TECHNOLOGY IN WESTERN CIVILIZATION

The Emergence of Modern Industrial Society Earliest Times to 1900

Volume I

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along with the development of writing to extend human powers of memory and speech. Thus, in the very beginning of civilization, technology played an important role and was advanced by the very civilization which it had helped to create.

4 / The Classical Civilizations

A. G. DRACHMANN

THE GRECO-ROMAN BACKGROUND

The culture of the Western world is built upon a double foundation: the Christian religious tradition and the Greco-Roman civilization of Classical antiquity. From about 900 B.C. the Greeks inhabited what is the country of Greece today, plus the surrounding islands in the Aegean and Mediterranean seas and the coast of Asia Minor. They also colonized Sicily and southern Italy, which was known as Graecia Magna (Large Greece). Their contributions to Western culture included a literature that has never been equalled (the epic poems of Homer; the tragedies of Aeschylus, Sophocles, and Euripides; the comedies of Aristophanes); the first rational philosophy (Socrates, Plato, Aristotle); and the foundation of the exact sciences: mathematics, astronomy, and physics.

One thing the Greeks could not do: live at peace with each other. Even though they spoke the same language and worshipped the same gods, the various city-states of Hellas (Greece) were always fighting. For a brief time in the 5th century B.C., Athens, under the leadership of Pericles, almost succeeded in unifying Hellas by bringing the other city-states under the domination of an Athenian "empire." But quarrelling factions within Athens weakened the Athenian control, and the other city-states chafed under their subordination to Athens; Sparta led the city-states in the Peloponnesian war that put an end to the Athenian empire at the close of the 5th century. The city-states resumed their quarrelling, each trying to dominate the others. They proved unable to unite when Philip, king of Macedon (in the northern part of the Greek peninsula), threatened them; he brought unity to Greece by conquest in the middle of the 4th century B.C.

Alexander the Great, Philip's son, went on to conquer the Middle East—Syria, Egypt, Palestine, Persia, and even part of India—near the close of the 4th century B.C. A lover of Hellenic civilization—his tutor had been the great philosopher Aristotle—Alexander spread Hellenic culture among his Oriental subjects; the result was a fusion of Eastern and Western cultural elements, which is known as Hellenistic civilization (to be distinguished from the pure Greek, or Hellenic, culture). But the political unity of East and West did not survive Alexander's death (323 B.C.); the realm split into warring states.

However, the cultural fusion of East and West—Hellenistic civilization—did survive. It was to be assimilated by a people new to Western history, who were again to unite East and West into a great empire which lasted for centuries: the Romans. It is because the Romans adopted and adapted Hellenistic civilization, based on that of Greece, that it is sometimes known as Greco-Roman civilization.

Founded in 743 B.C., Rome was at first but a small city-state among many others in central Italy. The Romans fought their neighbors and eventually conquered them; instead of keeping them perpetually subjected, they gradually extended Roman citizenship to them and changed their former enemies into allies. By degrees all Italy, then all the countries around the Mediterranean, including Greece, were added to the Roman dominions. At its height Roman rule reached from the border between Scotland and England to the Danube, and south to include all North Africa and the Middle East. Inside this enormous territory there was peace from 40 B.C. to the 5th century A.D.; this *Pax Romana* (Roman Peace) was a longer period of peace than has been experienced by the Western world since then. A standing army took care of any fighting that came up along the borders, while law and order reigned in the rest of the empire.

As a city-state Rome had begun as a tribal kingdom, but its first expansion occurred under a republican form of government. However, the quarrels of domestic factions and politicians, and the ambitions of strong men, such as Julius Caesar, put an end to the Roman Republic. From about 40 B.C. under Augustus, the nephew and heir of Julius Caesar, Rome became an empire with a single man, the emperor, at its head. Some emperors were great statesmen, a few were madmen; but to most of the population of the Roman Empire this did not matter. The efficient administration established by the first emperors kept things going, regardless of who was the nominal ruler. Law and order, government and administration, were the main contributions of the Romans to the civilization of the Western world, while at the same time the technical requirements of such an empire led to important mechanical and engineering innovations.

THE BACKGROUND OF GRECO-ROMAN TECHNOLOGY

By the time we first hear of the Greeks, about 900 B.C., most of the early inventions that secured mankind's supremacy over the rest of the animal world had already been made: the use of fire; the domestication of animals; agriculture; the use of metals and iron for weapons, tools, and utensils; spinning and weaving; the potter's wheel and the glazing oven for pottery; the building of houses of wood, brick, and stone; the use of wheels for transport; and the art of writing. In many respects daily life during antiquity already resembled closely that which prevailed in Europe up to the invention of the steam engine: agriculture was the basis of the economy; the home was the center of most production; and almost the only source of power was the muscle power of man or beast.

What we know about the technical achievements during Classical antiquity comes from three sources: there are the writings—a few technical books describing inventions and machinery, and casual mentions in works on other subjects; there are the actual tools, excavated by archaeologists and now preserved in museums all over the world; and, finally, there are pictorial representations in sculpture, in paintings like those preserved to this day on the walls of Pompeii, in mosaics, and in pottery. Greek vases especially have figures of great beauty which illustrate the daily life of the time.

GREEK INVENTORS

Three great inventors, all of them Greeks, are known from antiquity: Ktesibios, Archimedes, and Heron of Alexandria.

It is interesting to note that all these men lived during the Hellenistic period; although none of them lived in Greece proper, they were Greek in culture. Interesting too is the fact that although the preceding Hellenic period (up to about 350 B.C.) had been a period of great cultural activity in art, literature, and philosophy, little was accomplished in the way of technical progress. Some Classical scholars claim that it was the stimulus of the meeting of Eastern and Western cultures, accomplished through Alexander the Great's conquests, which produced the technological advances of the Hellenistic period.

KTESIBIOS

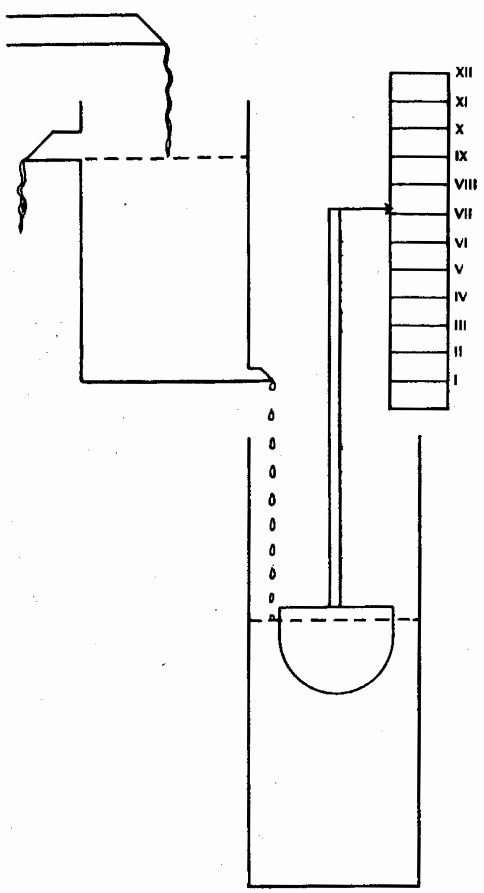
The first, Ktesibios (spelled Ctesibius in its Latin form), lived in Alexandria about 270 B.C. This city, founded by Alexander the Great on the delta of the Nile, although geographically in Egypt was a Greek city in spirit. With its university and its library it became a center of Hellenistic culture. The first three kings (Ptolemy I-III) who reigned in Egypt after Alexander's death promoted the arts and sciences and supported Ktesibios and other inventors.

Ktesibios was the son of a barber, and he put up in his father's shop a mirror hanging on a string with a counterpoise, so that its height could be adjusted to the size of the customer. The counterpoise was placed in a corner, neatly hidden by boards. But as it came down, the air in the enclosed space was compressed and escaped with a loud noise. On the strength of this experience, Ktesibios made the first cylinder with a plunger, and so constructed the first force pump. With his air pump he made the first organ, with many pipes of different lengths and a keyboard for playing them. It was called the water organ, because water was used to keep the pressure of the air constant. Ktesibios also experimented with air and water pressure, studying siphons and founding the science of hydraulics (then known as "pneumatics").

He also invented the water clock. Before his time the sundial was the only means of telling time, and it of course did not work at night or in cloudy weather. Ktesibios constructed his "night clock" or "winter clock" on the following principle: a small stream of water fell into a container called the *klepsydra* (or clepsydra) which had a small hole near its bottom and an overflow hole higher up. As long as more water came in than went out through the hole in the bottom, the water level was constant, and the flow from the small hole was also constant. The water trickled into a cylindrical container with a float that carried a vertical rod and a pointer to indicate the hours on a scale. All reliable timekeepers were built on this clepsydra principle until the invention of the verge-and-foliot escapement in the 12th century A.D.

Ktesibios delighted in mechanical contrivances. Having made a clock that moved by itself, he added a rack and pinion drive to the float and made it perform such tasks as striking the hours and sounding trumpets at noon. (In this respect our cuckoo clock with its performing bird is a direct descendant of

Fig. 4-1. Clock, or klepsydra. (Courtesy of *P. Haase & Son,* Copenhagen)



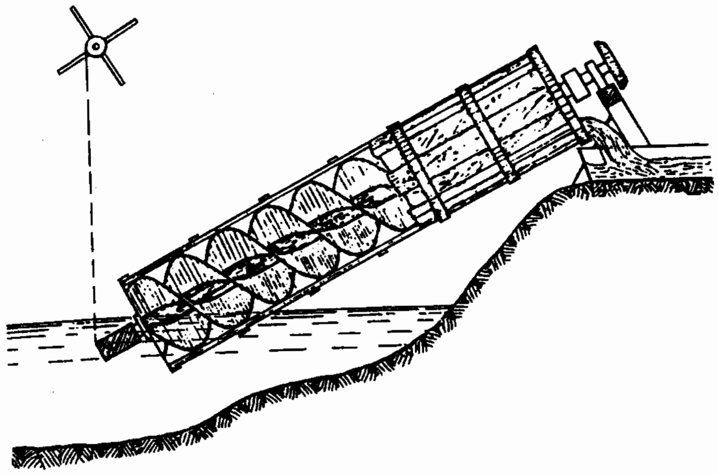


Fig. 4-2. Water-snail. (*P. Haase & Son*)

Ktesibios's water clock.) He was the first to use a toothed wheel, and he also tried to make catapults driven by springs or compressed air. These did not succeed, however, for the technical resources of the time were not sufficient.

ARCHIMEDES

Archimedes (287-212 B.C.) is known as an outstanding methematician, but he was also an inventive genius. Of inventions ascribed to Archimedes, at least four are still in use. He studied the theory of the balance and invented the steel yard (fulcrum scale); he studied the mechanics of the lever and invented a differential gear of ropes and drums; he studied the screw line, and he invented the water snail, which is still in use. He also connected the screw with a gear wheel, making a worm-and-wheel-gear, or endless screw, as it is also called. This is one of the most powerful transmissions ever made, and while it was not much used in antiquity, it is today found in a great number of engines. Furthermore, when his native town, Syracuse, was besieged by the Romans, he kept the enemy at bay by all sorts of mechanical contrivances.

HERON OF ALEXANDRIA

Heron (in Latin, Hero) of Alexandria lived about 60 A.D. (an eclipse of the moon described in his book, *Dioptra,* took place in 62 A.D.). We know nothing of his life, but he was probably connected with the University of Alexandria. Several technical works by him have come down to us: *Pneumatics, Automatic Theater, Dioptra, Belopoiica* (Book of Catapults), all written in Greek, and another, *Mechanics,* has reached us in an Arabic version.

The *Dioptra* describes an invention made by Heron himself, an instrument

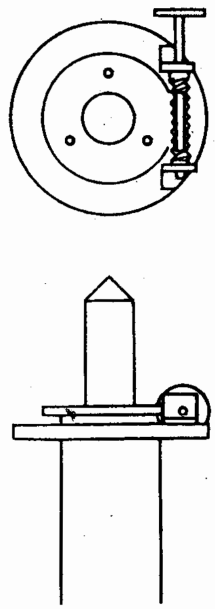


Fig. 4-3. Heron's Dioptra. Around the pivot (attached to the horizontal disc on the upright column) was placed a ring with teeth which were engaged by a screw turning in bearings fastened to the disc. The screw had a longitudinal furrow as wide as the gear-wheel was thick, so the wheel could be turned freely and locked in any position. (*P. Haase & Son*)

for surveyors. It is a combined theodolite (for measuring horizontal and vertical angles) and level, meant to supersede two older instruments, the *groma* and the *chorobates*. (See Figs. 4-3, 4-4, and 4-5.)

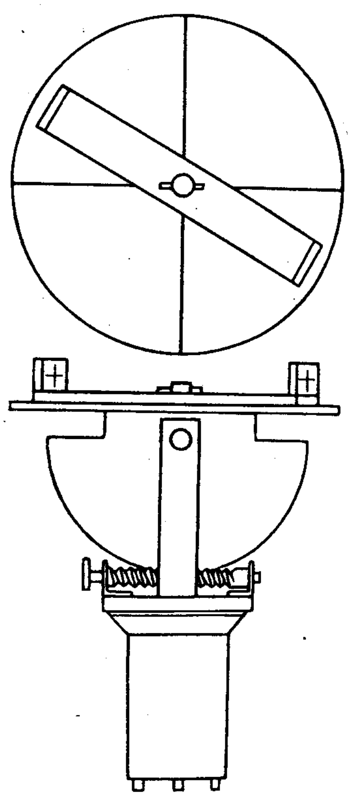
The *groma* was used for staking out lines at right angles; its major drawback was that it did not work in windy weather. The *chorobates*, or "land-strider," was a rather cumbersome instrument for taking levellings. It consisted of a 20-foot-long plank with a leg and a plumb line at each end, and for windy weather it had a furrow in the plank to hold water for indicating the horizontal position. No other water-level was known; horizontal beams or walls were tested with a triangle and a plumb line.

Heron's *dioptra* consisted of a stake thrust into the ground on which there was a column with a round disc, and from this horizontal disc a thick pivot stood upright. The rest of the instrument consisted of two different parts, the *dioptra* (theodolite proper) and the level, each of them mounted on a hollow column that fitted the thick pivot. The column carried three pegs to fit into three holes in the ring, and this is the only example known from antiquity of interchangeable parts. The construction and operation of Heron's *dioptra* allowed for much more accurate observations and measurements than earlier instruments.

Heron's instrument shows both the possibilities and the limits of fine mechanical work during antiquity. The brass screws in the level, for example, were inserted into smooth holes and engaged by a small peg driven in from the side. The threaded hole was not introduced until many centuries after the time of Heron, and the familiar pointed wood-screw was not invented until the mid-19th century.

Heron's *Mechanics* was a textbook for architects, contractors, and engineers, and most of the tools described in it were already old before Heron wrote. One thing was new, however: the use of the screw press. Oil and wine were very important products of ancient agriculture; a press was necessary to get the last of the juice out of the grape pulp and to get anything at all out of the olives.

Fig. 4-4. Heron's Dioptra (Theodolite). The dioptra consisted of a vertical half-circle of brass, with teeth on its circumference; it turned on a horizontal axle and was held by an endless screw from below. A round disc was fixed at right angles to the upper, flat edge of the half-circle, and on this disc was mounted the sighting-rod, turning on a pivot in its middle. Two lines at the right angles on the horizontal disc completed the instrument. This was enough for staking out lines at right angles; but if the horizontal disc was divided into 360 degrees, the dioptra could also be used for astronomical observations. (*P. Haase & Son*)

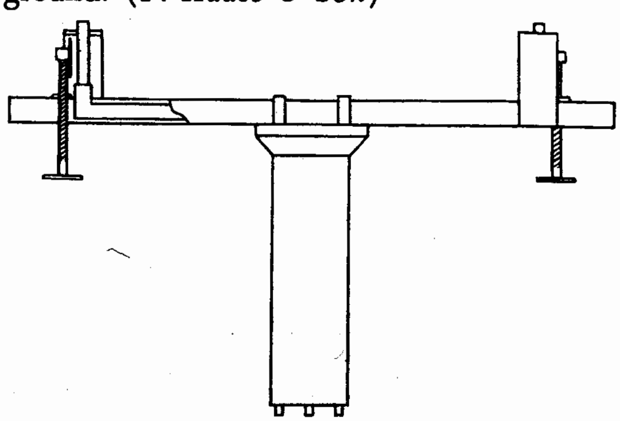


The first presses, using a long lever and a winch, were laborious and time consuming to operate, and they were not very effective in squeezing out the last grape juice or olive oil. The application of the screw to the lever press saved labor, and the direct screw press also saved space. Heron's use of a female screw enabled the screw to press directly on the substance to be squeezed, and hence extracted more juice and oil.

Heron's book *Automatic Theater* describes a plaything, a toy theater, that moves by itself, performing a play without being touched by any human hand. It is driven by a heavy weight resting on mustard seeds that run through a narrow hole, after the manner of the sand in an hour-glass (or the water in a clepsydra). All movements were performed by means of drums and strings, and there were no springs or gear wheels.

Heron's *Pneumatics* also consists mostly of playthings. We find a fire pump, however, and a water organ, but the rest is parlor magic for entertaining: bowls of wine that cannot be emptied, jugs and jars that give out wine or water at

Fig. 4-5. Heron's Dioptra (Level). Heron's level consisted of a very long, horizontal rod of wood, into which was fitted a long tube of brass with upturned ends. These ends carried glass tubes so that when water was poured into this U-tube, the surfaces of the water in the two glass tubes indicated a horizontal line. The sight-holes were made in two small brass plates that were moved up or down by means of brass screws; a slit in each plate was made to coincide with the level of water in the tube. The column with three pegs, which carried the level, was fitted with a plumb-line, for if the "transverse rod," as the level was called, canted to one side, the water levels in the glass tubes could not coincide with the slits. Two targets, half white, half black, were used on the staffs; they were moved up or down by a string over a pully, and carried a pointer to show their height over the ground. (*P. Haase & Son*)



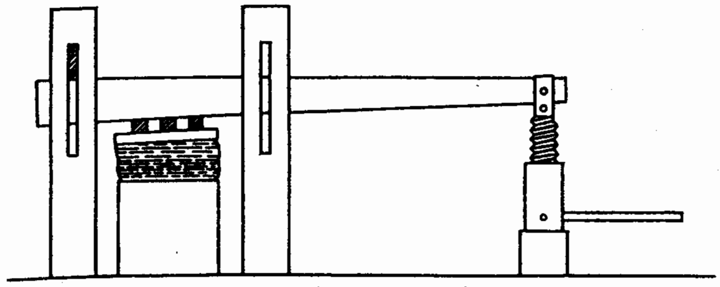


Fig. 4-6. Screw press. (*P. Haase & Son*)

will, a figure of a horse that will drink if offered water, birds that sing or are silent as an owl turns away from them or toward them, and many others. The most interesting feature of these devices is the use of hot air or steam to operate them: a temple door is opened when an altar is lit; in another temple two puppets offer libations when the altar is lit. Both are toy theaters, not life-size. There is a water heater for mixing hot drinks which generates steam for blowing on the charcoal. There is even a small steam turbine: a hollow ball turning on two pivots rising from the lid of a boiling kettle; one pivot is hollow, and the steam coming into the ball escapes through two bent tubes, thus causing the ball to rotate by reaction. This toy was not, however, the forerunner of any real steam engine, then or later.

CONFLICTING INTERPRETATIONS OF HELLENISTIC TECHNOLOGY

Some scholars have argued that Heron's technical devices, despite their ingenuity, constituted no technological advance, that they did nothing to assist man in the performance of work or to further his control over his physical environment. Designed to be used in the temples—if they were actually meant to be put into practice at all, rather than mere doodlings of Heron's imagination—they were meant to amuse, impress, or delude the worshipper, not to lighten man's physical burden. Why, they ask, was so much technical ingenuity "wasted" in this fashion?

One explanation, advanced by the British scholar Benjamin Farrington, is that the ancient Hellenistic economy rested on slave labor. An abundance of cheap human muscle power was available, so there was no need to develop labor-saving devices. And why bother to make things easier for slaves? Even the slaves themselves had little incentive to make their work easier, for they would still remain slaves and be forced to work to the limits of their strength.

In addition, it has been pointed out that there was a gap between the scholarly, or clerical tradition, and the craft tradition. Farrington contends that the ancient world, following the example of Plato, looked down upon manual labor —that was left to slaves—and that men such as Heron, of the intellectual elite,

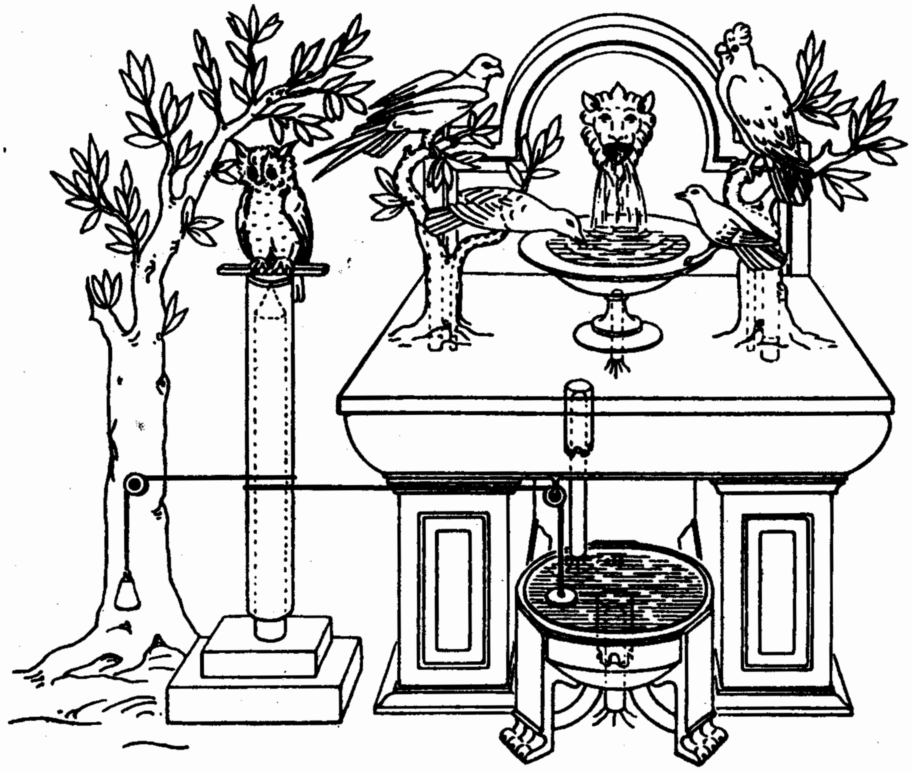


Fig. 4-7. Heron's owl from his *Pneumatics*. (*P. Haase & Son*)

had little knowledge of technical processes and would scarcely concern themselves with developing devices which would make manual labor easier for the despised lower classes. The workers, who might have been interested in some adaptation of Heron's devices which could make their work less toilsome, had no opportunity to learn of them, for they could not read or write.

The result, according to Farrington, was that few of Heron's devices were translated into devices which could actually be used to perform work. By this interpretation, such devices represent technical ingenuity but not technological progress.

However, a closer examination of the historical evidence would cast doubts upon the validity of Farrington's interpretation of the nature of Greek technology. For example, it would be a mistake to believe that Heron was not interested in practical technical devices designed for the performance of work. Although it is true that in his *Automatic Theater* and in *Pneumatics* Heron was describing toys, not all of them were merely imaginative; indeed, most of the chapters in *Pneumatics* describe existing devices for the entertainment of guests at a feast to which Heron has added improvements. Furthermore, in his other books—*Mechanics, Dioptra, Belopoiica*—Heron deals almost exclusively with implements designed for practical purposes.

Similarly, it is mistaken to state that the abundance of cheap human muscle power hindered the invention of labor-saving machinery. As we have seen in the case of Ktesibios and Archimedes—and Heron's *dioptra* and screw press—many important labor-saving devices were invented during this period. True, slave labor might have been cheap by modern standards; but there was no lack of competition, and such competition would lead to the use of labor-saving machines.

Furthermore, it is questionable if Farrington's interpretation of Plato truly represents Plato's thought. In the *Apology,* Plato's earliest work, Socrates finds that craftsmen know their crafts; in Plato's last work, the *Laws,* he refuses to allow craftsmen to take part in governing the state, for that in itself is a craft, and no man can learn two crafts. Throughout his *Dialogues,* whenever he uses for an illustration a man who knows his job, Plato always refers to a craftsman: a surgeon, a trainer of horses, or the like. Such evidence would indicate that Plato did not lack respect for craftsmen as such.

Nevertheless, the most convincing evidence in opposition to the Farrington thesis of the technological sterility of Classical antiquity is the fact that notable technical advances were made during Greco-Roman times, in order to ease the burden of human labor. A prime example of this was the development of the water wheel.

THE WATER WHEEL

Two of the most laborious tasks in antiquity (and later) were the pumping of water for irrigation and for the city water-works, and grinding grain to make flour for baking. Like most technical problems in antiquity, these were solved not by the inventive feats of such individuals as Heron or Archimedes, but rather through the slow accretion of craftsmen's skills.

Grinding was originally done with a round stone that was rubbed along a hollow in another stone (the quern). Then the grinder (top stone) was made square and provided with a slit for feeding in the corn; the lower stone was flat and was placed upon a table, and the grinder was moved to and fro over it by means of a long wooden arm. This was hard work, and disobedient slaves were sometimes punished by being banished to the mill. By about 150 B.C., two other mills were widely used. One was a rotating hand-mill (or handquern), in which a round millstone was turned backwards and forwards by a handle; the other was a big mill turned by a horse or a mule. In this the grinder was formed like an hour-glass and rested on a fixed lower stone shaped like a cone. The grain was poured in from above, and the top stone was turned by an ass, a mule, or horse harnessed to a long wooden pole attached to the upper stone.

The water mill was not introduced until about a century later, just before the end of the pre-Christian era. It probably had its origin in the water wheel of the period, which was a large wheel with buckets fixed to the circumference, and

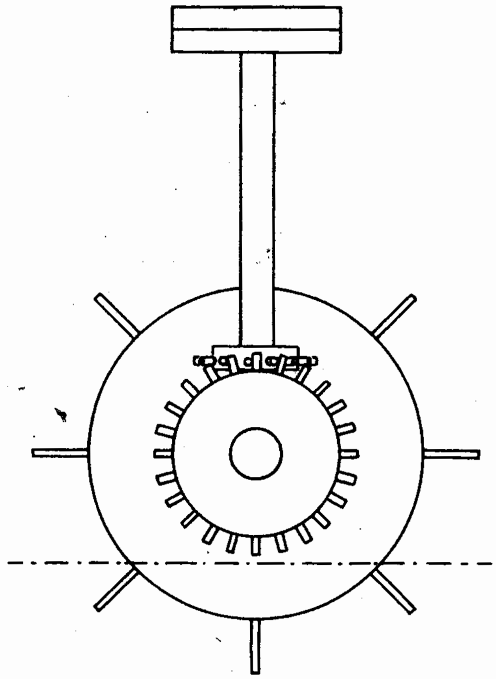


Fig. 4-8. