–1948), whose invention was called the “Flyer”. The Wrights built both the plane and the engine and made their first flight at Kitty Hawk (North Carolina, USA) on 17 December 1903. Before that historical event, many other inventors built flying machines but none of them showed a satisfactory performance and some of them killed their inventors.

The desire to fly is as old as mankind and many legends have been narrated describing flying devices built by man. It did not require much acumen to observe that dry leaves, incapable of motion, were actually lifted if pushed by the wind. And that a slim sail was needed to make flying possible, a sail resembling a giant leaf, to capture the favourable wind, constant and intense. This intuition was surely strengthened by the vision of the large swollen sails that pushed boats. It followed that, in order to move along a plane, the sail had to oppose the wind vertically and in order to move upward, it had to do so horizontally! A light and robust frame was required, the aerial variant of the shaft and pole for ships. To this frame would be harnessed the pilot, or rather the aerial observer.

The ceiling of amphitheatres, in effect a light curtain, which in the case of the Coliseum was maneuvered by sailors from the Miseno fleet, was the first example of a horizontal sail. It was extremely probable that on windy days, or even when the heating of the arena caused strong upward directed warm currents, the curtain tended to lift, providing additional inspiration. Leonardo da Vinci gave this device a more useful and controllable feature, by adding ropes to suspend and fasten them, making it very similar to the modern glider.

10.10.1 Legends and tales

Paradoxically, to navigate the skies, it was necessary to call upon the skills of the most expert men of the sea, the Minoans. Their emblem, the labris or two bladed axes, gave its name to the grandiose royal residence of Crete, the Labyrinth. More than a palace, it was an intricate and indecipherable myriad of environments, connected by terraces overlooking the Aegean. Such a monument was conceived and built by Daedalus who ended up closed within it with his son and attempted to overcome that azure barrier by flying. To remain with the famous legend from Greek Mythology, dated to about 2000–1600 B.C. and reiterated by Sophocles, Euripides and Aristophanes, he built wings of rush, feathers and wax: but ended in tragedy.

A much more likely explanation would be the construction of a pair of giant kites made of rush and canvas. When these two wide sails were placed on a terrace and inclined to capture the upward directed thrust of the breeze, they lifted. Of course, it was impossible to control them in any way: the flight is certainly plausible but much more plausible is the fall! Strangely, something similar is also found in Japanese mythology, more than 2 millenniums later. Around the year 1100, a noble samurai, named Minamoto Tametomo, was condemned to exile together with his innocent son on the inhospitable island of Harchijo. He succeeded in helping his son to escape by suspending him from a giant kite of wicker and paper that he constructed. Two legends are not evidence but hearsay, a fleeting indication in the best of hypotheses.

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 maneuvers: 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 forerunners 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 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 Figure 10.33 are shown two photographs, taken in 1914, of a Japanese giant glider. We cannot therefore exclude that news of their existence reached the west from the silk route.

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 from Tarentum (Taranto, Italy 428–347 B.C.), a philosopher, mathematician, astronomer, statesman, and strategist, invented a mechanical dove powered by compressed air. According to other scholars, the dove could fly by beating its wings.

10.10.2 Ancient gliders

In 1891, in a tomb at Saqquara, Egypt, a bird shaped object was found whose length was about 14 cm with about 18 cm span; it was made from sycamore wood and weighed 39.12 g and was dated about 200 B.C. That time was 12 years before the first flight by the Wrights and the object was identified as a stylized bird. Figure 10.34 is a model of the Saqquara bird. It can be observed that the bird has no legs, the wings are straight and the tail is vertical. These circumstances suggested to Dr. Khalil Messiha, an Egyptian archaeologist and physician, that the find was not a bird but a glider (Messiha et al., 1984). Subsequently, Martin Gregorie proposed a reconstruction of the bird that could really fly. Nevertheless its flight performance was very poor and, in order to fly, the bird needed a horizontal stabilizer on the tail (that could have been lost); Gregorie concluded that the bird could have been a weather cock. This could explain the vertical tail.

Fig. 10.33 Japanese giant gliders.

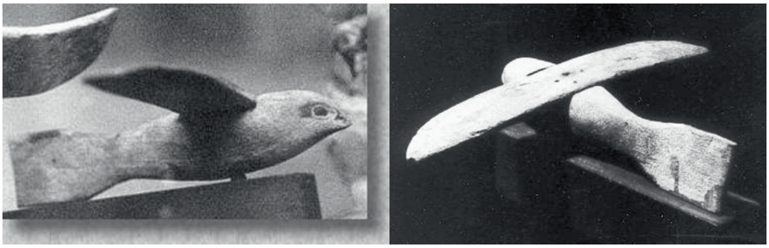

Fig. 10.34 The Saqquara bird.

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 convinced that the Saqquara bird is a proof that the ancient Egyptian had the capability to design gliders.

10.10.3 Ancient rockets

Devices based on the action–reaction principles are very old; with reference to this we can consider the flying dove by Archytas, mentioned in a previous paragraph and the aeolipile by Heron, a first example of a reaction steam turbine, that is discussed in Chapter 12.

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 13th century. Paradoxically the first Italian town to be 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 applications by the Chinese is dated A.D. 1232 in the battle of Kai-Fung-Fu against Mongol invaders. In the treatise Huolongjing or Huo Lung Ching (=fire dragon manual), written by the Chinese officers Jiao Yu and Liu Ji in the 14th century, they describe a large number of bombs and fire arms; among these are two-stage rockets stabilized with fins. In the same treatise, different compositions for gunpowder and rocket propellant are also described.

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 author. 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-Saky al-Meliki al-Nasir; in this second part, rocket bombs and burning arrows are described.

Another Arab inventor, the Syrian Hassan Al Rammah, around 1275, described a rocket powered torpedo having the shape of an egg, filled with gunpowder and stabilised on its course by a rudder.

Also Giovanni Fontana (already cited in Section 10.9 and more widely mentioned in Chapter 15 for his automata) in his treatise ("Bellicorum instrumentorum liber") designed some rocket powered devices; on the folio 37 recto, it is possible to observe two rocket powered objects: a 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 discussed a rocket powered torpedo very similar to the one described by Hassan al-Rammah that must have been used against enemy vessels.

The most well-known examples of use of 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 for the first time by Wellington's army at Waterloo.

Most of the rockets mentioned above were powered by black powder and essentially consisted of a hollow cylinder, closed at one of its ends, filled with 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, which 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 depicted in Figure 10.35.

The modernity of some of the Haas' rockets is very surprising: first of all he can be considered the inventor (probably the first in Europe) of multi-stage rockets, and he is very probably the first to use a liquid propellant. Another surprising modernity of Haas' knowledge is also represented by his use of 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 fireworks maker Johann Schmidlap, attached smaller rockets to the tops of bigger rockets as they would reach higher altitudes.

Before the treatise by Haas was discovered, the inventor of multistage rockets was considered Kazimierz Siemienowicz, a Polish general of artillery and a 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.

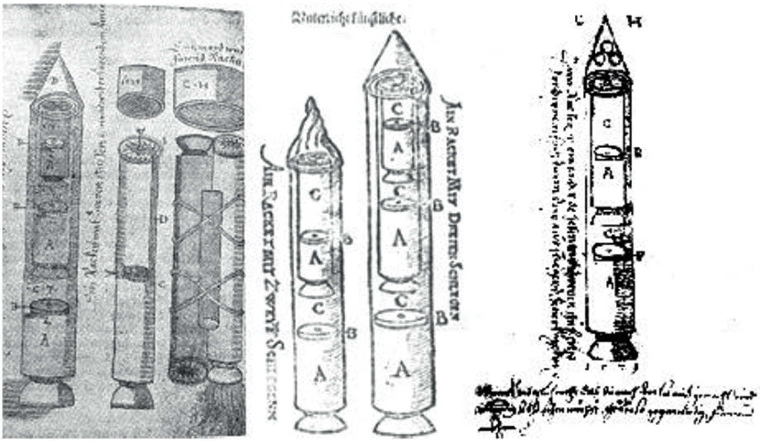

Fig. 10.35 Multi stage rockets by Conrad Haas.

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, and standardisation in the dimensions of wheels, hubs and gauges for carts, is confirmation that, in the first centuries after Christ, a first industrial revolution took place, as narrated in the introduction of this book.

Interesting developments of the self-propelled cart were designed by Francesco di Giorgio Martini (Siena, 1439–1501), already mentioned in Chapter 7. He designed carts with three or four wheels having a steering mechanism for the front wheels and two or four driving wheels. In Figure 10.36 are reproduced a pair of his drawings. 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.

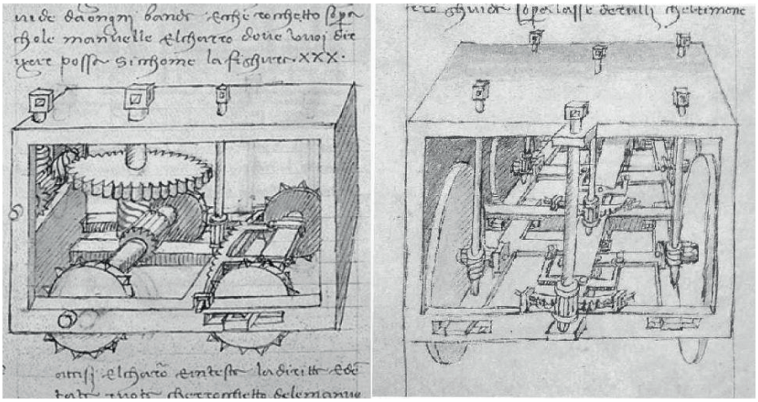

Fig. 10.36 Self propelled carts by Francesco di Giorgio Martini.

Chapter 11 – TELECOMMUNICATIONS

Introduction

Within the animal kingdom, relations are often established by the characteristic and conventional sounds made by 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 their communication systems.

In the following paragraphs some early systems will be presented; they will be divided depending, roughly, on their working principle.

11.1 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

C. Rossi et al., *Ancient Engineers' Inventions: Precursors of the Present*,
History of Mechanism and Machine Science 8, 189–205.

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 Figure 11.1 we show some examples of ancient acoustic communication systems: Carnyx players from the 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.

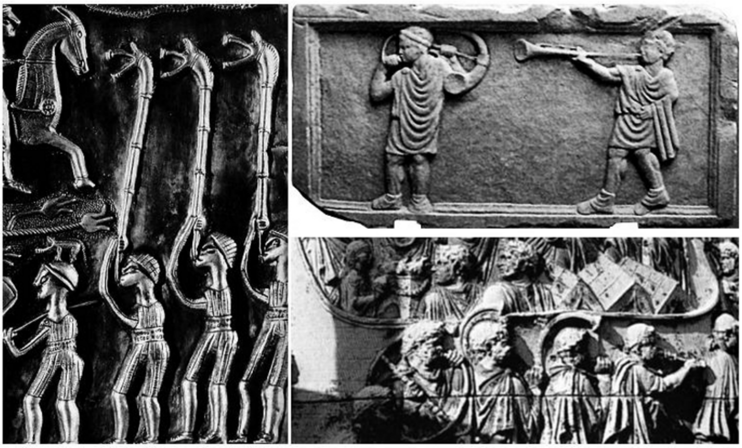

Fig. 11.1 Ancient horn players.

11.2 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 1,000 km in a single day, directing itself perfectly and easily returning to its 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 Second World War to such an extent that up to a few decades ago a special permit was required to raise pigeons!

In Figure 11.2 are shown the remains of a portable dovecote found at Pompei and its virtual reconstruction.

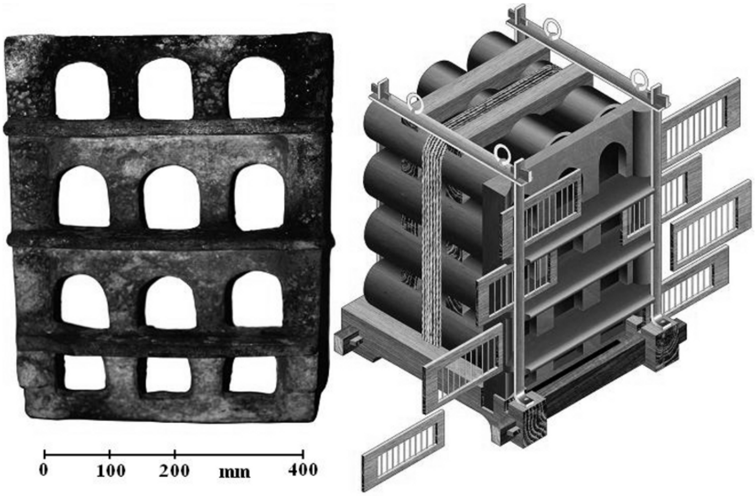

Fig. 11.2 Portable dovecote.

11.3 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 13 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.

11.3.1 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 5th. 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 maneuvering 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 Figure 11.3 a virtual reconstruction of a rod telegraph is depicted.

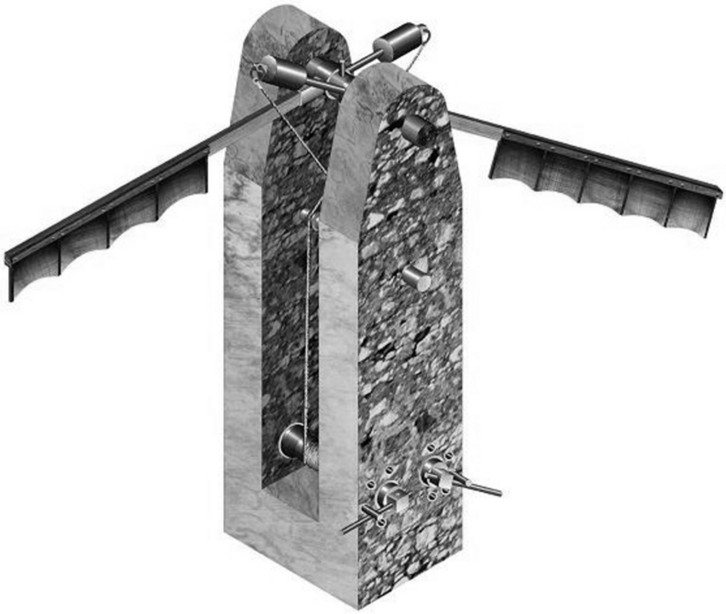

Fig. 11.3 Authors' virtual reconstruction of a Roman rod telegraph.

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 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 are 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 Figure 11.4 are depicted a detail of the Trajan Column in which a probable pole telegraph device has been highlighted and three prints showing Chappe telegraphs.

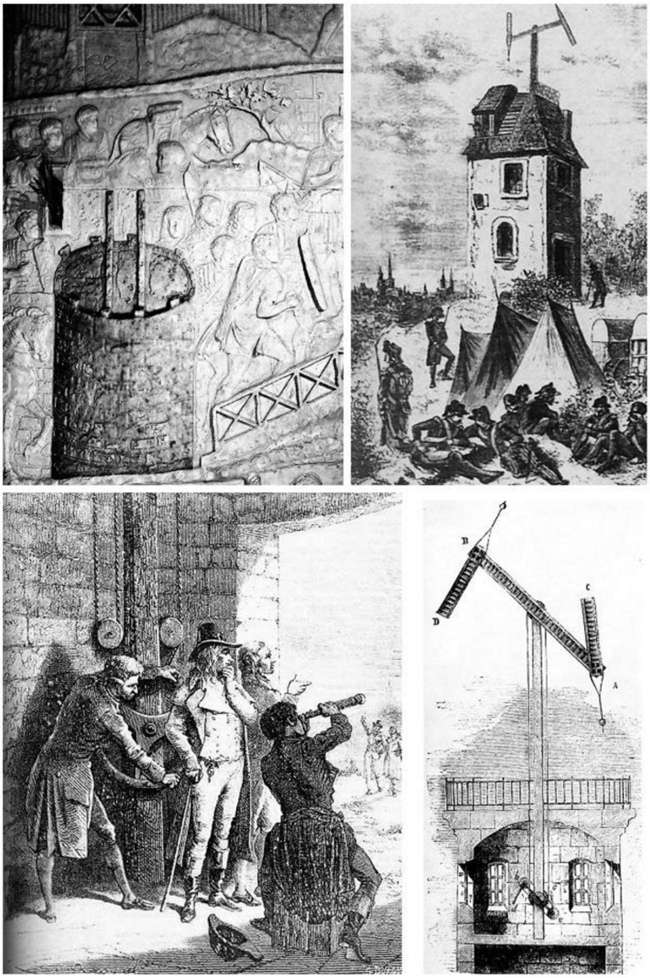

Fig. 11.4 A detail of the Trajan Column and pole telegraphs.

From a conceptual point of view this communication system is still used 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. Figure 11.5 shows a bracket semaphore for trains and some examples of the flag signaling system.

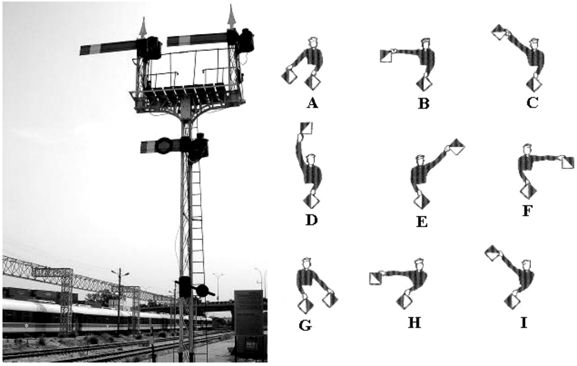

Fig. 11.5 Modern bracket semaphore and flag signaling examples.

