Chapter 2
Chinese Inventions and Machines

For over 2,000 years Chinese society was pre-eminent in technological development. It was only at the beginning of the fifteenth century that it began to decline and was passed by Europe. Its technology began with agricultural, textile, and war machines; it was enhanced with hydraulic machines; and it was completed with the ingenious clocks and automatons that were built while the rest of the world was just waking up.

One of the first Chinese books on technology and craft dates from the Zhou Dynasty (770–221 BC): the “Kao Gong Ji” or “The Book of Diverse Arts”, by an unknown author. It contains the knowledge gathered up to that time concerning astronomy, biology, mathematics, physics and engineering. Since then, Chinese technological development has constantly evolved with the help of explanations that were included in texts on manufacturing weapons, bells, dyeing processes, and irrigation devices.

Around the year 1040, Zeng Gongliang and Ding Du wrote the “Wu Jing Zong Yao”. This book is a collection of the most important military techniques of the time and it includes 160 diagrams of machines. Among these diagrams are some catapults that have evolved considerably as compared to the first ancient models.

Regarding hydraulic engineering, the golden age can be identified somewhen between the tenth and fourteenth centuries. There are some books that particularly mark this evolution: the “Meng Xi Bi Tan” (“The Dream Swimming-pool”, 1086) by Shen Kuo; the “Xin Yi Xiang Fa Yao” (“New Design for an Armillary Sphere and a Celestial Globe”, 1089) by Su Song, and the “Nong Shu” (“Agricultural Treatise”, 1313) by Wang Zhen. The last one is outstanding for the quality of its almost 300 diagrams and illustrations of the tools and machines for agriculture. Later, other titles can be found relating to a compendium of agricultural machinery such as the “Nung Cheng Chüan Shu” (“Complete Agricultural Treatise”, 1628) by Hsü Luang-Chi.

These books deal at most with milling and water raising machinery, ranging from hand-operated mortars and crank-operated stone milling machines to crank winches for cranes. It was not until the seventeenth century that that all those machines were listed in the “Thien Kung Khau Wu” (“Exploring the Works of Nature”, 1637).

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In textile engineering, the book entitled “Keng Chih Thu” (“Drawings of Ploughing and Weaving”, 1149) is an example of the great developments that was reached in silk manufacturing.

Chinese influence in surrounding countries was reflected at all levels, both scientific and cultural. An excellent example in the machinery field is the Japanese tea-serving automaton where the mechanics and assembly precision somehow overcame Chinese techniques.

With a few exceptions, there was no custom in Chinese culture of providing texts with drawings even though they dealt with technical matters. However, this changed due to the influence of European culture through the first Jesuit missionaries who tried not only to convert the Chinese people to Christianity but also to set Chinese culture towards European standards. Regarding machine techniques, European books dealt both with practice, like G. Böckler’s “Theatrum Machinarum”, and theory, like Guidobaldo del Monte’s “Mechanicorum liber” and Galileo’s “Le mecaniche”. At the same time, they attempted to understand the Chinese machines with the same vision. Since the influence of the Jesuits, Chinese experts learnt to draw machines in order to show technical features.

This is why many ancient books have no drawings of described machines and illustrations are included from later editions that were produced in the seventeenth and eighteenth centuries.

On War Machines

One of the first known Chinese inventions is the catapult. Little is known about its origins but it was based on the principal of the lever (Fig. 2.1) that was already used for raising water from wells or channels into canals. The mechanism looks very like that of the Shadoof used by the Arabs (Chapter 4).

The Chinese army dominated its rivals for millennia thanks to its superiority in weaponry. It was able to expand its territories by means of rapid growth and control that were based on military supremacy and its geographical borders stretched from Tibet to the Pacific Ocean. Chinese technology not only evolved due to its engineers’ brilliant minds but also because of a need to be superior to its neighbouring enemies.

The catapult was a basic element in ancient wars and the first known written reference to it is in the Mohist texts from the Period of the Warring States (fifth to third century BC). These texts describe the first version of what was later to be identified as a human powered catapult. These catapults were used to defend city walls by launching burning coals and logs or bottles of poison gas against the enemy.

Figure 2.2 illustrates the so-called “Whirlwind” catapult. This was a rotary catapult almost 2 m high that required the power of two men for an efficient launch based on the rotation of a horizontal shaft which drove an upright shaft and the projectile. For greater effectiveness, a series of catapults set in a row were used to launch more projectiles in less time.

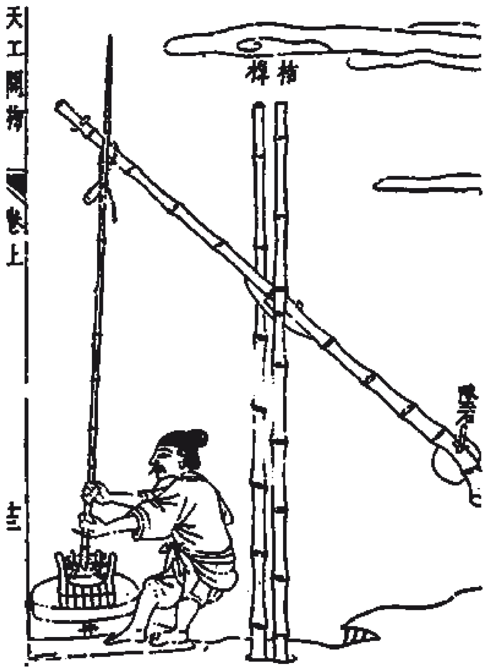

Fig. 2.1 Counterweighted lever used by farmers for obtaining water [86]

There are different types of catapults, namely the "trebuchets", tension catapults, and torsion catapults.

The "trebuchets" were based on the lever principle, the extremity of which was a counterweight to generate the force needed to launch the projectile over a long distance with a design similar to those shown in European sketches from the time of the Middle Ages (Chapter 4).

The so-called tension catapults stored energy by tensing a bow of wood. Torsion catapults took their energy from the spin of skeins of rope or tendons, while traction catapults were powered by human efforts. Examples are given in Fig. 2.2.

The illustrations in Fig. 2.3 show mobile catapults on wheels. The first illustration consists of an attack catapult which was used to launch or lift men. The operation power is obtained by human soldiers.

The second illustration in Fig. 2.3 shows the use of the kinetic energy that is accumulated by displacing the carriage. It was a heavy catapult that was developed at the same time as medium-range catapults known as "Hudun" (crouching tiger) or Xuanfeng light catapults. Large pebbles, animals, or grenades that exploded when launched were used as projectiles. It is believed that there were approximately 5,000 catapults in China around the year 1120 AD. This gives an idea of the use and need for this type of machine.

Another Chinese invention was the crossbow. It was used for the first time in 321 BC during the battle of Ma-Ling, although some scholars think that it was invented a

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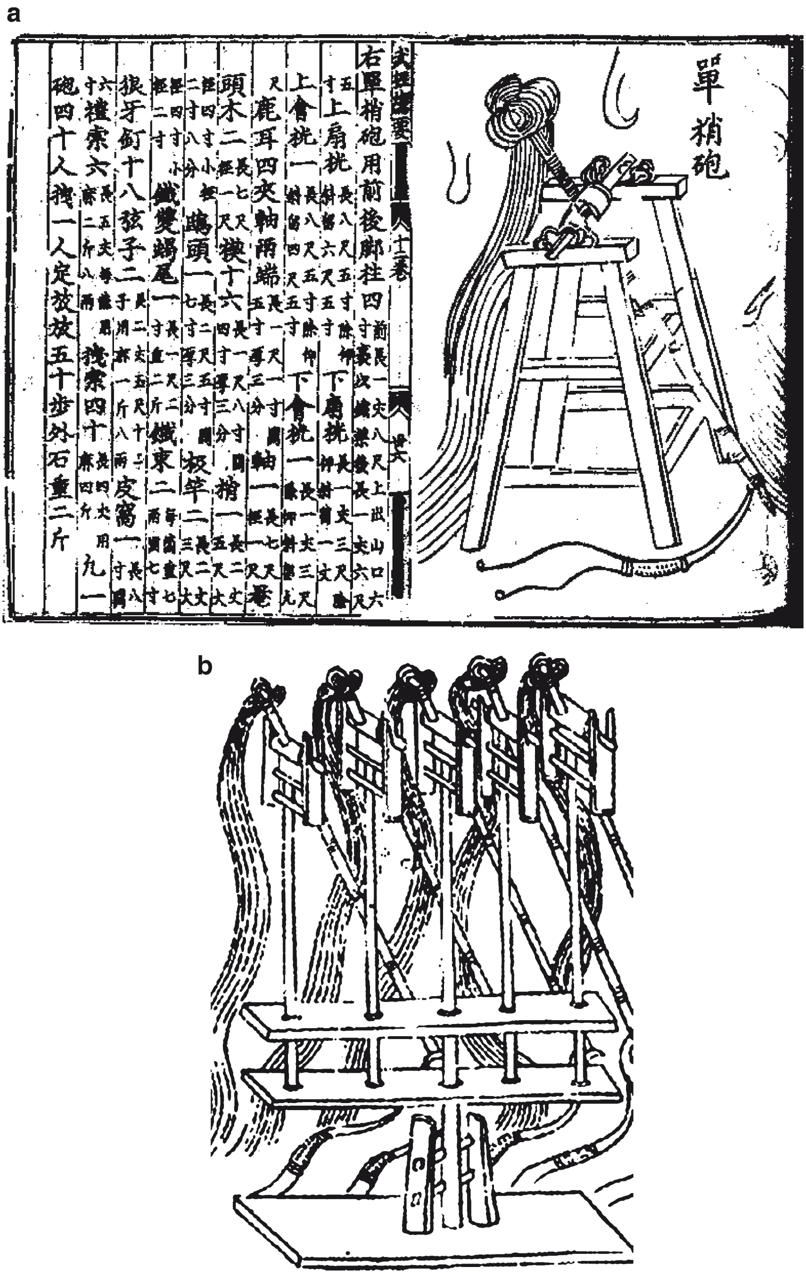

Fig. 2.2 A catapult and a battery of catapults [53]

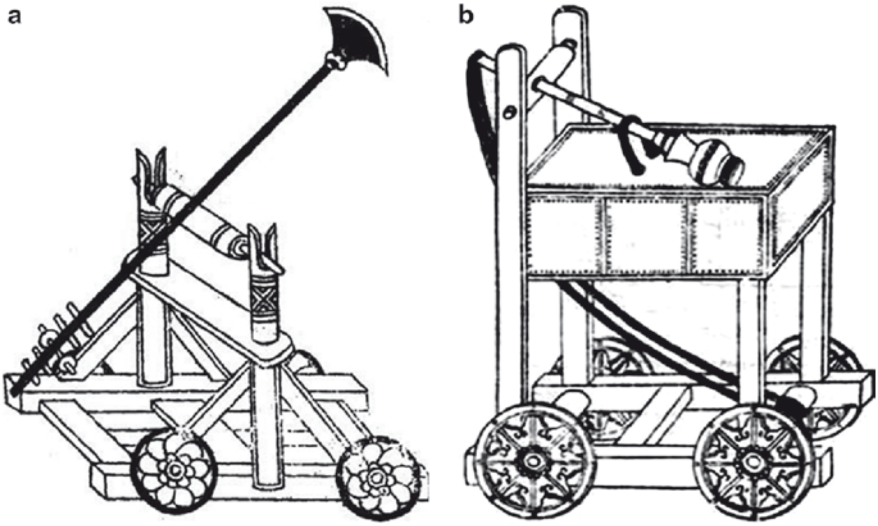

Fig. 2.3 An attack vehicle and a catapult [53]

in the seventh century BC. The crossbow evolved from the conventional bow and was widely used until gunpowder appeared on the scene, as another Chinese invention.

The crossbow consists of a horizontal bow and a release mechanism whose aim is to keep the arrow in place while the bow is tensed. When the release mechanism is triggered, the energy stored by the tension in a string is transmitted to the arrow which is launched with that energy. Usually, these crossbows had a longer reach than normal bows so that they were more effective than convention bows during battles.

Figure 2.4 shows a triple crossbow with a system for positioning it at a desired height for firing.

Summarizing, the described war machines involved the development of mechanisms for an efficient use of human energy. A lever enabled the multiplication of the launching speed. Both the heavy carriage and crossbow are based on the principle of energy accumulation (in inertial or elastic form according to the reported examples), which is released instantaneously on launching command.

On Textile Machinery

The manually operated distaff was the original concept for designing machines with three, five, and even ten spindles. Thus, efficiency of the manufacturing process increased so much that it was possible to supply all the population with clothes. This development gave an impulse to the textile industry and then to the country's

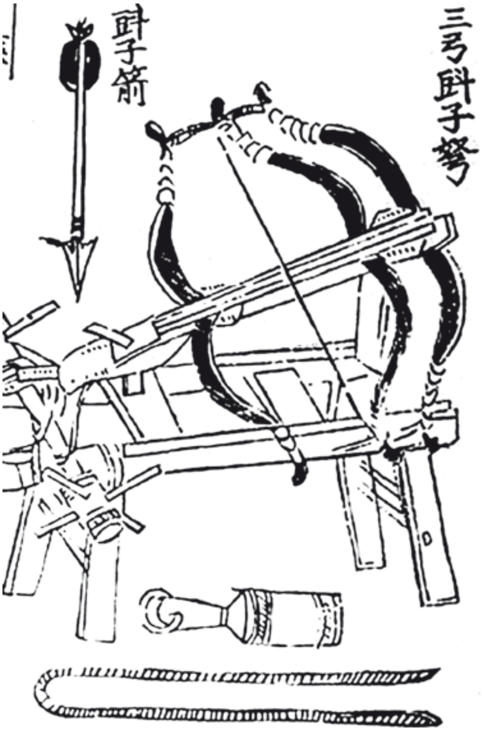

Fig. 2.4 Triple crossbow [86]

economy that lasted for more than four centuries during the Song (960–1279) and Yuan (1271–1365) dynasties. But since Antiquity, silk clothes were exported to the Roman Empire.

The textile machine in Fig. 2.5 was invented before the Christian era. Proof of its existence is due to its definition in a book entitled "Dictionary of Local Expressions" that was published in China in the year 15 BC. This machine was used mainly in the silk industry since it guides the silk threads to spools that are used by weavers. The mechanism is a multiple winder that is driven by a belt between the pulleys at each end. At one side, spindle shafts are operated by friction action. In addition, the shaft of a small pulley is operated with the aim of transmitting the movement to the shaft of the reels by means of another crossed-pulley system that permits a right-angle joint and, at the same time, a proper relationship between the rotations of the winder and spindles.

The design of this type of machine, together with similar spinning machines, can be compared to the first developments in textile machinery that appeared during the Industrial Revolution. The design in Fig. 2.5 shows a considerable similarity with Figs. 7.1 and 7.2 in Chapter 7, which illustrate machines that were supposed to be an "innovation", but 2,000 years later.

The powerful Chinese textile industry was forced to seek new energy sources as an alternative to human power, by giving important impetus to hydraulic power.

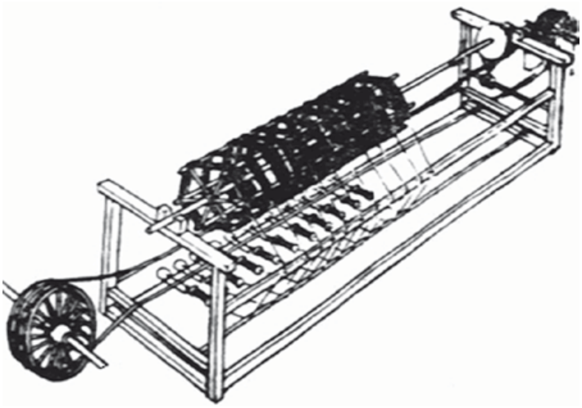

Fig. 2.5 A multiple winder

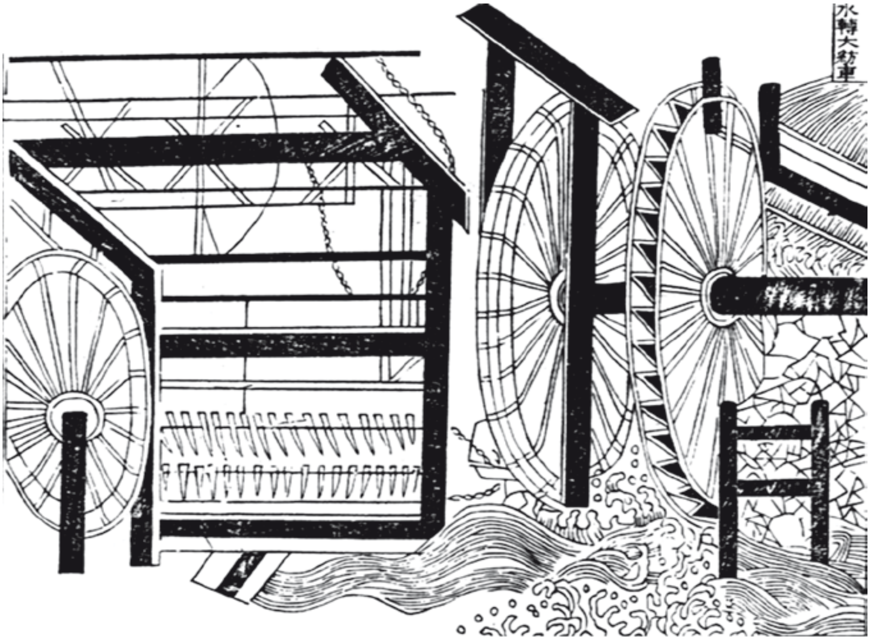

Fig. 2.6 Water mill power station for textile weaving (From the Nong Shu [86,141])

Figure 2.6 shows hydraulic power for operating a textile weaving machine as a means of increasing cloth production. By using hydraulic machines as power sources for the textile industry, China advanced with respect to other cultures that do not use the same process, until several centuries later.

On Hydraulic Machinery

In all cultures, hydraulic machinery is linked to irrigation for agriculture. The mechanism in Fig. 2.7 (possibly dating from the first century BC), consisted of a chain of buckets that is operated by a horizontal shaft through pedals attached to it. By observing the figure, it can be seen that the pedals were used by two men to rotate the shaft which is attached to a horizontal bar in the main frame of the machine. This action activates the wheel that moves the buckets which raise not only water but also sand or earth as required. The machine's performance depended very much on the perfection of its construction and the watertight solution by which water loss from leakage could be limited. Because of its efficiency, it is believed that this machine was capable of raising water to more than 4.5 m.

This invention spread throughout China thanks to its great utility and from there to the rest of the world centuries later. Since then, the variety of water wheels increased and different models were produced, made either of wood or bamboo (Fig. 2.8).

Figure 2.9 shows an important evolution. Besides a more refined and effective construction technique for transmitting movement, water energy has replaced

Fig. 2.7 Chain water elevator (From the Thien Kung Khai Wu [86])

Fig. 2.8 Bamboo water wheel (From the Nong Shu [86,141])

human power as the actuating source. This "water wheel for heavy weights", as it is called in Chinese books, made its first appearance in the book "The Nong Shu". On the other hand, the chain in Fig. 2.9 has several differences: instead of having bamboo buckets attached to the water wheel, they are fixed to each other by a rope, and the chain moves around the wheel where the bottom one is driven by the water and the upper one is used to realise the water.

Curiously, one of the most often-mentioned machines in ancient Chinese books is the drop-hammer water-driven machine. It was used to crush minerals or thrash seeds, and even in the metallurgy industry. The three figures (Figs. 2.10–2.12) show the changes from the twelfth to the seventeenth century. The first image of a hammer is as a man-operated tool (Fig. 2.10). But, because of its usefulness, it soon became necessary to operate it by hydraulic wheels. The first evolution can be observed in Fig. 2.10 where operation is not by hand but by foot. This gives a larger force for the operation and lets the operator's hands free to work. To produce the up and down movement, a hammer was attached to a perpendicular shaft that could rotate when supported by an upright structure.

Figures 2.11 and 2.12 show two models of water turbines that are used to operate a shaft with radial tongues that act as cam elements transmitting movement to

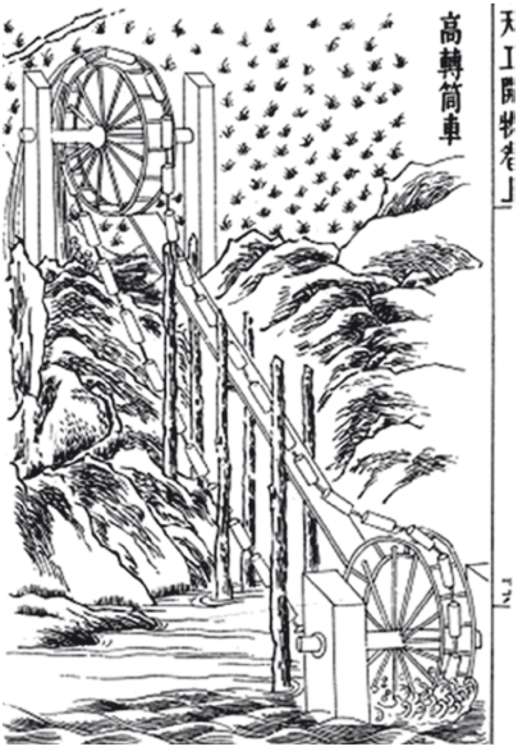

Fig. 2.9 Water wheel for heavy weights (From the Thien Kung Khai Wu [86])

several in-parallel hammers which, by falling down under gravity, give the desired blows in a synchronized, continuous operation.

Although the last two machines perform the same function, there is an important innovation differentiating them. While in Fig. 2.12 the waterwheel buckets are simple paddles that are installed perpendicular to the outer rings, the paddles in the hydraulic turbines in Fig. 2.11 are designed to optimise the hydraulic drive. With a difference of three centuries between Figs. 2.11 and 2.12, it is strange that the more modern one is less hydraulically efficient than the first one. Maybe the latter drawing was sketched simply to point out the mechanism itself rather than to show a detailed drawing of the water-wheel design. A machine that is referred to almost as often as the drop hammer in ancient Chinese books is the mill as a necessary instrument in everyday life for providing food.

In the mill in Fig. 2.13 there is a single millwheel that is operated by the lower horizontal turbine, which exploits the flow of water. It can be noted that two rings with paddles are used inside and outside the turbine in order to increase the efficiency with a simplified blade shape.

In order to ensure proper machine operation, a common practice was to fix the upright shaft to the ground rock by using cast iron as a cover for the hole.

Fig. 2.10 Foot-operated hammer (From the Kêng Chih Thu [86])

This can be considered as proof of the considerable knowledge that the Chinese machinists had about materials and their properties in the thirteenth century.

Similarly to previous examples, the Chinese tried to multiply the output of a machine with a single actuation. An initial solution was the use of animal power, as shown in Fig. 2.14 for the case in a mill with eight millwheels that are operated by gearwheels. Some time after, the machine evolved and animals were replaced by a vertical turbine (Fig. 2.15).

The machine consisted of nine horizontal gearwheels and three vertical ones that are connected to the shaft of the hydraulic turbine. When the shaft turned, the vertical wheels also turned and generated the movement of the horizontal gearwheels so that the nine wheels turned at the same time. Compared to the mill in Fig. 2.13 a single hydraulic turbine operated nine millstones.

Another usual practice was to use a hydraulic turbine not only as a means of driving mills but also as a waterwheel to raise water and therefore to make the work twice as useful. It is known that around the year 1100 AD there were more than 250 tea mills. This gives an idea of how necessary this type of machine was and the reason behind the efforts to increase its output.

The knowledge of materials in Chinese society has already been mentioned, but among all the materials, metals were the most worked and studied. Specific machines were designed from the year 30 BC, like the one in Fig. 2.16. In this illustration,

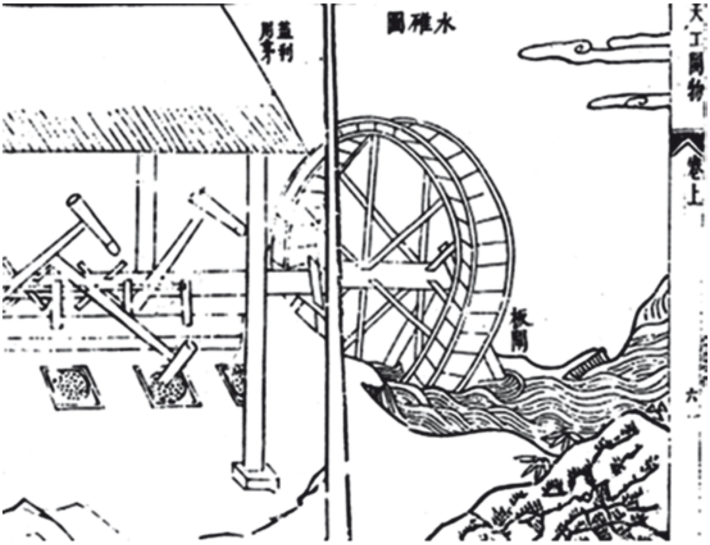

Fig. 2.11 Hydraulic drop hammer (From the Nong Shu [86,141])

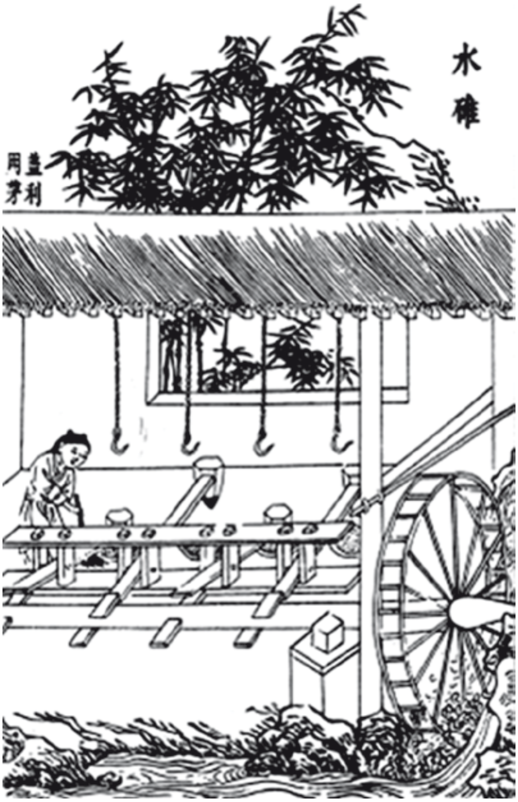

Fig. 2.12 Hydraulic drop hammer (From Thien Kung Khai Wu [86])

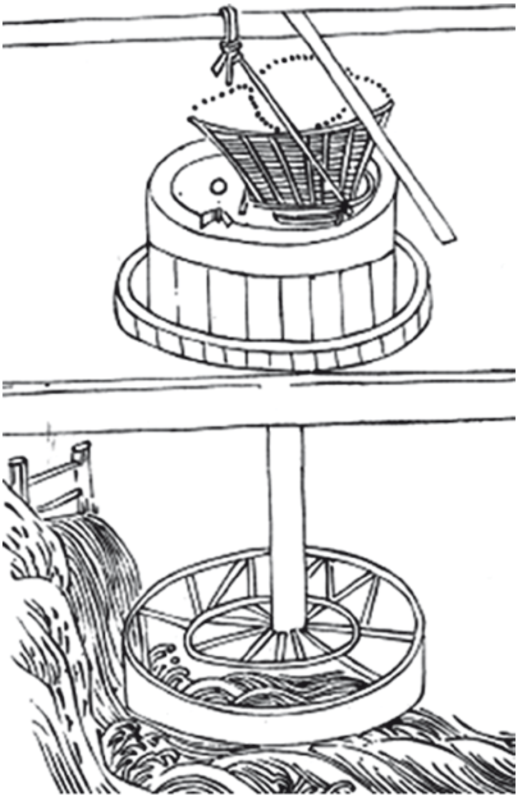

Fig. 2.13 Horizontal corn mill wheel (From the Nong Shu [86,141])

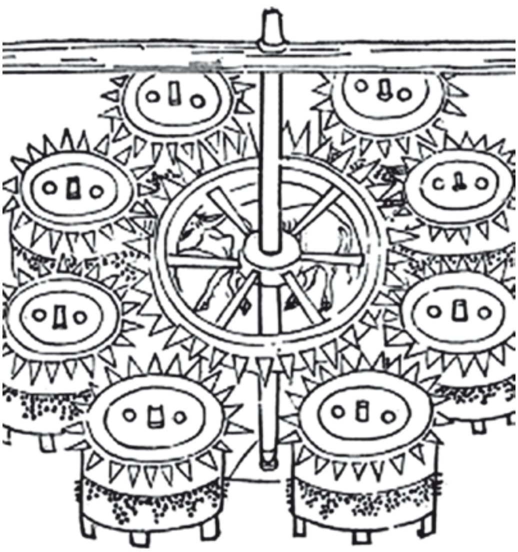

Fig. 2.14 Mill with eight wheels (From the Nong Shu [86,141])

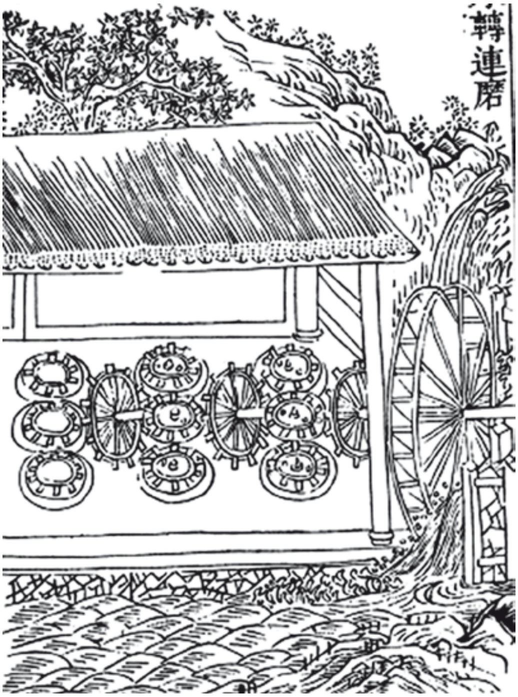

Fig. 2.15 Nine mills (From the Thien Kung Khai Wu [86])

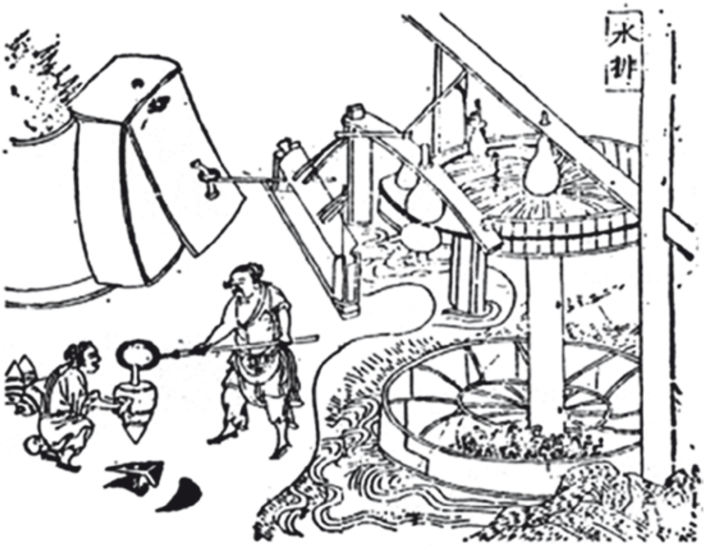

Fig. 2.16 Alternating motion generator (From Nong Shu [86,141])

the rotation of the waterwheel generates an alternating movement of bellows that maintain the fire by means of a beam operated by a horizontal cam. Remarkable are the double wheel and warped paddles that appear in the hydraulic turbine.

On Clocks and Automatons

One example of progress that was much beyond the comprehension of the rest of the world is “the south-pointing chariot” (“Chih nan chhê”) that was built between 2600–1100 BC. The first written reference to it is found in a paragraph of “Sung Shu” (“History of the Sung Dynasty”) by Shen Yueh in 500 AD: “The south-pointing chariot was first built by the Duke of Chou (first millennium before Christ) as a sure means of pointing the way home to those who had to return from a great distance beyond the borders”.

It is also known that the workers who collected jade used it to get their orientation (Fig. 2.17). It was used for centuries in ceremonies of emperor worship since many emperors ordered its construction as a demonstration of their power. Its complex structure is shown in Figs. 2.18 and 2.19. It is composed of a series of gears

Fig. 2.17 Drawing of the “south-pointing chariot” (From the San Tshai Thu Hui [86])

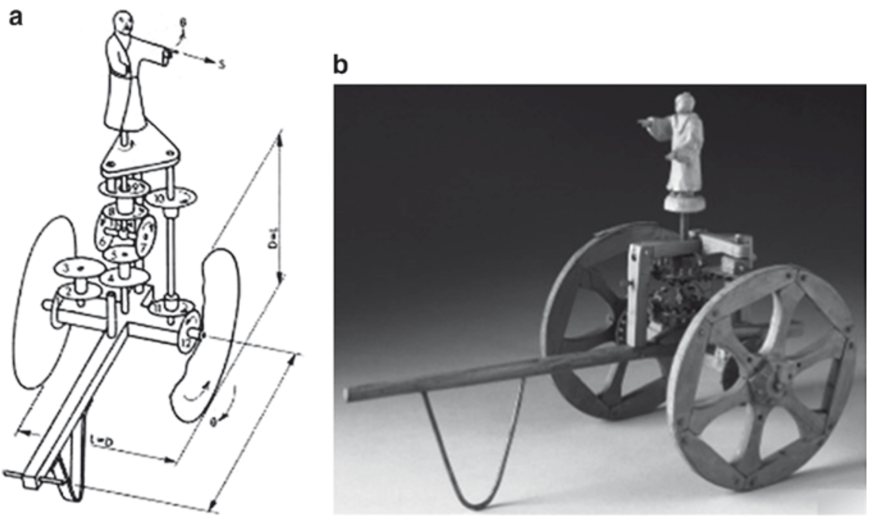

Fig. 2.18 South-pointing chariot: (**a**) a drawing, (**b**) a reproduction

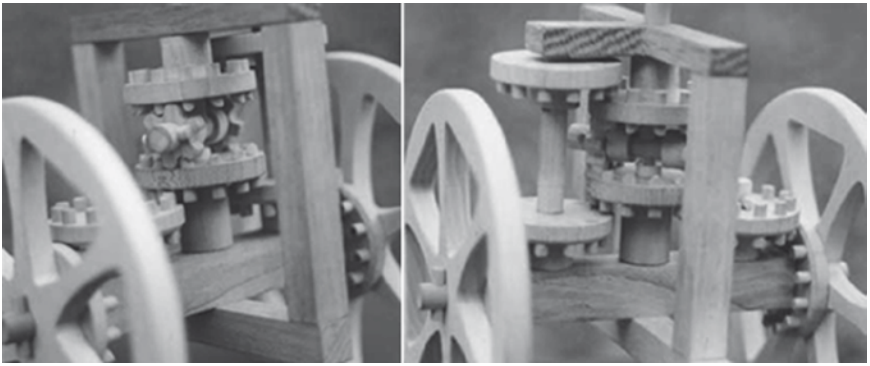

Fig. 2.19 Gears of the south-pointing chariot

and gearwheels that always kept the figure's finger pointing south. The shape of these gears or the assembly has never been fully explained in any past writings, but it is believed they could have been as in Fig. 2.18a. This solution involves gearwheels for each chariot wheel that is connected to a differential gear train, which locates the figure on top. Figure 2.19 shows details of the mechanical assembly.

Its operation works like a differential gear assembly. If the chariot moves along a straight line, the figure shaft does not to rotate. If the chariot turns, the wheels have different rotation speeds, which causes the upright shaft to rotate and thus the figure shaft rotates with it.

Much later, Su Song amazed the country by building an astronomical clock whose a reference is reported in his book, “Xin Yi Xiang Fa Yao”. (AD 1089) (Fig. 2.20).

The clock took 4 years to be built and was completed in 1089 AD. The tower was between 10 and 12 m high. As a result of the mechanisms housed in its interior, various figurines appeared indicating the hours as well as beating drums and striking gongs while the movement of a celestial globe showed the stars and the constellations.

The clock’s accuracy, less than a daily error of 100 of a second, was achieved by keeping the water in a tank at a constant level and this water operated the vertical wheel.

Figure 2.20 shows how the clock was made up of three levels. The upper level housed the armillary sphere (Fig. 2.21) representing the “the great circles of the heavens”. This armillary sphere enabled astronomers to see the position of the stars around the Sun or the Earth. The sphere was composed of 12 rings in three layers with each of the rings marked on a different scale. Due to this layout, the positions of the 24 solar periods could be read directly and a planet or star could be located by looking through a tube.

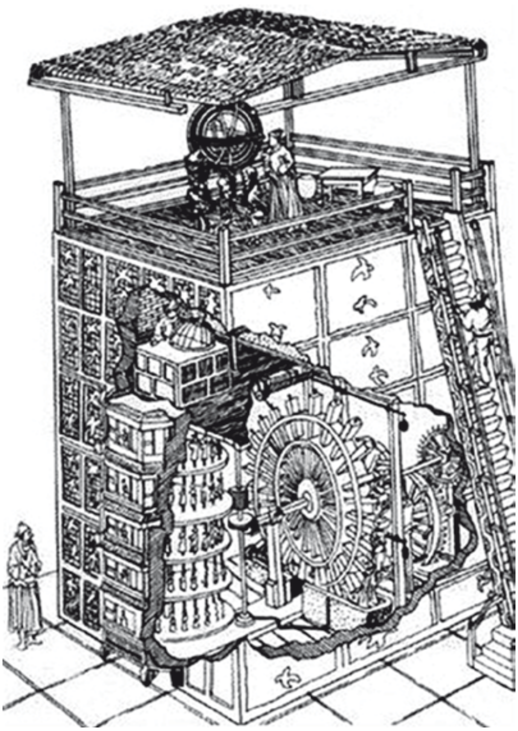

Fig. 2.20 Su Song’s astronomical clock [128]

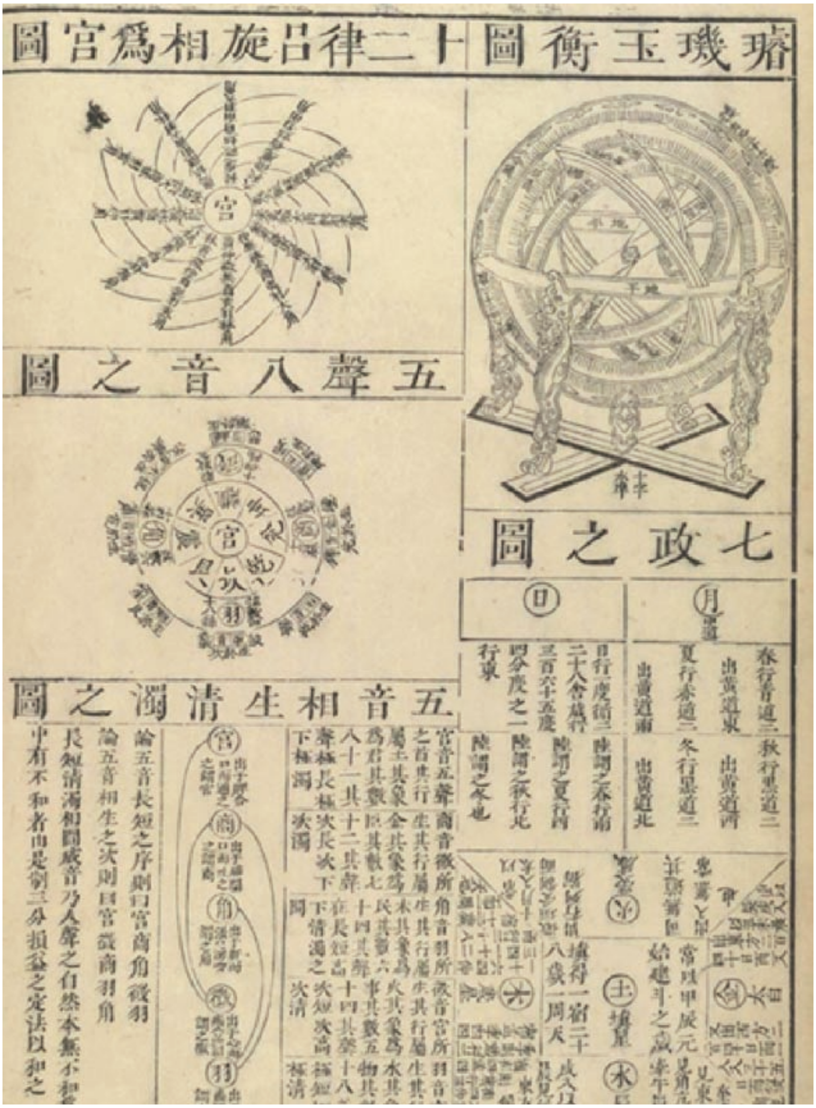

Fig. 2.21 Armillary sphere of the clock in Fig. 2.20

On the second or middle level there was a celestial orb showing the movements of the heavenly bodies which rotated fully in 1 day. The lower level had all the wooden mechanisms needed to make it work. Thanks to its precision, Chinese astronomers could not only observe the heavens but also make correct and exact measurements of the position of different heavenly bodies.

The astronomical clock only lasted 36 years before it was destroyed during the war in north China. Since then, various scale model replicas have been made

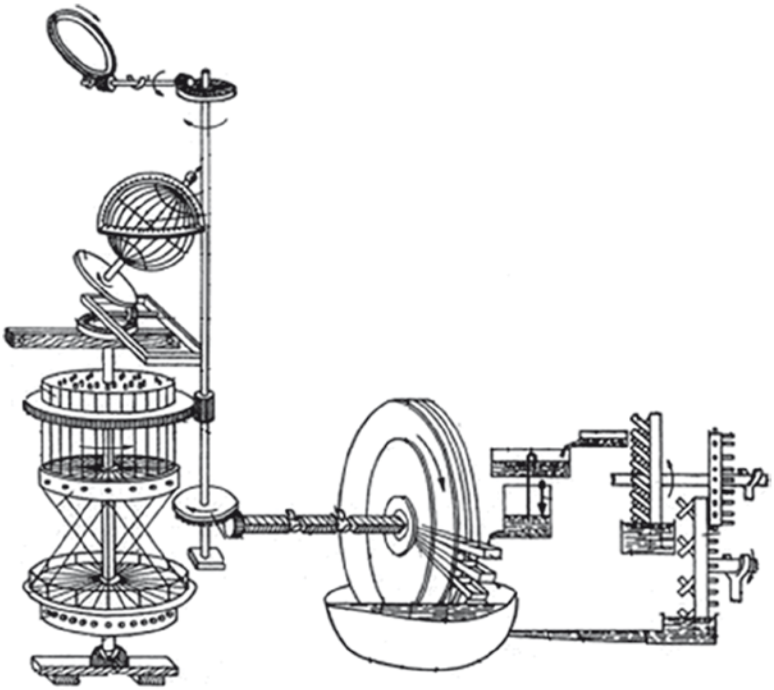

Fig. 2.22 Possible outline of the clock's full mechanism by J. Needham [86]

throughout the world in an attempt to unveil the secrets of its mechanisms which, even today, are still not fully known.

The outline in Fig. 2.22 shows the complex clockwork mechanism. It should be considered that all the gearwheels shown in the drawing had a specific number of teeth so as to be able to work with precision. Everything had to be carefully calculated so that the successive gears gave correct valid measurements that could be used by astronomers as proof of their ideas and theories concerning the heavenly bodies.

When the clock worked, the celestial globe and the armillary sphere turned to provide astronomers with the values of the variations of the Sun and other heavenly bodies throughout the day and seasons.

The most complicated part of the mechanics belonged to the water-operated wheel. Figure 2.23 shows part of its construction. The wheel was about 3.5 m in diameter; it had 72 spokes and 36 ladles which were attached to the outside ring of the wheel as can be seen in Fig. 2.23. The ladle was gradually filled with water, which poured into it at a particular speed so that the wheel turns under its weight. When the ladle was full, the counterweight was overcome and the wheel moved until the control system in the upper part made it to stop (the wheel was stopped at the next ladle) and the filling movement began again.

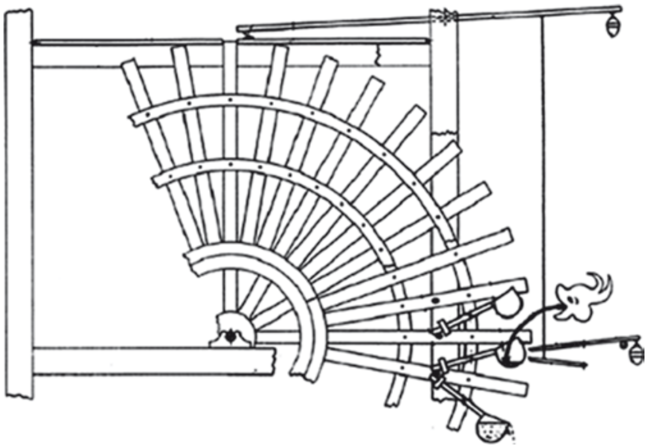

Fig. 2.23 Outline of the mechanism [86]

Once the wheel started its motion, this movement was transmitted to the drive mechanism that was made of a series of gear wheels. Su Song's book shows two different drive systems; namely, one that uses a main shaft that let the counting system rotate and another one with a worm gear that transmits the power to the rest of the system.

The time flow was gradually transformed into the movement of the armillary sphere, celestial orb, and the wooden pagoda that is composed of several interior rings. Accuracy in manufacturing and assembling the wheels was of vital importance.

The wheel of the drive system moved a shaft with six horizontal gearwheels that were hidden by a five-storey pagoda. Each floor had one or more doors. These horizontal circumferences housed different figures and mechanisms with sounds such as gongs or drums. When a row of doors was reached, the figures could be seen and the sounds of the musical instruments heard (Fig. 2.24).

In the book ”Xin Yi Xiang Fa Yao”, Su Song describes the clock by stating that it contains over 400 parts, including eight groups that work differently and were made of different mechanisms. Among the 63 drawings that are devoted to the clock, 47 are aimed at explaining how the mechanisms works.

In general, Chinese technology influenced both bordering and nearby countries. For the case of Japan, this influence led to the invention of automatons that are known as “Karakuri”. They are mechanical devices for playing a joke, playing a trick, or surprising someone. These mechanisms were developed at the beginning of the Edo period (1603–1806) and were used both in religious and civil celebrations. Among all those automatons, that are undoubtedly precursors of modern robots, the best-known was Zashiki Karakuri: the tea server.

The tea server automaton shown in Fig. 2.25 had several different mechanisms that were combined with each other, whose job was to serve the tea. Once tension had been generated in the mainspring with a handle, a cup of tea was placed on the

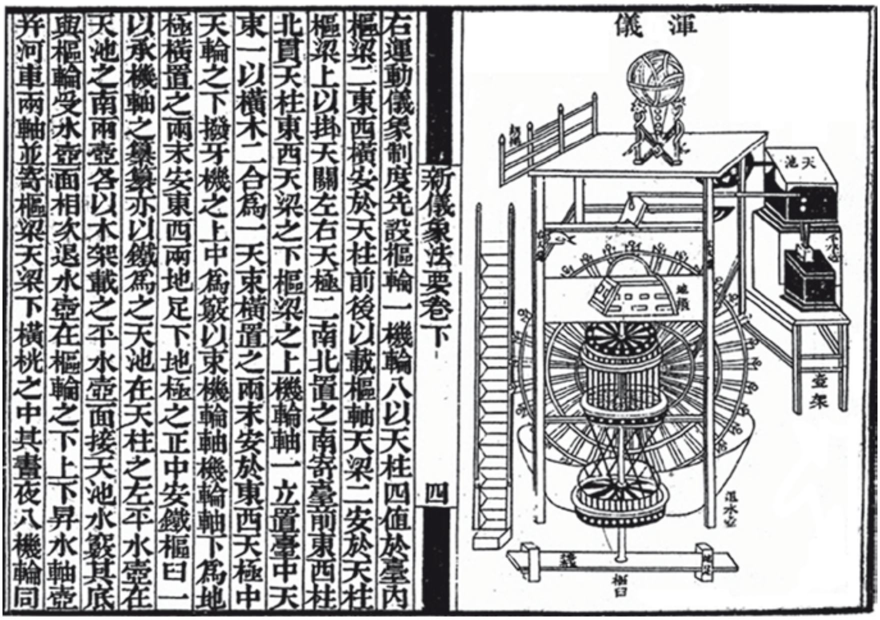

Fig. 2.24 Astronomical clock (From Xin Yi Xiang Fa Yao [114])

tray held by the doll which moved forward in a straight line until the cup was raised. Then it stopped and waited until the cup was once again put in its place. When pressure was once again felt on the tray, it did a half-turn and returned to whence it came. Moreover, as it walked away, it bowed its head deferentially up and down.

The way the automaton worked is described in the drawings in Figs. 2.26–2.28 that schematically interpret the description of Fig. 2.25.

Referring to Fig. 2.26a, when the tray is empty a spring causes a nail to be inserted between the teeth of the wheel, stopping its movement and making the automaton stop. The instant when a cup of tea is placed on the tray, the force of the spring is overcome and the nail rises by letting the automaton start again.

As the automaton moves, a cam mechanism (Fig. 2.26b) operates the bowing of the head, which rotates about the shaft that is indicated by a needle coming out of the neck. A spring ensures contact between the cam and the rod operating the load.

In the mechanism shown in Fig. 2.27, an eccentric rotating disc moves the fork that goes from the disc to the tea server's foot. This actuates the rocking motion of the automaton's foot and the backward and forward motion for the automaton walking. The eccentric discs of each foot are placed at 180° so that the movements of the feet alternate in moving forward so that the automaton walks without losing its balance.

The turning movement is obtained by a mechanism that is shown in Fig. 2.28a. It can be noted that the whole mechanism is in the lower part of the automaton. In order to keep the wooden lever upright, a spring is connected to the lever by a

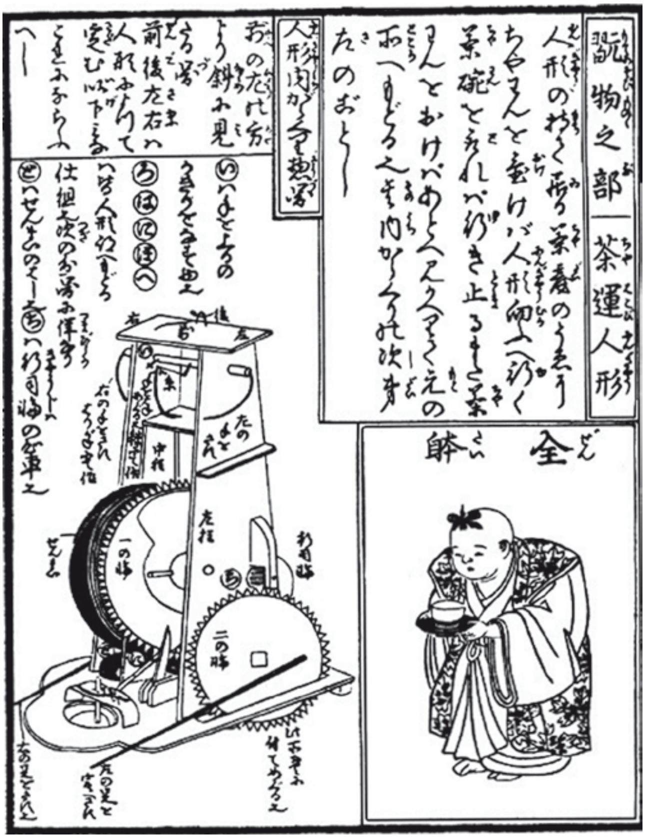

Fig. 2.25 The tea server

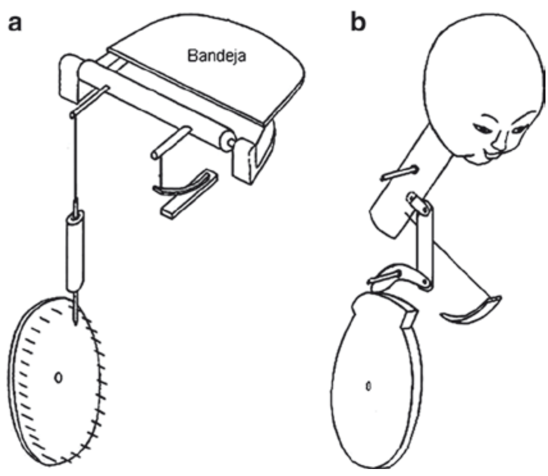

Fig. 2.26 Basic mechanisms in the tea servant automaton in Fig. 2.25: (**a**) Movement starting mechanism, (**b**) Head bowing mechanism

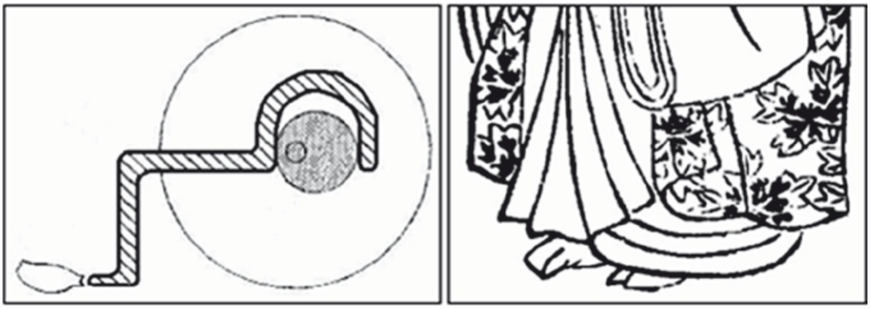

Fig. 2.27 Forward motion mechanism

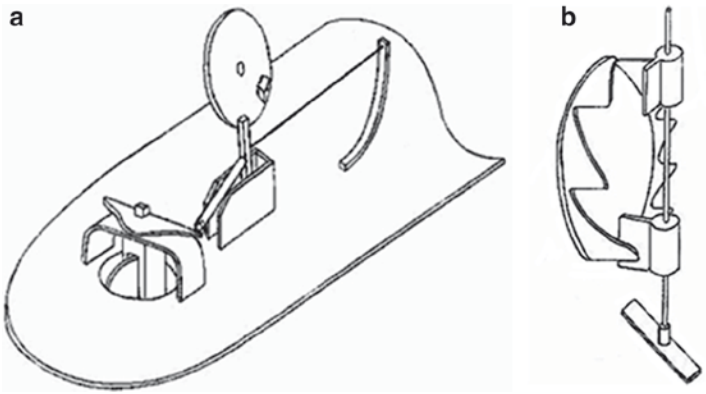

Fig. 2.28 Mechanisms in the tea servant automaton in Fig. 2.25: (**a**) Turning mechanism; (**b**) Speed control mechanism

tensed thread (Fig. 2.28a). The lever is composed of an upright rod and another horizontal one that is perpendicular to it whose aim is to make contact with the wheel that determines the movement. When the spin of the driving wheel actuates the projecting part into contact with the lever, the lever will move to push the horizontal rod to exert pressure on the turning platform and it generates the rotary movement of the automaton. The projecting part of the drive wheel needs to be of the exact height and width in order to obtain a 180° movement of the automaton. Once this rotation completed, the pressure that is generated by the wheel and tensed thread, switches the automaton operation to the forward mechanism.

The final mechanism in the automaton controls its speed. This is achieved by a toothed ring wheel which turns intermittently, thanks to two flanges which are shown in the right of Fig. 2.28b. It is a mechanism which is similar to the escapement of a clock.

On Continuity over the Millennia

The previous pages have shown the development of Chinese machinery up to the end of the seventeenth century. Let's compare the designs of the previous automatons with the reconstruction in Fig. 2.29 that is related to a fifth century BC chariot. The mechanism that operates the legs to simulate the horse's gait is remarkable, even more if as the chariot transported heavy loads Marco Ceccarelli wrote in "An Historical Perspective of Robotics Toward the Future" (2001), [33].

It is remarkable how each technical field evolved. Agricultural, hydraulic, military, astronomical, or purely mechanical techniques evolved at a speed that was stimulated by illustrated books as previously described by the examples in the pages of this book, so revealing a technology that was barely accessible beyond its borders.

It is evident that Chinese technical know-how surpassed the engineering skills in Europe or the Islamic world during the same period of time. It is also curious to reflect that some of their discoveries did not reach us (or were not reinvented in the West) until the middle or the end of the eighteenth century, being Chinese Society not involved with those inventions or reinventions.

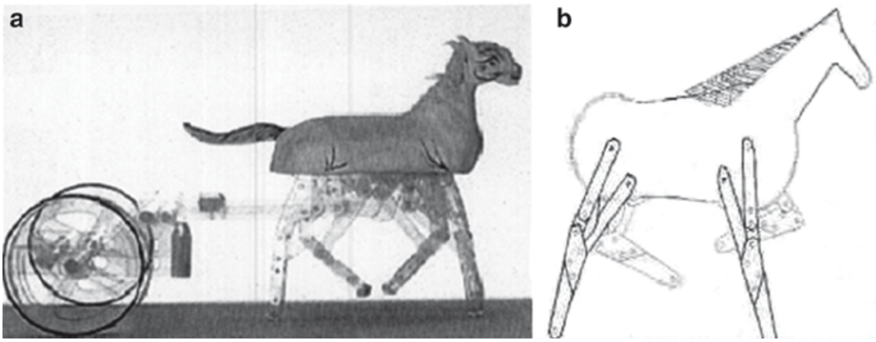

Fig. 2.29 A Chinese automaton chariot of the fifth century BC: (**a**) a diagram of the mechanism; (**b**) Reconstruction of the leg mechanism [129]

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