11.3.2 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 Hannibalis, 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 Hannibalis” 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 × 5 m, and interaxes, between 600 and 1,000 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 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.

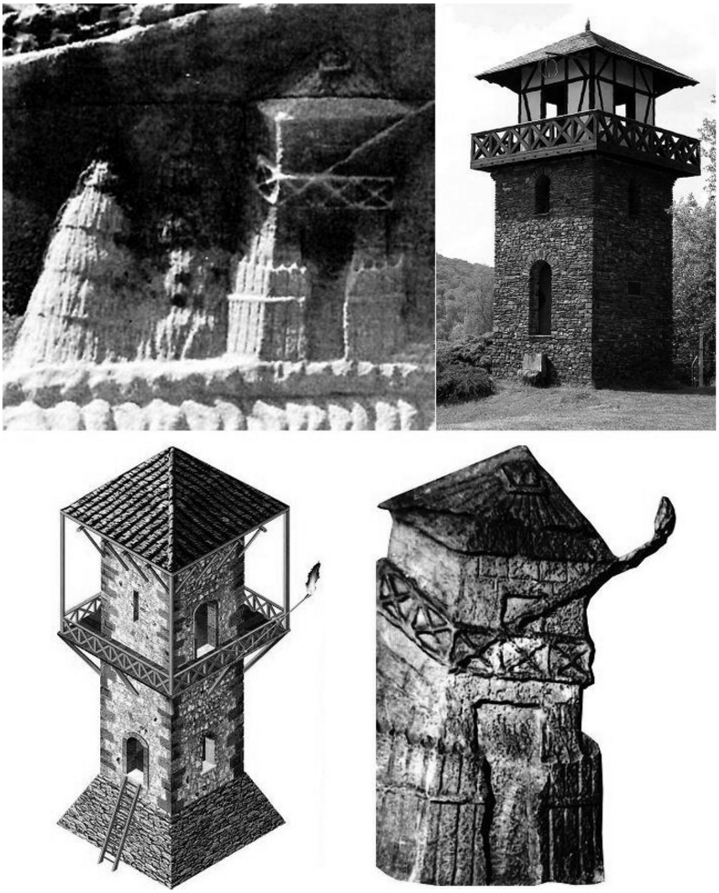

Fig. 11.6 Semaphore turrets.

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.

Figure 11.6 depicts 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 authors' 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.

11.4 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 became essential for all ships. Though lighthouses are still in existence and still function, their original purpose was very different.

In Figure 11.7 are shown some reproductions of the lighthouse of Alexandria: on a coin, and on a mosaic.

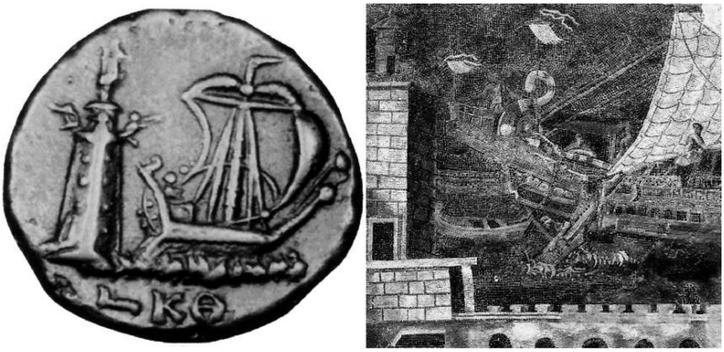

Fig. 11.7 Lighthouse of Alexandria.

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 3rd century 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.

Figure 11.8 shows a mosaic found at Ostia representing a Roman lighthouse and a virtual reconstruction of the lighthouse of Miseno.

Fig. 11.8 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 miniature reproductions 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.

11.5 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 ten notches, one every 10 cm. If equipped with a 10 litres/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 Figure 11.9 are shown 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 40 for the lighthouse of Miseno. However, we presume that normally this range did not exceed 30 km, as repeaters or other communication systems examined further on would have been required for greater ranges.

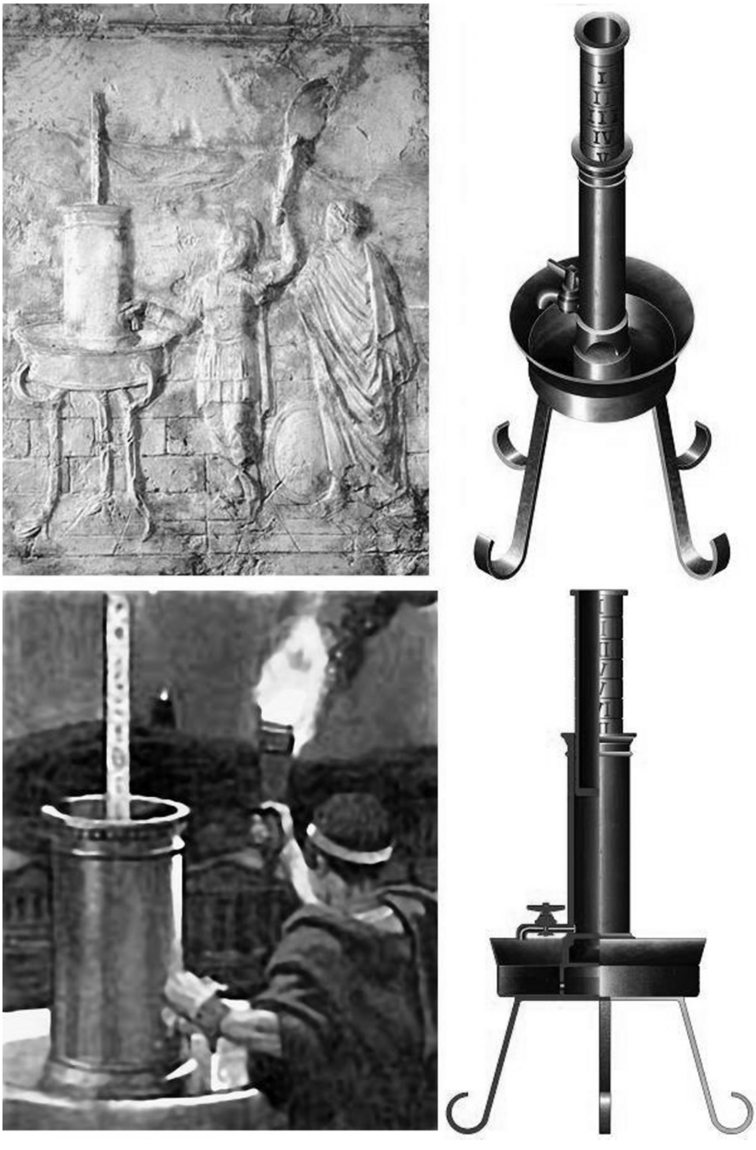

Fig. 11.9 The water telegraph.

Observations

One sector of Roman technology that has been 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 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!

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 a 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.

Part V – TOWARDS THE MODERN AGE

In this part of the book are presented some inventions that required a more advantaged knowledge and, hence, often belong to less ancient times than the ones shown in the previous parts.

The first group of inventions are in the fields of the secondary motors, that is to say those motors that do not make use of natural energy. As far as the latter is concerned, the precursors that the authors have considered generally are up to the Renaissance.

Then devices for spinning and weaving are presented; in this case, the ancestral ideas and devices practically had no significant improvements till the 18th century. The textile industry had a very relevant part in the industrial revolution in the 18th and 19th centuries and, in fact, in that period of time significant devices were invented in that field.

The next chapter is devoted to some devices for the use of fire. In this field many devices that can be considered as precursors of modern times were invented about 2,000 years ago and, until the Renaissance, when gunpowder came to Europe, almost no novelty was introduced in this field.

The last chapter of this part is about automata and automation. Although in this field the early examples are as old as the devices that have been presented in the previous parts, during the last 2,000 years an almost continuous development can be discerned. Although ancient automata could be considered as ancestors of modern industrial robots, the authors believe they are not and explain the reasons for their opinion in the observations of Chapter 15. Anyway, it is evident that these inventions represent ancestors of modern automation.

Chapter 12 – SECONDARY MOTORS

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 criterion 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 described in Chapter 5. 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 noted about gravity driven motors in Chapter 10. The observation of the movement of tow ropes and of sails as they were pulled taut 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.

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

C. Rossi et al., *Ancient Engineers' Inventions: Precursors of the Present*,
History of Mechanism and Machine Science 8, 209–233.

reasons for this action, it must be said that natural elastic properties were soon well understood and were used perhaps as early as 30,000–40,000 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 Figure 12.1 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.

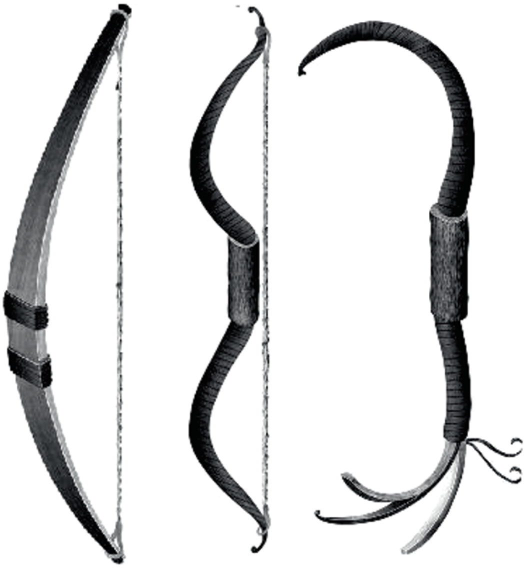

Fig. 12.1 Bows.

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.

12.1 Flexion elastic motors

According to numerous hieroglyphics, the four types mentioned above were already used in weapons during the 2nd 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. Figure 12.2 shows a reconstruction of a "gastrafetes".

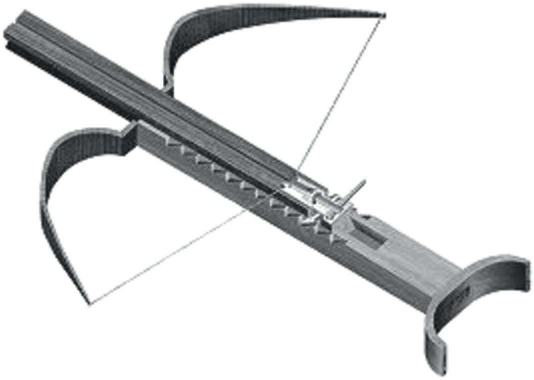

Fig. 12.2 Reconstruction of a gastrafetes.

The name gastrafetes (γαστραφετες) 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. According to E.W. Marsden, the range of its arrows was about 25% longer than that of a bow reaching ca. 180–230 m.

Figure 12.3 shows 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.

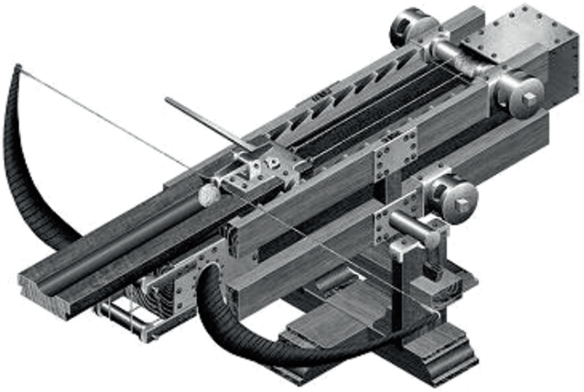

Fig. 12.3 Reconstruction of the ballista by Isidoro di Abidus.

12.1.1 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 we note that following: during the Classic Ages the first term indicated a machine that threw stones or balls, since it comes from the Greek word ballein (βαλλειν) = to hurl a stone; catapult (καταπελτης) generally indicated an arrow throwing machine. During the Middle Ages the terms were used with the opposite meanings. 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. Figure 12.4 shows a virtual reconstruction of Ctesibius' catapult with bronze springs according with his description.

Fig. 12.4 Virtual reconstruction of catapult with bronze springs.

Since steel was not yet available the leaves were made of a special bronze alloy, composed of 97 parts copper and three 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 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. Figure 12.5 shows a detail of the spring mechanism.

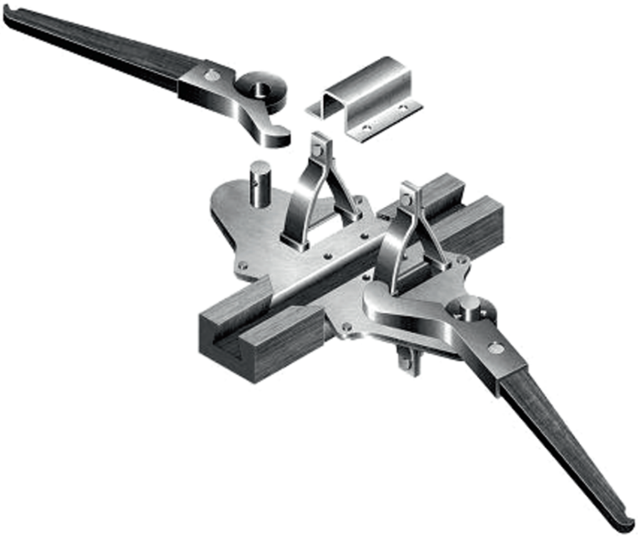

Fig. 12.5 Detail of the spring mechanism.

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 2 millenniums later, since this small item is used in a large number of our devices today.

12.2 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 replace 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 section was used to insert the shaft of the weapons, while the sides were for the two coils of twisted rope. Inside were the arms to which the rope was affixed, like the ends of an archery bow. Figure 12.6 depicts a virtual reconstruction of a Roman catapult with torsion motor, according to data provided by Vitruvius.

Fig. 12.6 Virtual reconstruction of a Roman catapult with torsion motor.

Figure 12.7 shows a propulsor of a Roman catapult found in Xantem, Germany and an exploded view of it with one of its coils.

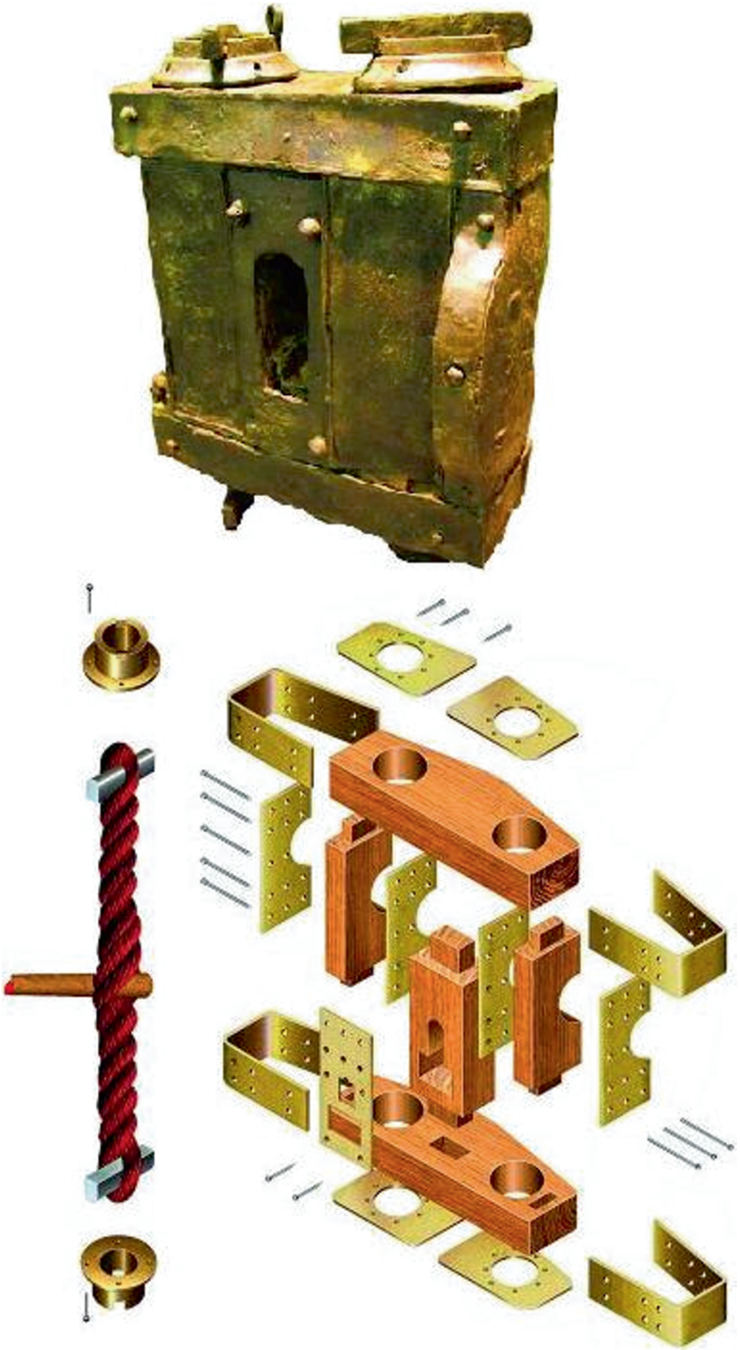

Fig. 12.7 Propulsor of a Roman catapult.

Contrary to traditional ropes, the coils were not made of twisted vegetable fibers but of bovine sinews, horsehair or women's hair. Keratinous formations were preferred for their superior resistance, excellent for elastic motors that worked by repeated cycles of torsion and immediate return. Since the kinetic power of a weapon depended on the diameter of the coils, the diameter became the dimensional module, just like the caliber in modern artillery. The only, and not insignificant, drawback of torsion motors was the strongly hygroscopic nature of the coils, which were weakened when they came into contact with water or a humid environment. Rain or even prolonged exposure to humidity or fog drastically decreased its potential. When they wanted to use torsion artillery in Nordic climates or in naval contexts, the motors had to be carefully protected in hermetically sealed housings.

Preparation for firing consisted of applying an initial torsion to the coils by means of special levers, almost up to the yield point. By effecting an additional rotation of approximately 50–60°, using the arms of the weapon rather than the levers and rotating them by pulling the cord with the crank, a tremendous amount of potential elastic energy was stored. When the restraint was released and the weapon fired, the coil would rotate rapidly in the opposite direction, pulling the arms to fire or hurl the projectile.

In Figure 12.8 is represented another Roman artillery piece powered by a torsion motor: the onager (onagrum).

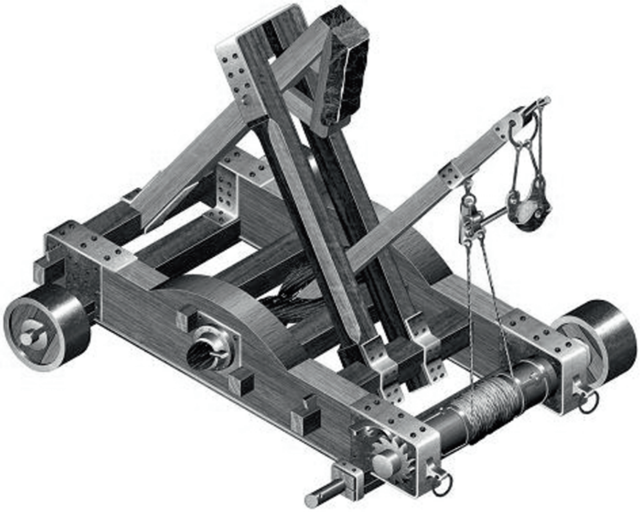

Fig. 12.8 Virtual reconstruction of a Roman onager.

The Roman onager, the only artillery projectile with one arm and a strongly parabolic firing line, already had a sling with automatic opening. The rotation of the lever, was produced by an elastic coil less powerful than the counterweight that was adopted in the later trebuchet, presented in Section 12.5.1. The onager, which from the 3rd century A.D. onward became the principal siege artillery used by legionnaires, stemmed from the simpler and smaller machine: the fustibales. Its additional evolutions can be traced back to the ground and naval weapons of the 13th century.

In this case also, the weapon consisted of an arm made to rotate on a vertical level, with an automatic or remote controlled sling. Polybius left us a detailed description and we know that it was in common use by the end of the 2nd century A.D., even though many authors consider it equal to the onager, used since ancient times. The onager is described by Philon of Byzantium with the generic words “monon ancon” = single arm and must have been widely and frequently used in the ancient world before it was perfected by the Romans.

12.3 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 m 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.

12.3.1 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 body 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 Belopoica, 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.

Figure 12.9 shows a virtual reconstruction of an air spring ballista.

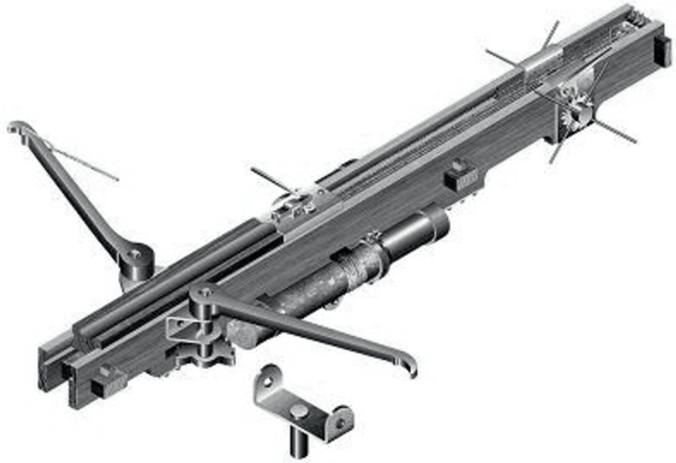

Fig. 12.9 Virtual reconstruction of the air spring ballista.

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. Figure 12.10 shows some details and an orthogonal drawing of the pneumatic (or air spring) ballista.

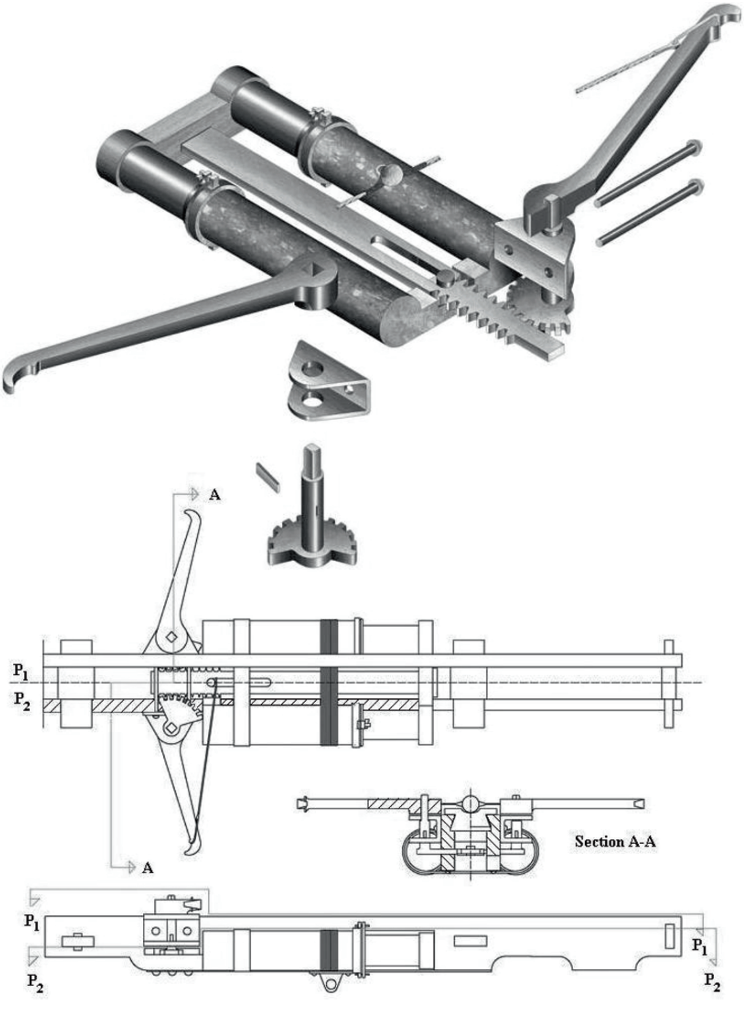

Fig. 12.10 Details and orthogonal drawing of the pneumatic ballista.

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 metre 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 merely incidentally called a 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.

12.4 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.

12.4.1 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 Pompei and Ercolaneum (Italy). Figure 12.11 shows some finds, a key with a lock plate, and a virtual reconstruction of the lock.

The lock 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 a 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 maneuvre 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 4,000 years ago; the mechanism of the Roman lock also reminds us of the famous Yale lock.

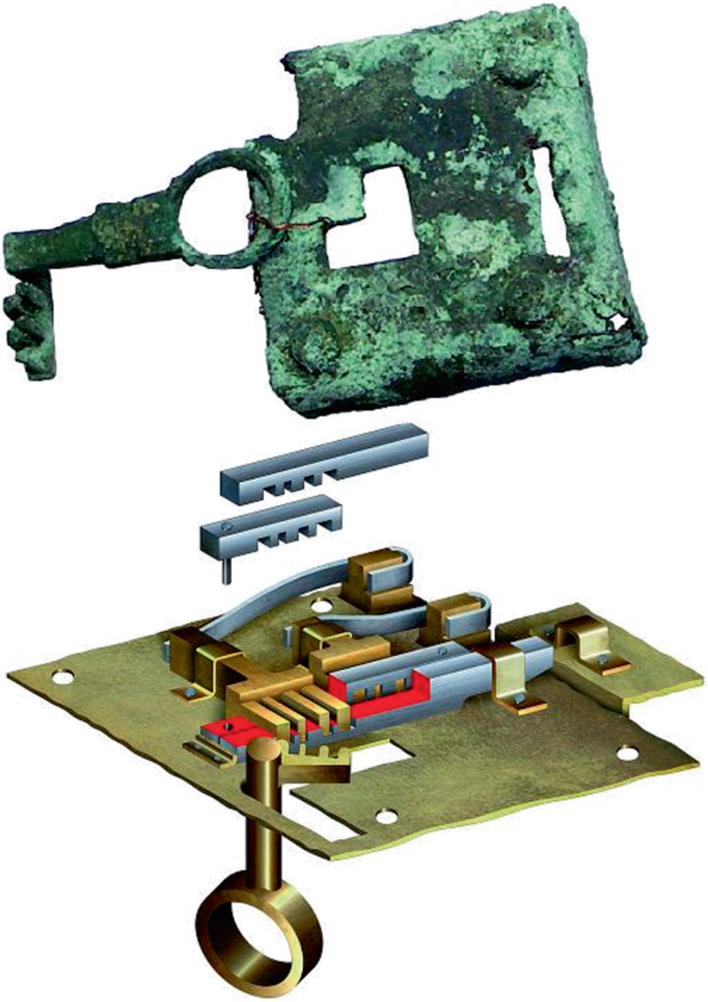

Fig. 12.11 Roman lock, finds and virtual reconstruction.

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.

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 Figure 12.12 is shown a find at Pompei and a virtual reconstruction of it.

Fig. 12.12 Pompeian padlock: a find and a virtual reconstruction.

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 Figure 12.13 is shown a find of a ring padlock and a virtual reconstruction of the padlock and a detail of its mechanism.

Fig. 12.13 Ring padlock: find, virtual reconstruction and mechanism.

12.5 Counterweight motors

Examples of ancient counterweight motors are represented by the gravity driven elevators that are presented in Section 10.2; since they are also lift machines they have been considered among the lift and transport machines. Another example of a counterweight motor is the trebuchet.

12.5.1 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 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 shown in Figure 12.14.

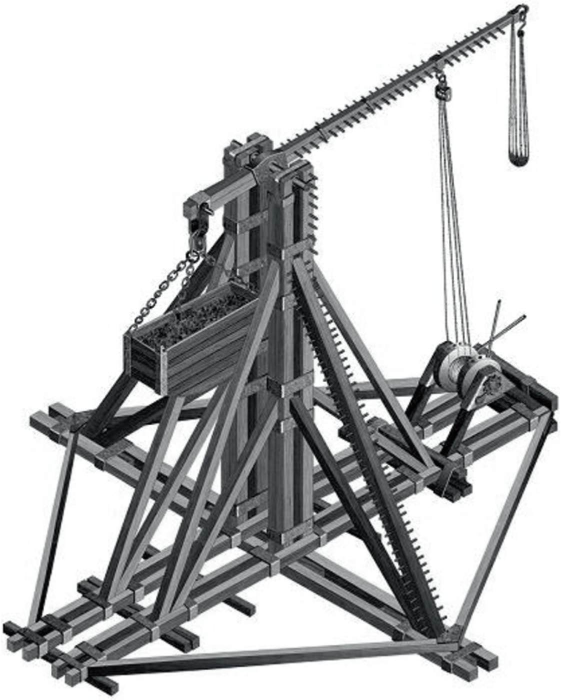

Fig. 12.14 Virtual reconstruction of a trebuchet.

12.6 Ancient steam engines

The first motor as we understand it today was a curious steam turbine, called a ‘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 two wait for Fulton’s steam boat, almost 2,000 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 2,000 years later. Between the two manifestations of the same thought, a complete void that can only be ascribed to their repudiation of manual work, a practice emphasised by an obscure sense of religion.

12.6.1 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 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. Figure 12.15 shows reconstructions of Heron's steam turbines: on the left a drawing by Fausto Veranzio (1551–1617), already mentioned in Chapter 6 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.

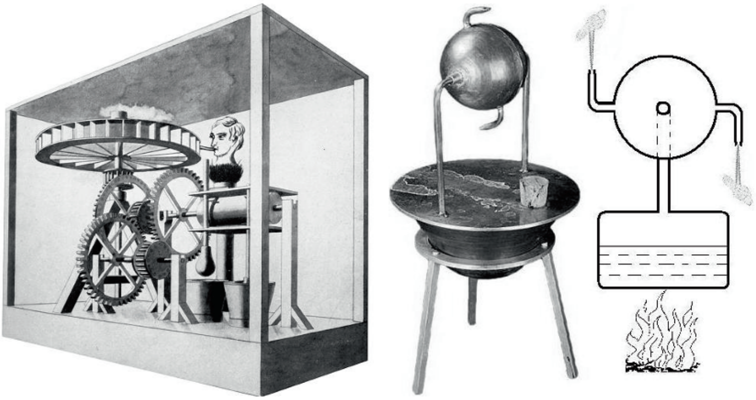

Fig. 12.15 Heron's steam turbines.

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.

12.6.2 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.

When Leonardo da Vinci first sketched this strange piece of artillery, defining it as architronitro – or superthunder – he said that he copied it from some notes left by Archimedes. In light of other details this appears to be a plausible observation. For the great Syracusean appears to have devised this instrument to equip Iberian ships that were about to fight Celtic ships. A steam cannon dating to the 3rd century B.C.

The mysterious steam ballista belongs to the same family as the weapons that functioned by the expansion of air and that Leonardo da Vinci called architronitro; he, honestly, attributed this invention to Archimedes by these words: the architronitro is a machine of fine copper, invented by Archimedes, that launches balls of iron with great vigour and furor. That this affirmation merits some credibility is suggested by a curious detail: in describing the function of the weapons, Leonardo does not use the linear and ponderal measurements of his day, or the Roman ones with which he may have been familiar, but the archaic Greek units of measure with which he was not at all familiar. Specifically, the weapon consisted of a: "cannon that depended upon the sudden generation of vapour to fire a shot out of the cylinder." The breech was made of brass like a basket and contained burning coal. After packing the round, and after having sufficiently warmed that section of the breech, a little water was injected into what would normally have been the powder chamber and "was resealed from below and all its water descended into the fiery section of the instrument and there it was converted into so much smoke that it was a marvel; and it is great to see the fury and hear the noise. It hurled a ball that weighed a talent, six stadiums away". Leonardo's words confirm the fact that such a cannon had in effect already been built.

In the Greek units of measure, the talent corresponded to 60 mina, each of which was 436.6 g: none of these units have an equivalent in Roman units, while the stadium, was 184 m if Roman, and 125 m if Greek. By obvious correspondence a projectile weighing about 30 kg launched for a distance of approximately 1 km was for the era extraordinary and fully justifies Leonardo's certainly not archaeological interest.

That this was the exhumation of an invention of Archimedes completely unknown to us should not come as a surprise, especially since Leonardo also mentions a sojourn in Spain by the great Syracusean, of which we are also ignorant. Proof that other sources containing a better description of the steam ballista may have existed during his lifetime, that later disappeared. It is not unrealistic to presume that such a conceptually logical machine may have actually existed in the classical era, such that with the arrival of the modern era of steam cannons, the same propulsion criteria was used to build numerous others that were all perfectly functional. Figure 12.16 reproduces the Ms. B, f.33, v. showing the drawings of the architronico by Leonardo da Vinci.

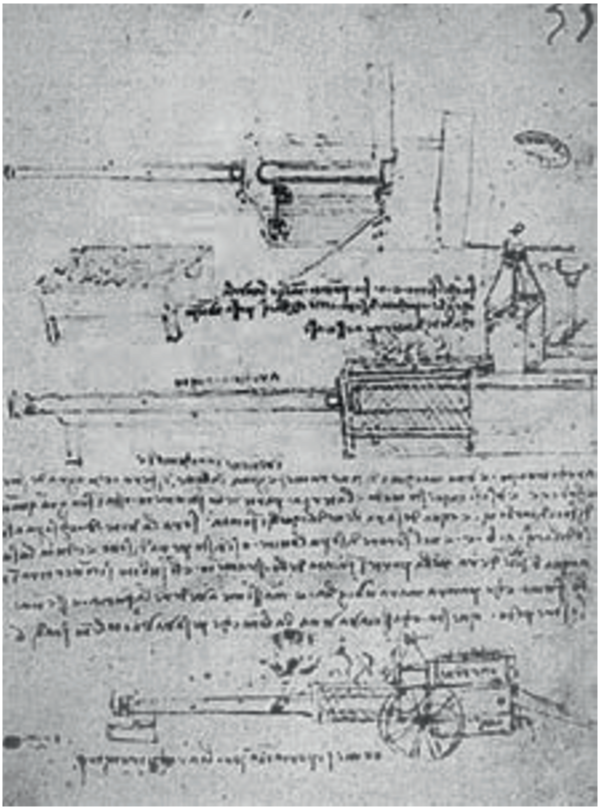

Fig. 12.16 Architronitro, Ms. B, f.33.

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.

Observations

The existence of a pneumatic ballista shows that air weapons are much older than one can commonly think, but it was an arrow throwing weapon. Pneumatic weapons such as rifles and guns were invented later. The oldest were built around 1644 by Hans Köhler at Kithzingen.

In Figure 12.17 is shown a pneumatic rifle built at the beginning of the 17th century (from Reiw, 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.

Fig. 12.17 Pneumatic rifle.

For a wider autonomy of fire, the gun had interchangeable air tanks.

In the 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 preferable to use compressed air as a 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 4 years old with his parents. He became an officer of the US 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. Figure 12.18 depicts 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 aiming had to be done by orienting the ship, and the range had to be adjusted by varying the air pressure.

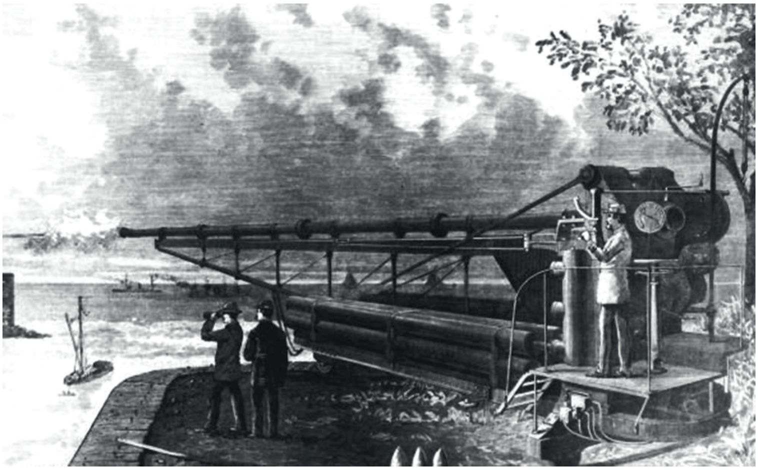

Fig. 12.18 Pneumatic Cannon.

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 13 – SPINNING AND WEAVING

Introduction

Cloth is among the most important and most useful objects of common use by mankind; also, the development of cloth is a milestone in the history of human civilization since it can be considered a first step towards technology.

13.1 The dawn of spinning and weaving

Almost all our cloth is woven; nowadays it is taken for granted that woven materials exist and are rather cheap and has been available for barely 2 centuries.

It is well-known that woven material is made from spun yarns that are joined together by weaving; this technology dates back to the Neolithic Age. From the 3rd millennium B.C., 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, which 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.

The hand spinning principle consists in using two tools: the spindle and the distaff. Spindles are rather similar in all civilizations and essentially consist of a cylindrical tool that can rotate around its axis.

Figure 13.1 schematically shows, from a pointing on a Greek pot, the spinning process and a woman spinning with spindle and distaff. The natural fibres are grouped on the distaff and, by one hand, are stretched in a thin band of 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 rolling it on the external side of the thigh; the spin of the spindle gives the band of fibres the desired

C. Rossi et al., *Ancient Engineers' Inventions: Precursors of the Present*,
History of Mechanism and Machine Science 8, 235–248.

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.

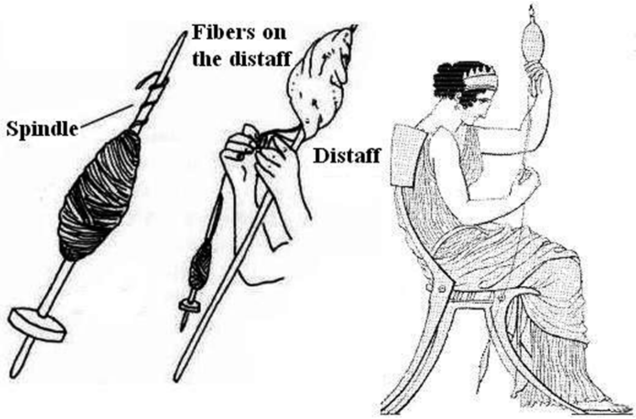

Fig. 13.1 Spindle and distaff.

Once the twisted yarn is obtained, it is woven by use of the loom. Obviously the loom is as old as the spindle. Figure 13.2 depicts an Egyptian loom from the tomb of Chemhòtpe at Beni Hasan, 12th dynasty (1976–1784 B.C.).

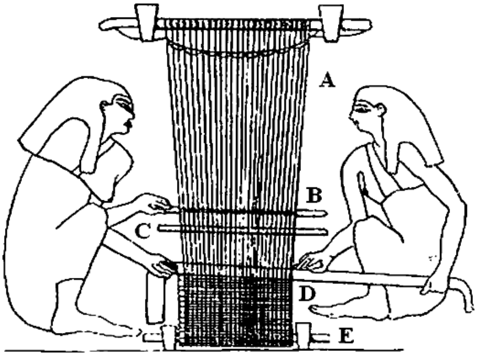

Fig. 13.2 Ancient Egyptian loom.

A number of parallel yarns A are disposed on a frame; these yarns will form the warp. The weaver threads a shuttle B on which the woof yarn 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 woven material 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, as is done nowadays. Hence, ancient Greek and Roman looms were built in different sizes because each cloth was woven 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. Figure 13.3 demonstrates the working principle of a loom with heddles; the working principle is the same as for modern looms.

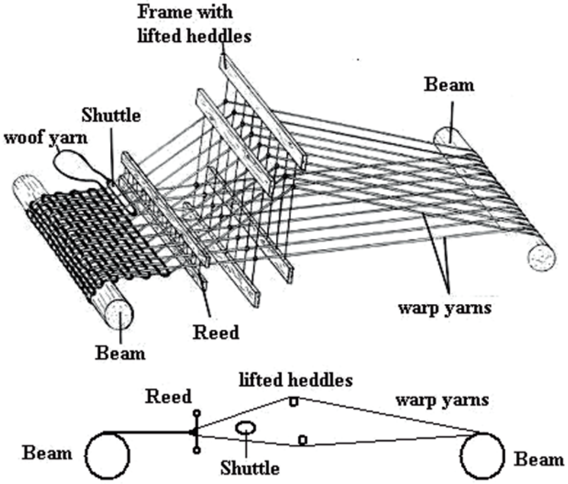

Fig. 13.3 Working principle of the loom with heddles.

In Figure 13.4 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.

The oldest attestation of a pedal operated loom was found in a Monastery near Thebes, Egypt that was established by Ephiphanius around A.D. 333. The excavations were made by expeditions from the Metropolitan Museum of Art in 1912–1914 and showed foot powered looms used in the early centuries of the Christian Era.

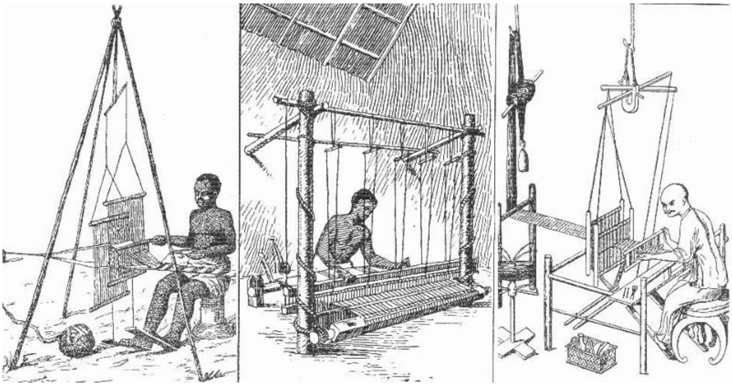

Fig. 13.4 Looms with heddles.

13.2 The spinning wheel

The first step to increase yarn production is represented by the invention of the spinning wheel. In Figure 13.5 is shown a castle (vertical) spinning wheel and a detail of the flyer.

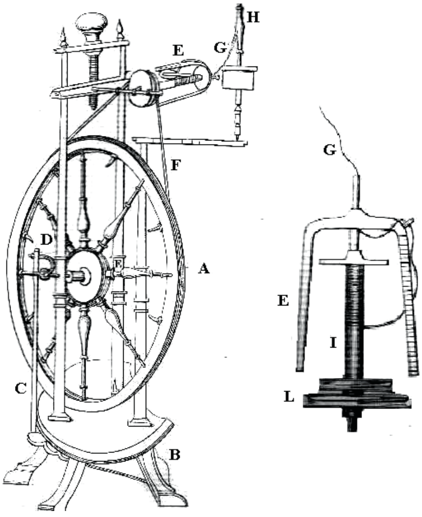

Fig. 13.5 The spinning wheel.

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, which 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 13th 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.

13.3 The mechanical spinning wheel

Although the spinning wheel has some mechanical components, the fibres have to be stretched by hand before being twisted. This aspect and the presence of just one flyer does not permit production of the large amount of yarn needed in Europe in the 18th century because of population growth.

In the 100 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.

13.3.1 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 machines with two flyers) but such devices had, normally, no more than two flyers. A significant increase in 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’s wife. In any case the legend says 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 shown in Figure 13.6. The roves made by parallel fibres are bound onto the bobbins A and pass through a press C that can be widened or grasped by the operator and then sent on 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.

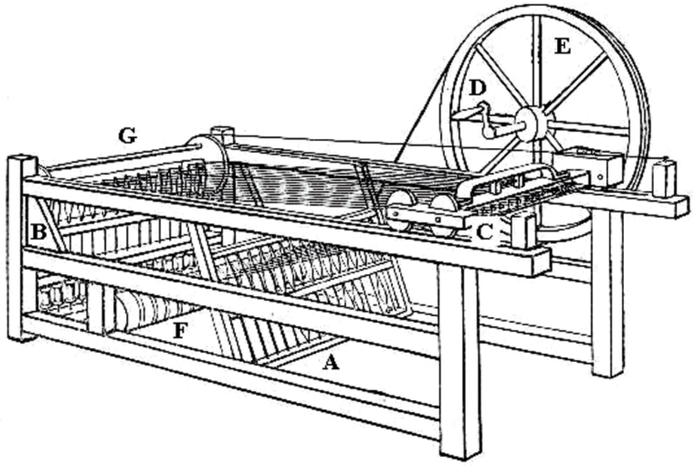

Fig. 13.6 Spinning jenny.

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 80 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 to sell the machines, spinners from Lancashire, being afraid of losing their jobs, destroyed all Hargreaves' equipment.

In the spinning jenny are present all the elements of the modern automaton: 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.

13.3.2 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. Figure 13.7 is a drawing of an Arkwright spinning machine.

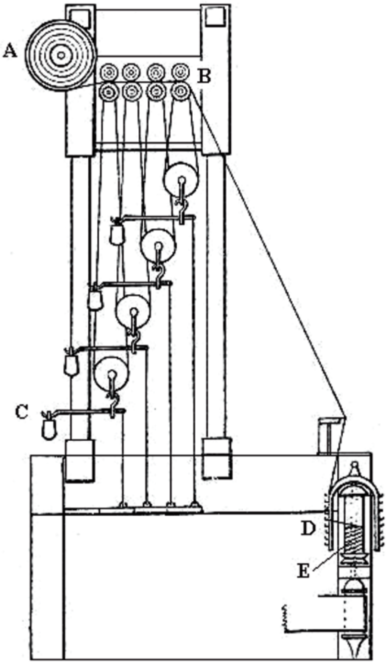

Fig. 13.7 Arkwright's spinning frame.

The roves are bound on bobbin A and pass through the rolls B; since the latter rotate at different speeds (slower for the first couple and faster for 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 are twisted by the fliers D and bound on spindles E. The rolls were made of bronze and covered with leather.

The device was also known as a “throstle” probably because of the noise the fliers made.

13.3.3 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 called a mule or a mule-jenny since it was a hybrid (like a mule) between the spinning jenny and the spinning frame.

In Figure 13.8 is depicted a mule-jenny built in 1812 that is now at the Musée des arts et métiers in Paris.

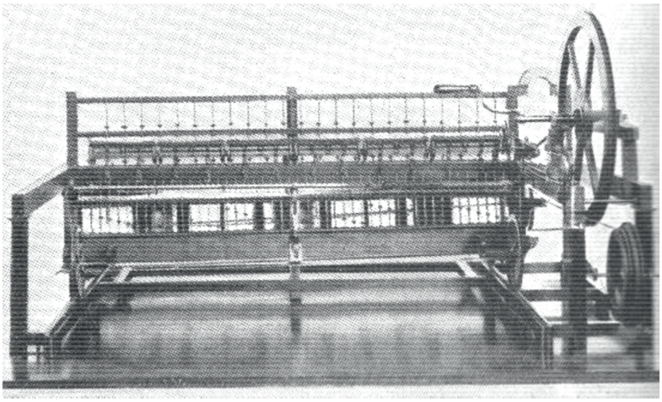

Fig. 13.8 A mule jenny.

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, 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 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.

13.3.4 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. Figure 13.9 shows, 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 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.

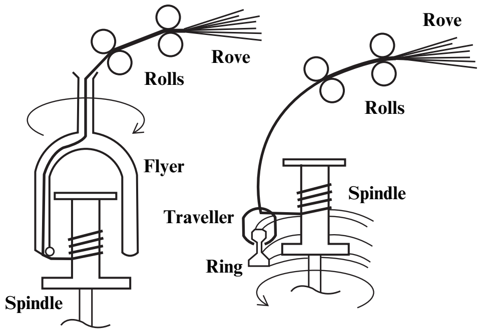

Fig. 13.9 Working principles of spinning machines.

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.

13.4 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 subsections the authors summarize the main steps in this field.

13.4.1 The first programmable loom

Generally the first programmable loom is considered the one by Jacquard or a similar device by de Vaucanson, who also invented the automata "the duck" we discussed in Chapter 15. Actually, the first example of a precursor of the programmable loom dates back to the end of the 15th 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", which has the same meaning in French.

It is known that the first European places where silk was worked, between the end of the 9th century and the beginning of the 10th, were in southern Italy at Catanzaro (Calabria) and Palermo (Sicily). This was probably because Catanzaro was under Byzantine dominion while Palermo was under the Arabs. Hence, both cities were narrowly linked to oriental culture. In 1466 King Louis XI decided to establish a major silk manufacturing factory in France and recruited a large number of Italian workers, mainly from Calabria. The draw loom that appeared in those years in France was called "the loom by Jean le Calabrais". One of these looms is at the Musée des arts et métiers in Paris and is shown in Figure 13.10.

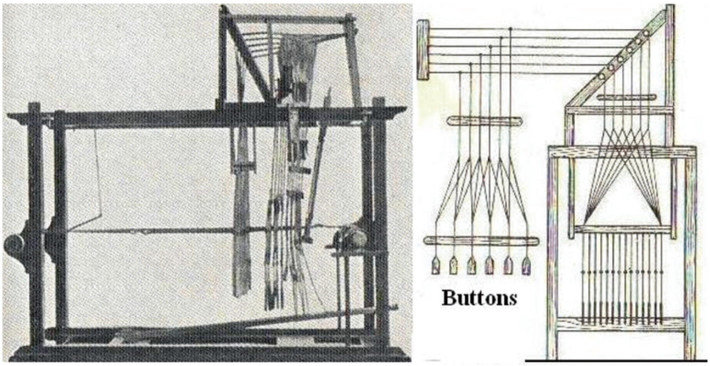

Fig. 13.10 The loom by Giovanni il Calabrese.

The loom 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 designated heddles and by inserting in the warp a woof yarn having a designated colour and so on. As shown in Figure 13.9, 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 the 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 and moved by an apprentice; this permitted the weaver a faster production.

13.4.2 The programmable looms of the 18th century

The course of development in he history of the programmable loom sees many improvements of the original idea of the draw loom. Among these, we can mention Basile Bouchon who in 1725 was the first to use drilled paper on a loom, 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 Jacquard (Lion 1752, Ouillins 1834). Jacquard was a weaving businessman who patented his programmable loom in 1804. In Figure 13.11 is shown a scheme of Jacquard's loom.

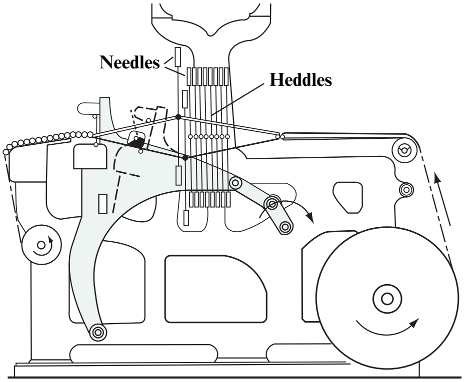

Fig. 13.11 Scheme of a Jacquard loom.

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 as the previously mentioned programmable looms but in the one by Jacquard, the process and the card feeding is automatic. The number of holes on the card board can be up to 1,200; this permits to obtain also very complex drawings.

The Jacquard 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.

13.4.3 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 in the 3 millenniums before the 18th century: the Egyptians threaded the woof yarn into 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 of a new component of the loom was 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 on the invention of the spinning frame.

A scheme of the working principle of the flying shuttle is shown in Figure 13.12. It essentially consists of a pair 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:

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 can be used to move the reed.

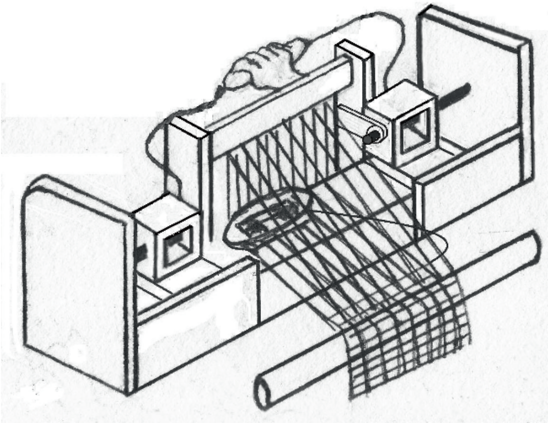

Fig. 13.12 Scheme of the flying shuttle (Courtesy of Dr. E. Scoppa).

This loom, even in its early versions, permitted production to increase 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.

Subsequently a device was invented to obtain the contemporaneous path of the fabric; this was made in about 1800. In this way the loom had been perfected in all its movements, and it was easy to order all of them so as to be operated by one 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 the wide and cheap production of fabric, and hence of different kinds of cloth were, in fact, in a few decades of the 18th century. Spinning and weaving certainly had a very important part in the industrial revolution, but it is even more important that the mentioned inventions and their development made it possible to dress a rapidly increasing population right up to the present days.

Chapter 14 – SOME APPLICATIONS OF FIRE

Introduction

The discovery of fire was obviously man's first 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 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 humans 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 was further exploited in a magnificent lighthouse on a small island off the coast of Alexandria, with the strange name of Pharos, which became one of the most famous and suggestive icons of a 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.

C. Rossi et al., *Ancient Engineers' Inventions: Precursors of the Present*,
History of Mechanism and Machine Science 8, 249–268.

The unnatural symbiosis of fire and water had already been abundantly used in 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 was placed on the bottom acting as a diffuser: like 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 were 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 of the time, 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 had 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, we present a few examples of the management of fire.

14.1 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 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 for certain is that several centuries later the Romans ignited fire and cauterised wounds by concentrating the rays of the sun using spherical lenses.

14.1.1 Optical flints

It was well known that the strong percussion of siliceous stones worked to make blades generate sparks. From this the Romans soon learned that these sparks could ignite light-weight tinder. And finally that if these stones were struck by an iron object, the resulting sparks were even more suitable to igniting an even heavier type of 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 Figure 14.1 are shown prisms of rock crystal of extraordinary precision, used to fractionate light, found at Pompei.

Fig. 14.1 Prisms of rock crystal found at Pompei.

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 opposita 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 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 Figure 14.2 is shown a magnifying glass found at Pompei; similar crystal lenses were used by the Romans to ignite fire.

Fig. 14.2 Magnifying glass found at Pompei.

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 Chapter 2), 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.

It is 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.

14.2 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 kilometres. 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 sulpur 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 immerge 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 consultation 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 immerged 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. It is logical to suppose that a few decades later the Romans would have highly effective fire generating liquids to use in warfare.

14.3 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 Figure 14.3 is shown a detail of the Trajan column.

Fig. 14.3 Detail of the Trajan column showing a wind lantern.

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.

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 Figure 14.4 are shown a relict of a wind lantern found at Herculaneum and an author's virtual reconstruction of it.

Fig. 14.4 Wind lantern found at Hercolaneum and virtual reconstruction.

14.4 Fire for warming

The use of fire for heating is certainly as old as 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, those adopted during the age of the Romans were of considerable effect.

14.4.1 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 2 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.

14.4.2 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 Pompei, 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^2, 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^2 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 (hipocausis), 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, semicylindrical container, in the shape of a testude 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 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 baths are depicted. In Figure 14.5 is shown a picture of the finds at Saint-Romain-en-Gal (central eastern France) and some axonometric drawings showing the heating system.

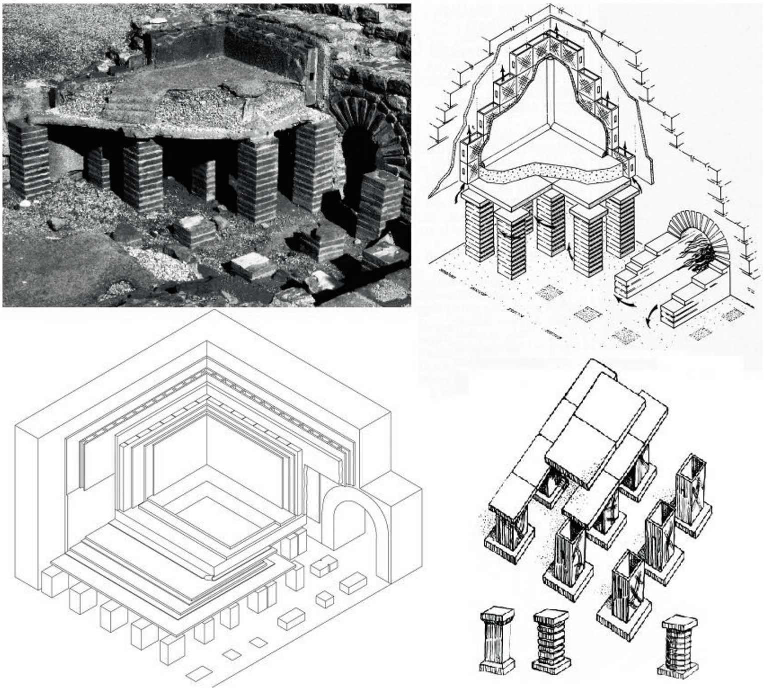

Fig. 14.5 Finds at Saint-Romain-en-Gal.

In Figure 14.6 is shown a picture of the large Roman thermal baths at Bath, England.

Fig. 14.6 Roman thermal baths at Bath, England.

14.4.3 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. 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 40 l, 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 3 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 table, bringing the desired tap to the cup. In Figure 14.7 is shown 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.

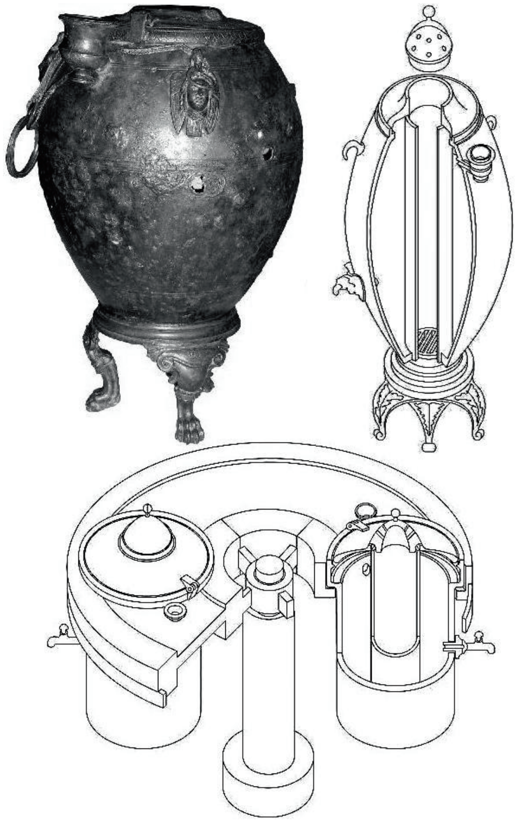

Fig. 14.7 Roman samovar.

14.5 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.

14.5.1 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 Figure 14.8 is shown a print from the 18th century depicting the use of burning glass in the defence of Syracuse.

Fig. 14.8 Print depicting the use of burning mirrors.

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 metres 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.

14.5.2 Flamethrowers

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 Chapter 7, a twin cylinder operated flame thrower, designed by Ctesibius, has already been presented as an example of a reciprocating pump.

14.5.2.1 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 metres.

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 Figure 14.9 are shown an 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.

14.5.2.2 A probable single cylinder pump flamethrower

A singular relic is stored in the municipal Antiquarium of Rome, of which we do not know 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 Figure 14.10 are shown the finds and an authors' virtual reconstruction.

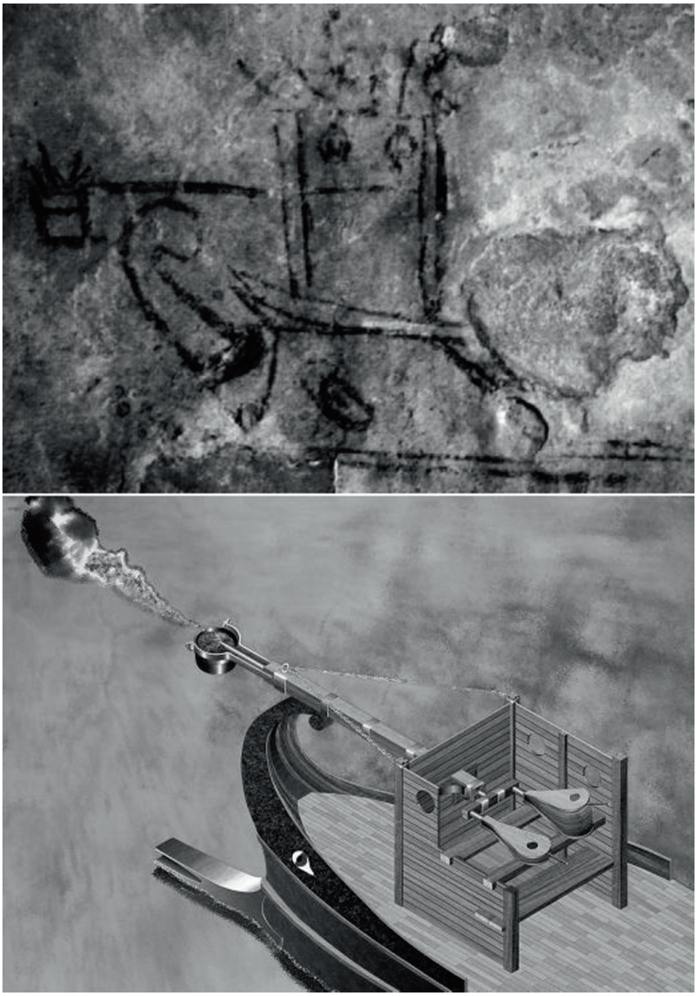

Fig. 14.9 Flamethrower: Egyptian graffiti and virtual reconstruction.

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.

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 Chapter 12).

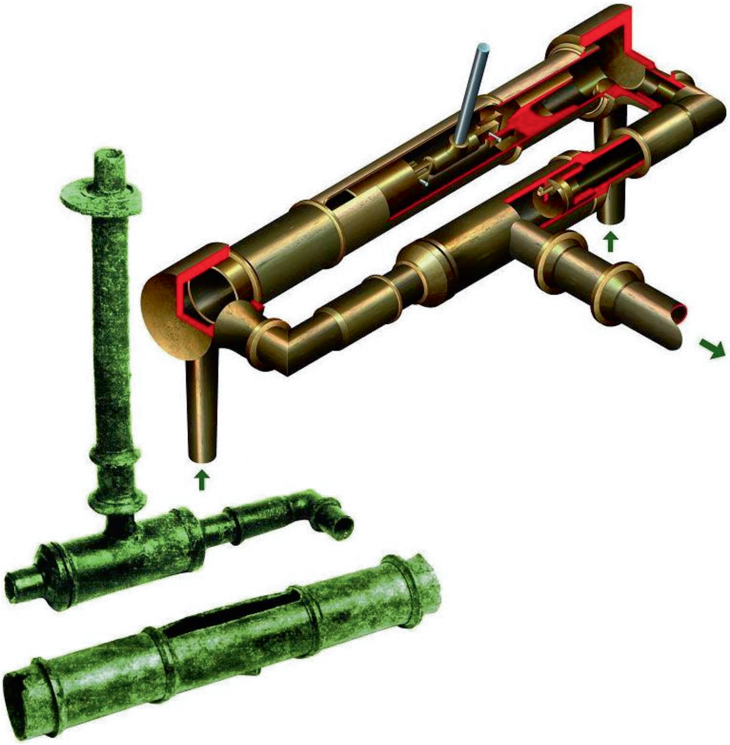

Fig. 14.10 Single cylinder Roman pump: finds and virtual reconstruction.

14.5.2.3 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 (Russo, 1996)".

In addition to the above evidence, we note that the Greek fire was 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. It is 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.

14.6 Protection from fire: Asbestos

The first material that was used as a protection from fire is a very old one: asbestos. The word comes from the ancient Greek ασβεστος (asbestos) that means: inextinguishable; this word was used by many ancient authors like Pliny (Gaius Plinuis secundus A.D. 23–79), 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 becoming contaminated.

In ancient times, asbestos was also called "salamander's wool" since it was believed that this amphibian could stay in fire without suffering any damage.

Pliny has left us many references about 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 be cleaned and purified by just leaving them in the fire.

In Figure 14.11 is shown an ancient illustration of a portable flamethrower (see Section 14.5.2.2) used during a siege and a detail of it. Since the fire resistant proprieties of asbestos were known in antiquity, in the detail it is possible to interpret the dress and the boots of the man as fire resistant protections, possibly made from asbestos.

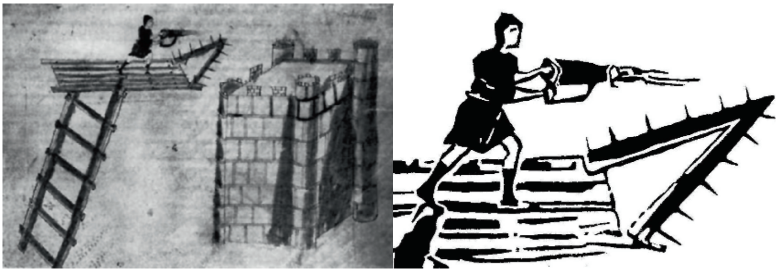

Fig. 14.11 Portable flamethrower and possible asbestos defences.

Pliny also refers to asbestos as a soundproof material: he says that big towels made from asbestos were put around trees that had to be cut down, in order to dampen 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.–A.D. 17), tells us that the men who worked in the asbestos mines often became ill.

Chapter 15 – AUTOMATA (TOWARDS AUTOMATION AND ROBOTS)

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 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 smithy. Another legend tells us that king Minos used a bronze mechanical giant, named Talos and forged by Hephaestus, to patrol the isle of Krete (Figure 15.1).

Fig. 15.1 Talos.

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 followed 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 were designed before the electronic control system was invented.

C. Rossi et al., *Ancient Engineers' Inventions: Precursors of the Present*,
History of Mechanism and Machine Science 8, 269–301.

The chapter is divided into sections that pertain to historical periods.

15.1 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 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 of Egypt (31 B.C.). But the influence of Hellenistic thinking and knowledge of science and philosophy was very strong for some centuries after the 1st century B.C.

15.1.1 Heron of Alexandria

Heron of Alexandria (A.D. ≈10–70) 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) he described statues having human semblances (automatons) that were moved in a theatre acting as human characters, 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 Figure 15.2.

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.

In Figure 15.3 is shown a reconstruction, made by Giovan Battista Aleotti in his "Gli artificiosi et curiosi moti spiritali di Hero Alexandinus" (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.

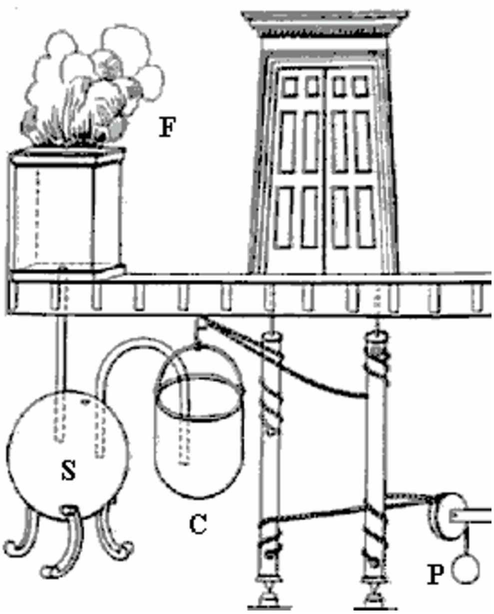

Fig. 15.2 Heron's mechanism for temple doors.

In a few words: the dragon hisses, Hercules beats it with a club and the dragon spits on Hercules. The working principles were 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 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 Figure 15.4.

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.

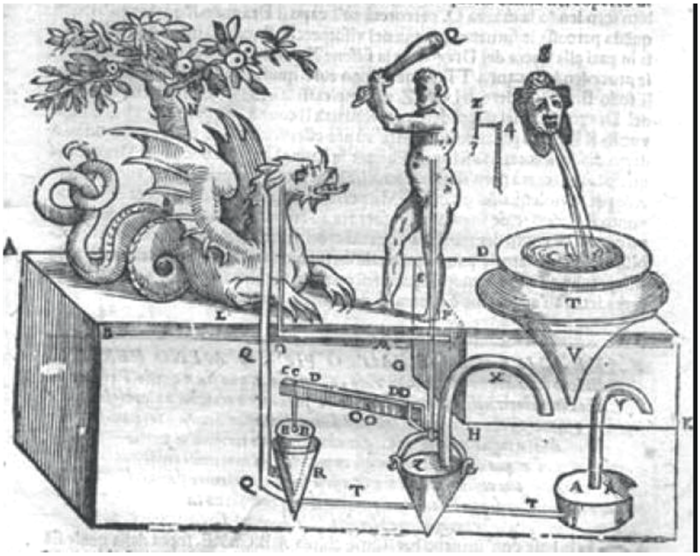

Fig. 15.3 Reconstruction by G.B. Aleotti of a Heron's automaton.

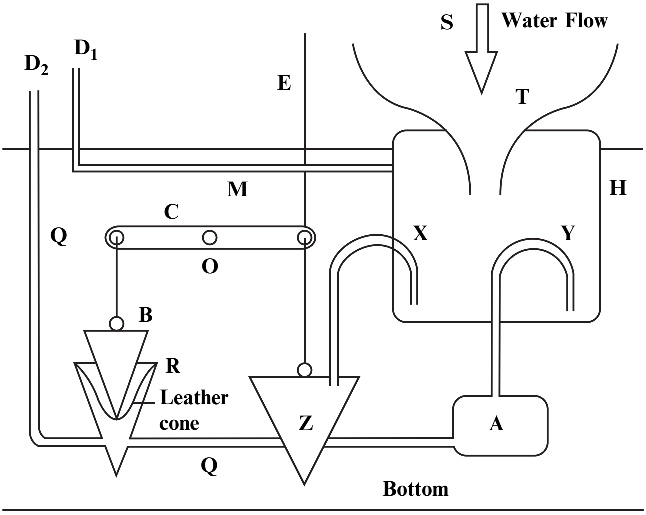

Fig. 15.4 Working principle of Hercules and the dragon.

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 reproduced in Figure 15.4.

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 made it possible to somehow program the motion.

In Figure 15.5 an example of motion programming by means of ropes wound onto cylinders is demonstrated.

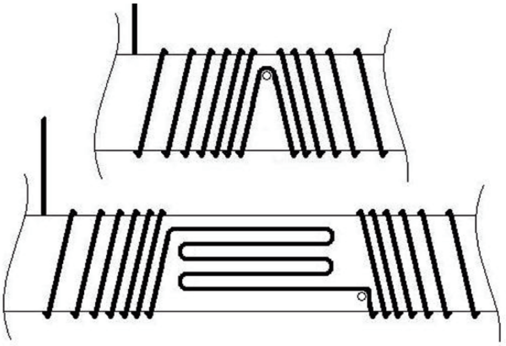

Fig. 15.5 Ropes wound on cylinders.

In the figure the ropes are wound onto a cylinder with different pitch and winding directions. 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.

15.1.2 The Roman Empire: The repeating catapult

The catapult, the meaning of this term and the working principle of this device have already been discussed in Chapter 12. In this paragraph a repeating version of this device is presented.

A pictorial reconstruction of the repeating catapult is shown in Figure 15.6. 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.

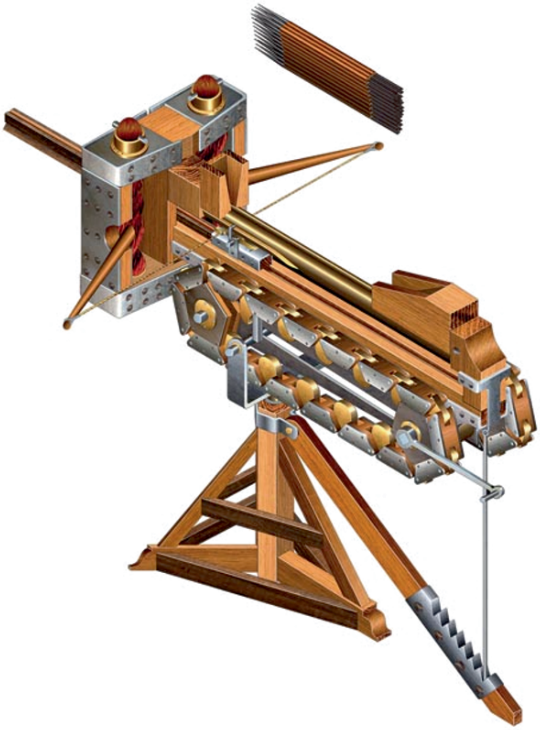

Fig. 15.6 Pictorial reconstruction of the automatic catapult.

The repeating device essentially consisted of 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 Figure 15.7 some details of the mechanism are shown.

According to Philon, the arrows were located in a vertical feeder (see Figures 15.6 and 15.7) 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.

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 Figure 15.7. 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.

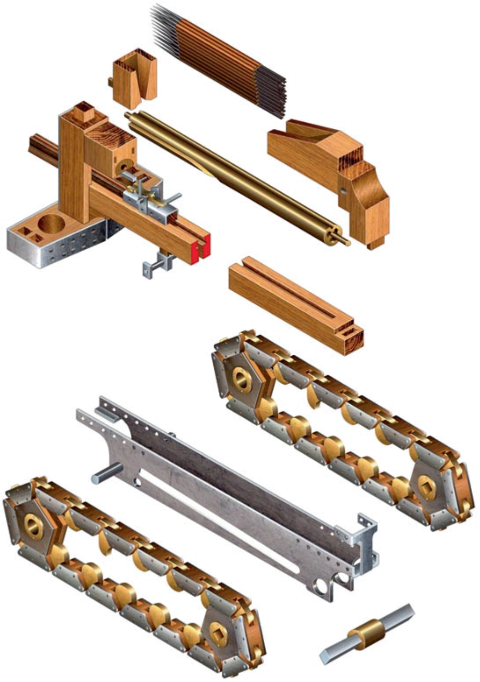

Fig. 15.7 Details of the mechanism.

Reconstruction of very ancient devices is often difficult. The one of the repeating catapult, for instance, is based on old texts (e.g., Baldi, "*Heronis Ctesibii Belopoiika, hoc est, Telifactiva.*" Augusta Vindelicorum, typu Davidu Frany, 1616), on the work made by Schramm (Schramm, "*Die* *antike Geschütze del Saalburg*" Berlin, Weidmannsche Buchandlung, 1918) that is also described by Marsden (Marsden, "*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 no technical terms: for instance in "Ta Filonos Belopoika" 75, 33–34, chainmail is called "πλινθια" = little brick and the teeth of the chain are called "περοναις" = fin.

The difference between our reconstruction of this device and the previous ones mainly consists in the reload sequence: 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 Figure 15.8, 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 Figures 15.8 and 15.9). When the slide reached the rear of the weapon, the cog released it, while another opened the release mechanisms. An instant

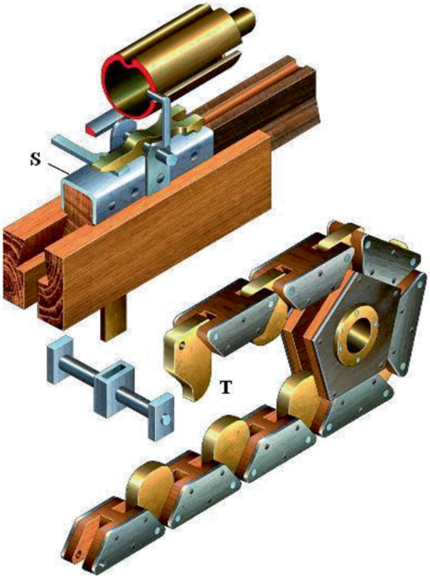

Fig. 15.8 Chain and trigger mechanism.

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.

In Figure 15.9 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.

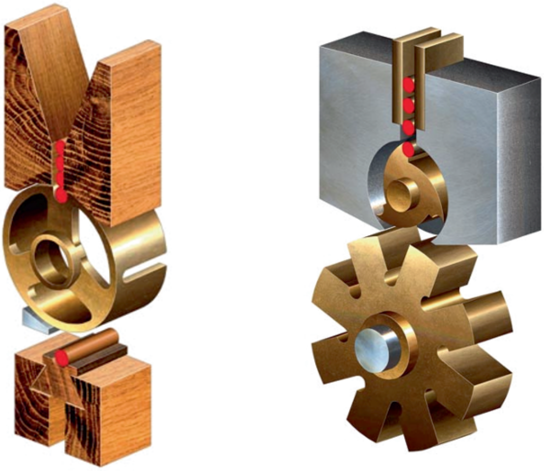

Fig. 15.9 Repeating catapult (*left*) and Gatling machine gun (*right*) feeding mechanisms.

In Figure 15.10 is represented a perspective section of another author's reconstruction and a detail 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 Figure 15.11 are shown side views of the author's reconstruction; from top to bottom: unloaded catapult, a detail around the front sprocket and loaded catapult. In this reconstruction the crank is substituted by levers disposed in a 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 author 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.

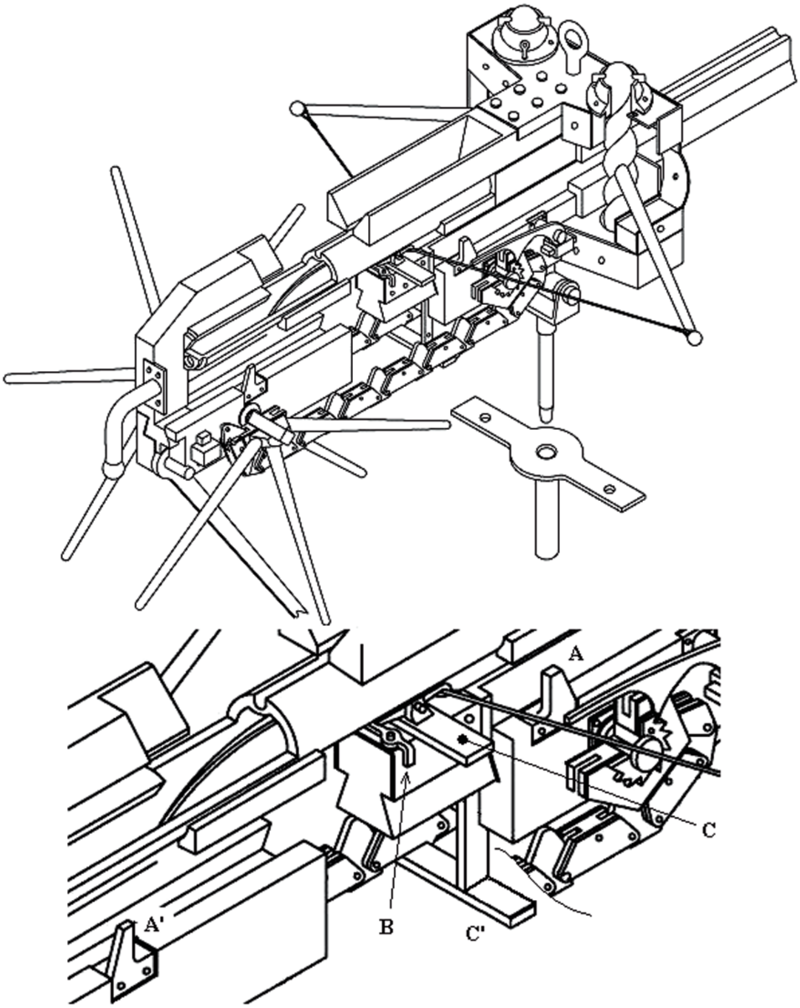

Fig. 15.10 Perspective section of the repeating catapult.

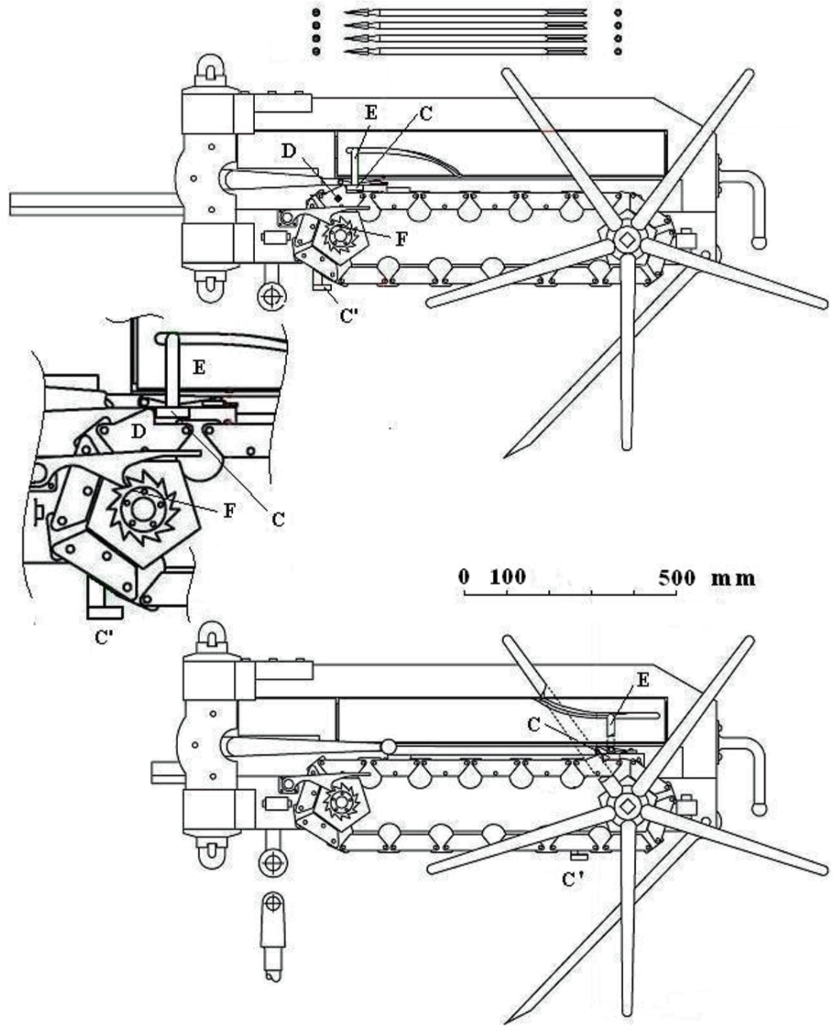

Fig.15.11 Side views of the repeating catapult.

The author believes that it is simpler (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 author's reconstructions, the entire 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 before the Kaiser, one of its arrows split another arrow exactly in two!

15.2 The Middle Ages

In the Middle Ages some improvements were made on the devices designed by Greek and Roman engineers.

One of the reputed inventors of automata in the Middle Ages was a most controversial Pope, Silvestro II (Gerbert d'Aurillac ca. A.D. 950–1003). He was an accomplished mathematician with a strong interest in scientific experiments but he was also suspected of being a sorcerer. This infamy was probably due to his interests in some machines that, during that age, seemed 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 us that, unfortunately for him, Silvestro II was not able to understand one of his automaton's reply about his fate.

Talking heads were quite common in the Middle Ages up to the Renaissance. Another legend concerns a talking head made by Albertus Magnus (ca. A.D. ~1200–1280), a great German philosopher and theologian who advocated for a peaceful coexistence of science and religion. Another legend tells us that the head was a real and complete android made of metal, wood, wax, glass and leather that could talk and that it was made to work as a servant at the Dominican monastery in Koln. This automaton was destroyed by Saint Thomas Aquinas who was one of Abertus' students. Incidentally, the term "android" was probably invented by Albertus Magnus and used to indicate living creatures made by man by means of alchemy.

15.2.1 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) was 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) which is the land where he was born in the 12th century.

Al Jazari is known for a number of significant inventions in many fields, e.g., mechanical control devices, water pumps, astronomical clocks and automata; these inventions were described in 1206 in his *Book of Knowledge of Ingenious Mechanical Devices*.

Among his automata the most interesting is the Elephant Clock; Figure 15.12 shows 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

Fig. 15.12 Elephant Clock.

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 m long and 1.85 m high. A modern reconstruction of it, 8 m high, is at Ibn Battuta Mall, Dubai.

15.2.2 The astronomic clock of Strasbourg

One of the most famous and interesting automata of the Middle Ages was the cock of the astronomic clock in the cathedral of Strasbourg (or Strassburg).

The first cock, at present in the Musee de Oeuvre Notre Dame, is shown in Figure 15.13. The clock has a long history that was recorded 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.

Fig. 15.13 The cock of the Strasbourg Cathedral.

Figure 15.14 is a drawing of 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 of a case about 12 m high including a calendar dial and an astrolabe dial. Every hour, moving Magi kneeled to a statue of the Virgin with the Holy Child. At 12 o'clock a cock moved its pinions, opened its bill, moved its tongue and sang three times.

This device can be considered one of the first examples of automata activated by a clockwork motor, while those of the classic ages were powered by steam or water.

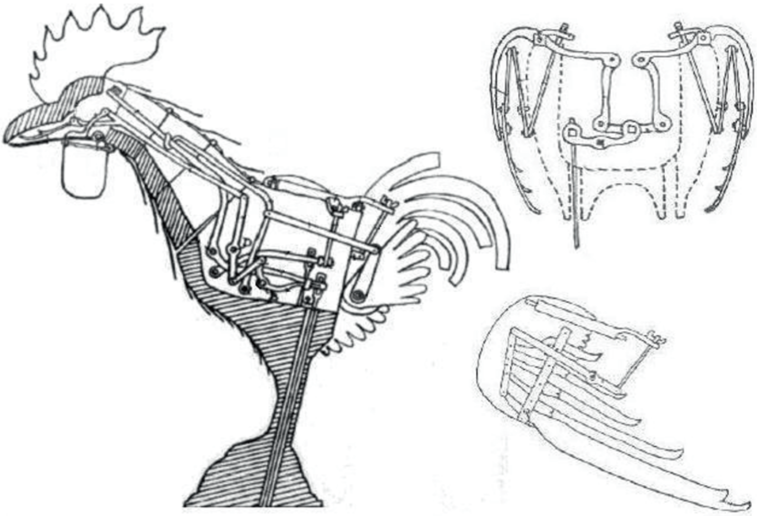

Fig. 15.14 Cock's interior.

15.3 The Renaissance

During the Renaissance, studies and works on automata increased 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 was Giovanni Fontana. He was born in Padua (Italy) ca. 1395 and died after 1454. After earning 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 was written between 1420 and 1449 and is now at the Bayerische StaatsBibliothek and can be read on line on the Munchener Digitale Bibliotek. In the book many interesting devices are described, generally by using a text in cipher; the drawings in the book demonstrate Fontana's considerable knowledge in hydraulics and mechanics. Figure 15.15 is a drawing of an automaton representing a witch (op. cit. folio 63 verso). This automaton, known as the blazing witch, can advance along an inclined rail and is controlled by a cable on a capstan. A spring permits the automaton to throw an arrow or an explosive bomb. The witch's body is articulated and can oscillate, move its head and its wings that are linked to the arms and the tail. A candle inside illuminates the automaton, which spits rockets out of its mouth and ears. On the right side of the figure is shown a hamper that shields the inner mechanism.

Fig. 15.15 Automaton by G. Fontana.

In Figure 15.16 (folio 59 verso, 60 recto) some details of the wings and legs joints of another of the Fontana's automaton are shown along with some lines of the text. The text, which 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 some similar 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.

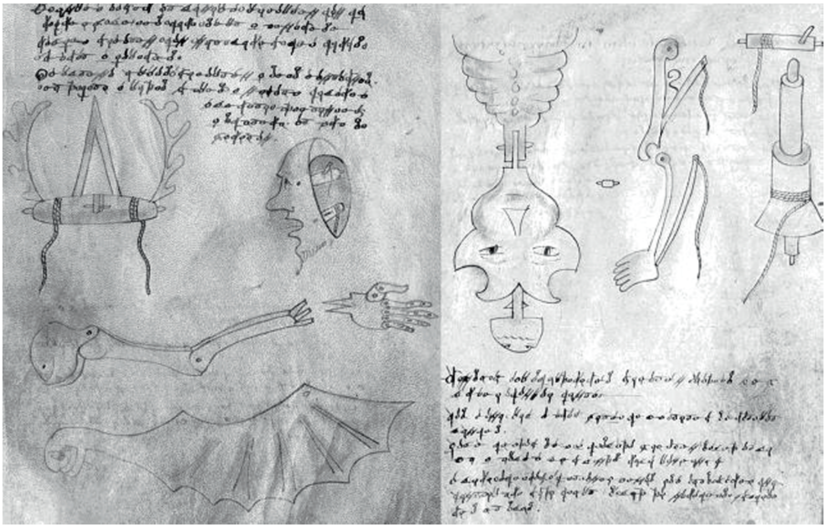

Fig. 15.16 Joints of Fontana's automata.

Figure 15.17 shows a drawing by Leonardo of a leg study (from Madrid Ms. I) and in Figure 15.18 a drawing interpreted as a study of elements of the robot.

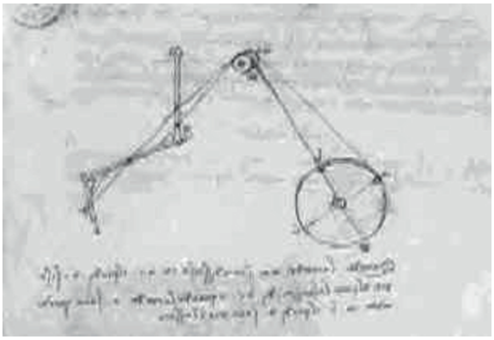

Fig. 15.17 Mechanical leg, study by Leonardo.

Another renowned mobile device by Leonardo is the mobile cart that has been recently reconstructed from his Atlantic Codex. Figure 15.19 reproduces the folio 812r. It must be observed that working reconstructions are very recent after many attempts that did not work. 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.

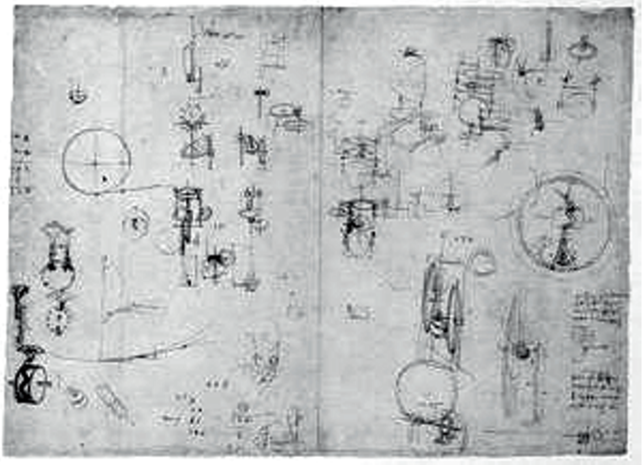

Fig. 15.18 Elements of a robot, drawn by Leonardo.

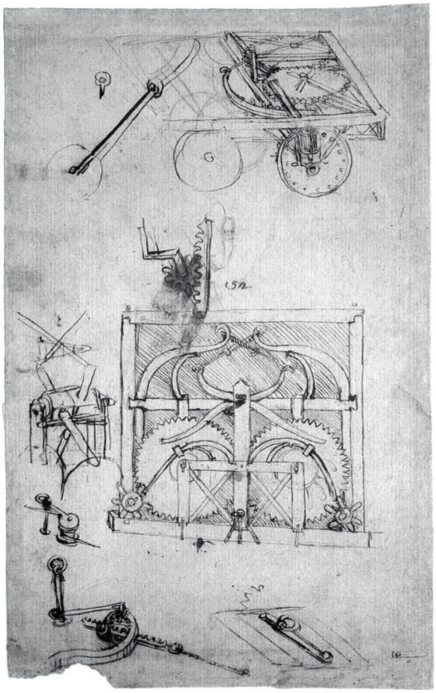

Fig. 15.19 Atlantic Codex f. 812r.

According to one chronicle, da Vinci built one (or two) walking lions in homage to Francis I, King of France. The lion walked for a number of steps and then opened its front part to reveal a bouquet of 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 of them are not available.

Another interesting device was designed by Parè Ambroise (Bourg-Hersent, Laval, 1509 – Paris 1590), a French surgeon who is considered as the father of modern surgery. He did not have an academic education and did not know Greek or Latin, hence he wrote in common French; this was an advantage because it helped the circulation of his treatises.

Parè Ambroise designed a number of prostheses that are described in his "Dix livres de chirurgie"; although to all intents and purposes they cannot be considered automata, they are very surprising because of their modernity. In Figure 15.20 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.

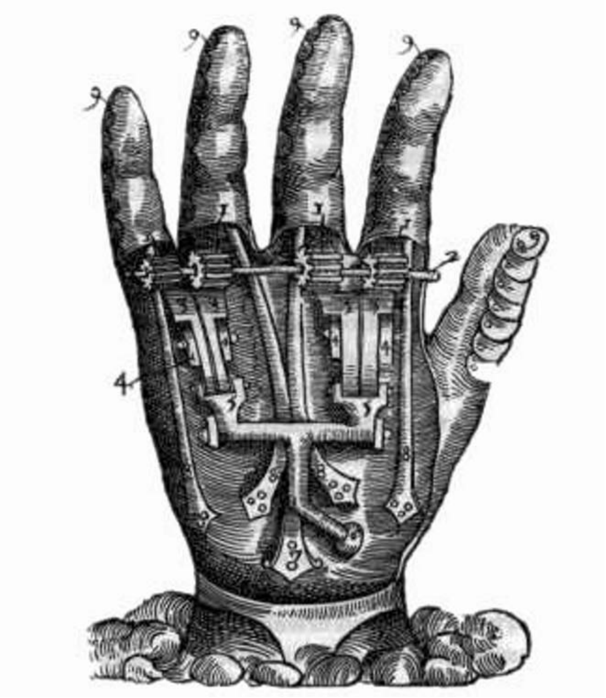

Fig. 15.20 Hand prosthesis by Parè Ambroise.

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 mechanical clocks were designed and many of them featured moving puppets. Up to the 17th century these devices were considered as automata. Among these clocks we can mention the famous tower clock in Venice. It was built from 1496 to 1499 by Gian Carlo Rainieri. The tower and clock are depicted in Figure 15.21.

Fig. 15.21 The tower of the clock in Venice.

From bottom to top we can observe 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) every hour moves on a rail line a procession of automata representing the characters of the Nativity and the Three Kings (Magi). Then the winged lion representing Saint Mark and Venice and, on the top, two automata. The latter are the famous “Mori di Venezia” and consist of two articulated bronze statues, 2.6 m high, representing two shepherds who, every hour, hit a large bell with a hammer.

15.4 The 18th century

In the 18th century, together with great progress in science, a great advancement of technology and crafts occurred; this also applied to clock making. This century also represents an ideal context in which mechanical wonders were developed to be shown in European courts and to be given as gifts for kings and emperors.

One of the most famous automata builders was Jacques de Vaucanson (Grenoble, 1709 – Paris, 1782) who is mentioned also in Chapter 13. Between 1737 and 1741 he built some automata, the most famous of which was the duck shown in Figures 15.22 and 15.23.

This automaton 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 automaton 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. A copy of the original automaton, made by Frederic Vidoni in 1998, can be seen at the Musée des Automates in Grenoble, France.

The duck is made of more than 1,000 pieces, in order to copy as best as possible the movements and functions of a living duck. The automaton actually moves, drinks and pecks at grains like a real duck.

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.

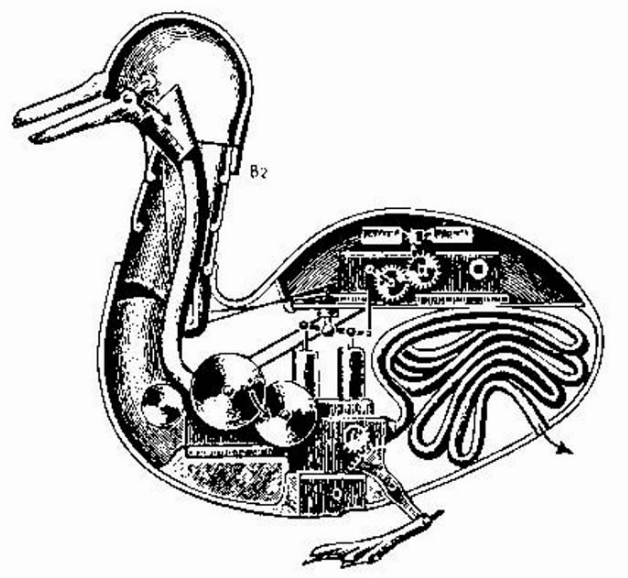

Fig. 15.22 Inside view of Vaucanson’s duck.

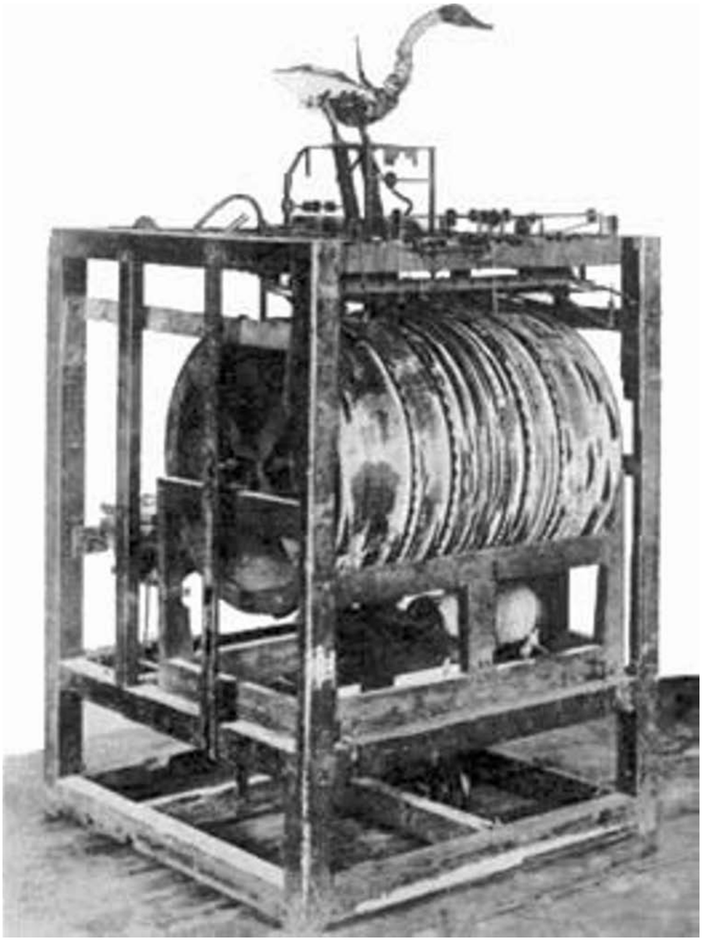

Fig. 15.23 Vaucanson's duck.

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, another observer 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 teethed cylinders as shown in Figure 15.22.

A few decades after the duck by Vaucanson, Pierre (1721–1790) and Henri-Louis (1752–1791) Jaquet Droz 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 Musèe 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 automata at the museum.

The three automata are shown in Figure 15.24.

Fig. 15.24 The automata by Jaquet Droz.

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 6,000 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 2,500 pieces and the draughtsman of 2,000 pieces. The musicist represents a young woman who can play different pieces on a real, little, keyboard. The draughtman 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 shown in Figure 15.25.

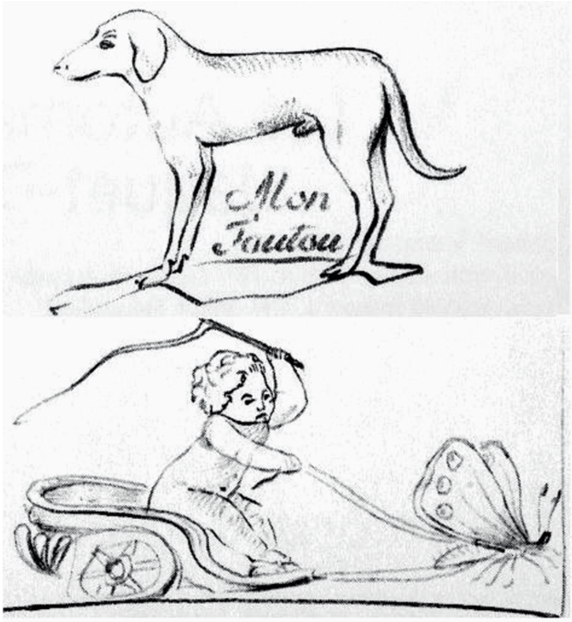

Fig. 15.25 Drawings by the Draughtsman.

Figure 15.26 is 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 reliefs that, when the wheel rotates, act on a rocker. Each relief corresponds to a certain letter or maneuvre. Above the wheel are visible three sets of cams that function as memory and activate the levers that move the automaton's hand in the three directions. Depending on the height of the reliefs, another lever moves vertically the three sets of cams.

Since all these automata could be used to make up different devices (although chosen from a restricted number of them) they truly represent the first examples of a 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.

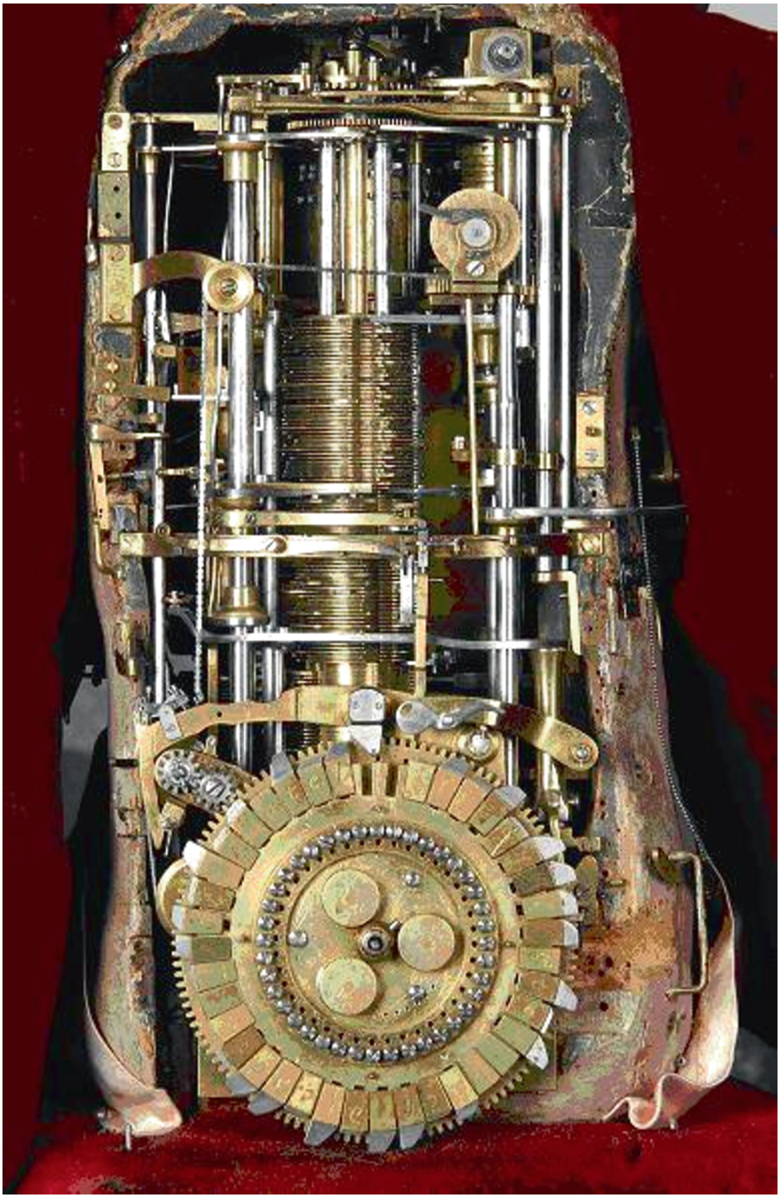

Fig. 15.26 Writer mechanism.

15.5 The 19th century

At the beginning of the 19th century, three Swiss brothers Jacques-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 Maillerdet" (Written by the Maillardet's Automaton), thus revealing its inventor.

The following figures of Maillardet automata are presented with the kind permission of the Franklin Institute of Philadelphia. In Figure 15.27 is shown the automaton.

Fig. 15.27 Maillardet's 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 Droz had their memories in their body, the one by Maillardet has a cams mechanism in a large chest at its base. In Figure 15.28 is a view of its mechanism.

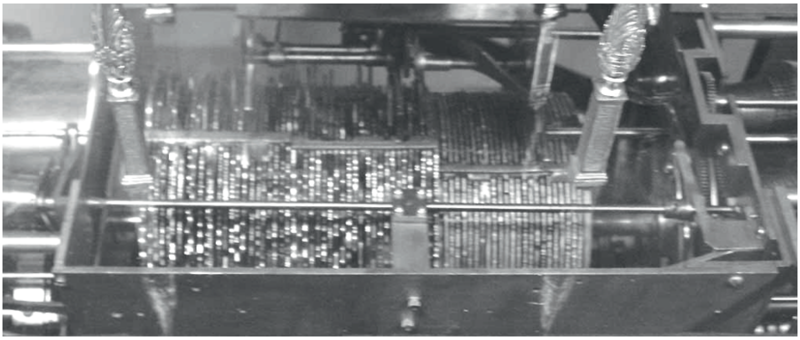

Fig. 15.28 Detail of the cams.

Figure 15.29 shows a drawing and a poem by the automaton.

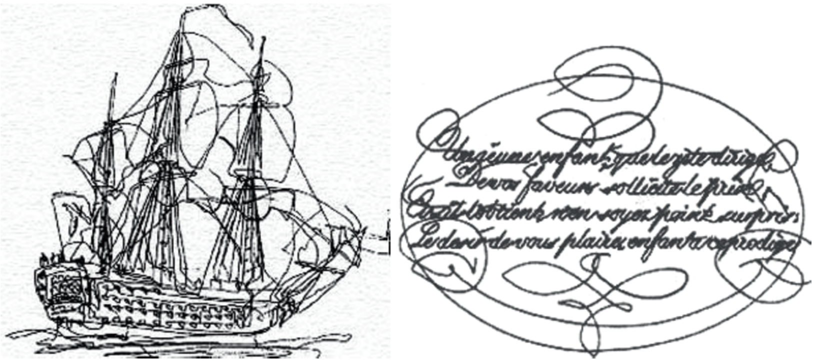

Fig. 15.29 A drawing and a poem by Maillardet's automaton.

As it can be observed, the quality both of the writing and the drawing is very high, especially if one considers that all of the marks are obtained by a cam.

With the industrial revolution the number of automata inventors rises but, generally, these automata are not so refined as the ones mentioned above. 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 their engineering and their fantasy. They seemed to be suspended between the real world and the land of dreams and they belonged to a time that has been irretrievably lost. In the following years many automata were designed or used by inventors or conjurers who were, in that age, very fashionable.

The steam engine had reached its maturity, which made it possible to make machines that were capable of making 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 who pulled a cart. The man was powered by a 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. Figure 15.30 shows a drawing of the U.S. patent 75874.

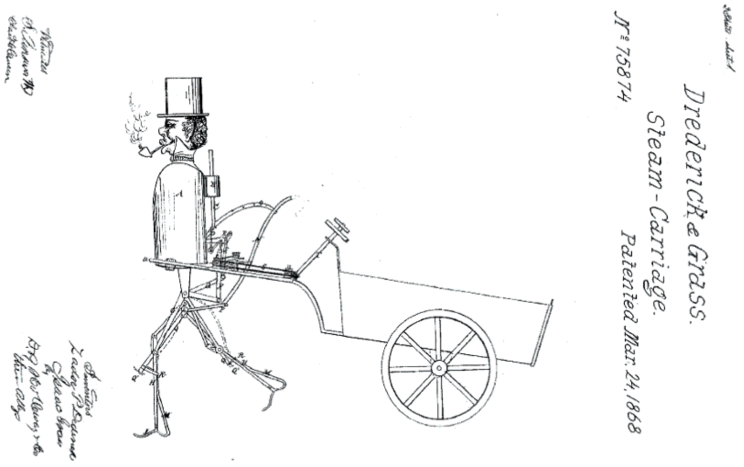

Fig. 15.30 Dederick's automaton, U.S. Patent 75874.

Dederick's automaton inspired a long series of fantasy stories about 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 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.

15.6 Automata of the Far East

Automata were built also in the far East, mainly in Japan, China and India. These automata generally consisted of 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 the 18th and 19th centuries. 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, one of which is shown in Figure 15.31, dressed and undressed to reveal the mechanism.

Fig. 15.31 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, their motor is a wound spring made of whalebone, and the actions are controlled by a set of cams and levers.

15.7 Between the 2 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 was made possible by the advent of the modern computer and by the evolution of electronic components that began in the late 1940s.

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) and defines a robot as: "A re-programmable multi-functional 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 both built by Honda, those built by Toyota, Sony and Fujitzu, and the doggy AIBO built by Sony.

In Figure 15.32 are shown the P3 and ASIMO. Both look like astronauts; P3 is 1.60 m tall, can walk (about 2 km/h) keeping its balance on its legs, accomplish some tasks with its arms and hands and even go up and down stairs. All its limbs have the same joints as 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 recently the main function of these machines has been to serve as demonstrators of technological developments; from this point of view, although they differ in many aspects from ancient automata, humanoid robots could be considered as their most recent evolution.

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** (also written E2PROM and pronounced e-e-prom or simply e-squared, which stands for Electrically Erasable Programmable Read-Only Memory) that is programmable by means of a PC. Therefore, the ubiquity and low cost of electronic components permit many people, nowadays, to build what we can call "grand-nephews" of the 18th century's automata. However, it has to be said that these modern toys have neither their mechanical perfection nor their fashion.

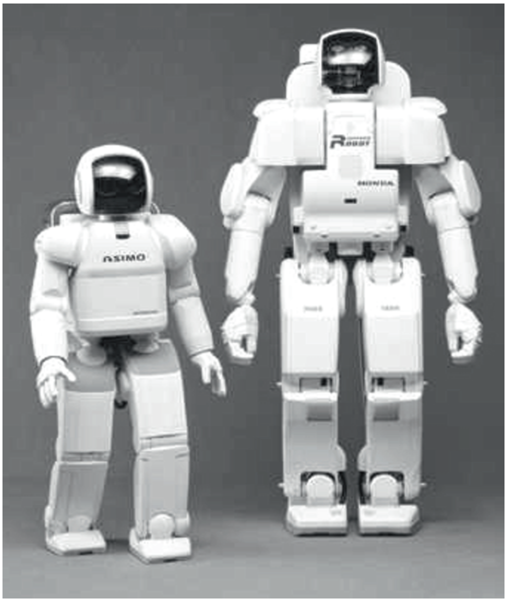

Fig. 15.32 ASIMO and P3.

Observations

Whether the ancient automata were ancestors of 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 servo-motors and the motion of each of them is independent of the motion of the others; hence it is a multidegree 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, to all intents and purposes, the ancestors of modern robots.

From a conceptual point of view, we observe that modern robots are designed and built for practical utility purposes; generally they are used to substitute for or to improve efficiency of manual labour in all those fields in which this substitution is useful. Automata, instead, have traditionally been 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 motivation was the yen to fulfil a desire of their own, to surprise even themselves and, perhaps also to pursue a dream. Thus it is perhaps mainly from this conceptual point of view that automata cannot be the ancestors of industrial robots. Whatever the case, it seems to be meaningful that the automaton's age ends quite completely at the beginning of the 19th century.

The authors feel it necessary to remember that in past centuries there were many scientists/engineers/craftsmen whose mechanical knowledge was much more advanced than one would 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; while admitting the excess, we embrace the thought.

Part VI – ANCIENT BUILDING TECHNIQUES

In the previous parts we have mainly considered machines, devices and systems as inventions. From a wider point of view, however, some building techniques and criteria are also inventions. For this reason, in this last part, some of these building techniques and criteria are presented; they were adopted during a period of time ranging from the prehistoric age to the Roman era.

Building techniques have changed considerably over time and often were adopted, in different areas, depending on what kind of building materials were available there.

In the following, some of the techniques adopted in antiquity are briefly mentioned and referred to by 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 according to their primary material: stone buildings and concrete buildings.

Stone buildings

We refer here to buildings is made of a number of stones that have been put together without using any mortar. (Mortar 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.)

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 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 as will be discussed in Chapter 16.

Opus quadratum

This word can be translated into English as “squared work”; it essentially consists of a number of squared stone blocks, having all the same height and set in parallel rows without using any mortar.

Examples of stone buildings are shown in Figure VI.1: opus poligonalis on the left and opus quadratum on the right.

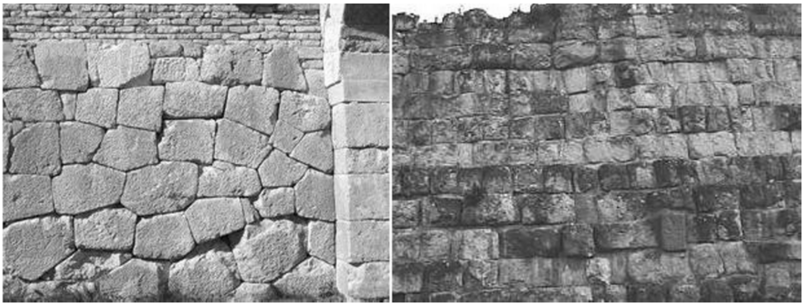

Fig. VI.1 Examples of stone walls: Opus poligonalis and opus quadratum.

Concrete buildings

The invention of a binder for building materials represented a very important innovation in building techniques: a binder permitted one 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 materials that were used by the Romans were: gypsum ($CaSO_4·½H_2O$), lime (hydrated lime ($Ca(OH)_2$) and a volcanic dust widely known as “pozzolana”. The latter was the best one and its performances are comparable to those of Portland cement.

Opus caementitium

This term, which 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 simply consists of 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.

Opus incertum

This technique essentially consists of randomly 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 (1.34–1.68 kg/m^3) and whose color is often light yellow or, sometimes, light gray with darker areas.

Opus quasi reticulatum

This technique is halfway 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.

Opus reticulatum

This term can be translated into English as “reticulated work”; it describes a building technique that consists of a number of rather small bricks, all equal in size and having the shape of a perfect square (called cublia), placed so that their sides are inclined by 45° with 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 Figure VI.2 we show some examples of Roman concrete building techniques; from above to below and from left to right: opus cementitium, incertum, quasi reticulatum, reticulatum.

Opus latericium

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 consisted of coarse laid clay bricks cemented by a binder. Sometimes these walls represented the face of a core made by opus caementitium.

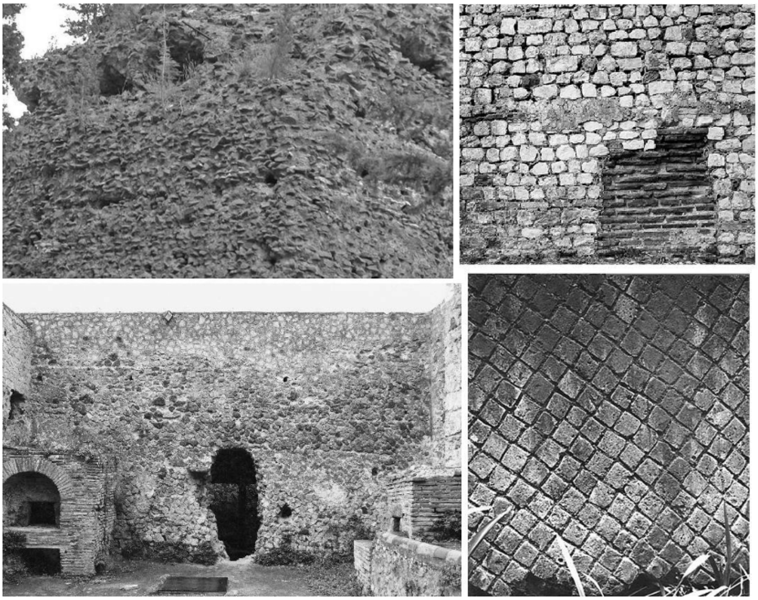

Fig. VI.2 Examples of Roman opera caementitia: cementitium, incertum, quasi reticulatum and reticulatum.

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 of bricks or cut stones disposed in herringbone shape.

Opus mixtum

This term can be translated into English as “mixed work” and indicates a building technique that consists of a mix between opus reticulatus and opus latericium: 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.

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 of rows of bricks alternated with small tuff blocks.

In Figure VI.3 are shown some examples of Roman concrete building techniques; from above to below and from left to right: opus latericium, spicatum, mixtum and vittatum.

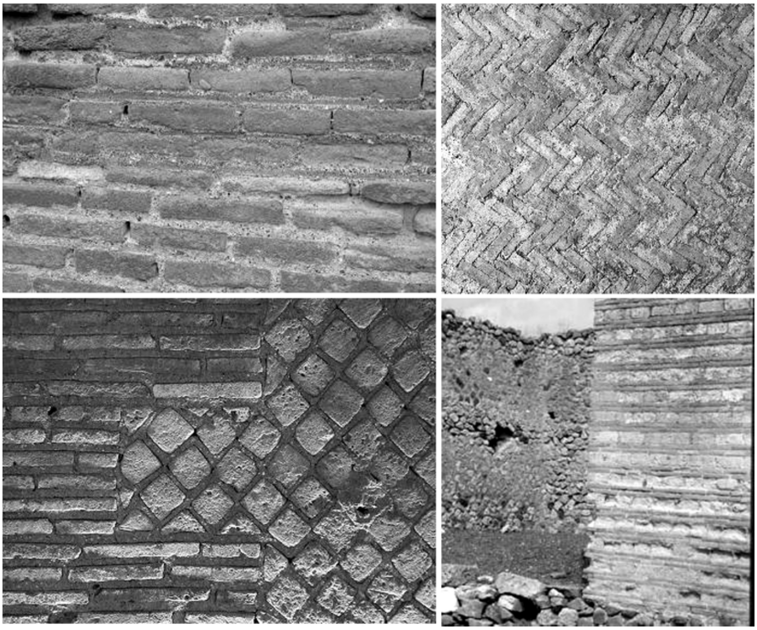

Fig. VI.3 Examples of Roman opera caementitia: latericium, spicatum, mixtum and vittatum.

Chapter 16 – CONSIDERATIONS ON SOME ANCIENT BUILDING TECHNIQUES

Introduction

This last chapter is dedicated to the building techniques and criteria that were adopted during a period of time ranging from the prehistoric age to the Roman era.

The examples reported in this chapter mainly (but not only) pertain to archaeological finds in Italy but are, in most cases, of general interest.

16.1 Polygonal work

Polygonal work is a building technique used in early Italic fortifications. This technique, at least during the first 4 centuries, was 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 to express 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.

C. Rossi et al., *Ancient Engineers’ Inventions: Precursors of the Present*,
History of Mechanism and Machine Science 8, 309–325.

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 2nd millennium B.C. and the 15th century A.D. 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 be 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

16.1.1 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 was Gerhard

(Gerhard, 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 constructions 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 were 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, 1938) 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 at 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 century 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 highlights 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 6th–5th centuries BC, basically contemporaneous with the proliferation of these fortifications. Although it chronologically reiterated the indirect Mycenaean influence due to the presence of an 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 *manners* 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:

“1st 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 6th...” (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
Siculians: Termini Imerese

"2nd 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 parallelpipedal 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 Olympia 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

“3rd 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 ones that one 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
Siculians: Cefalù

“4th 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 16.1 illustrates some examples of the four manners (Lugli) of the polygonal works.

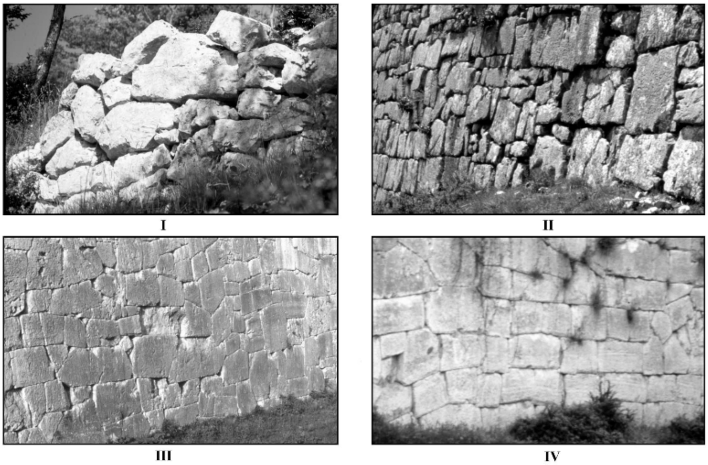

Fig. 16.1 The four manners of the polygonal works.

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 *anathyrosis*. 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

16.1.2 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, Siculians 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 in contact with the surfaces 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 an 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.

16.2 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 1 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 the same properties as cement, and if inert substances are added, such as sand and gravel of different sizes, 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 (SiO_2) and aluminium oxide (Al_2O_3) in physical conditions such that, in the presence of water, they may react even at room temperature with calcium hydroxide ($Ca(OH)_2$), leading to the formation of silicates and aluminate 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 or if square, opus reticulatum; with facings in brick it was called opus latericium. 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 satisfactory resolved, thanks to the introduction of courses of “bipedal” (brick 2 ft 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 was used, one of the first great applications of opus latericium 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 A.D.)...” (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 opera incertum or 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 2nd century 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 (Toinbee, 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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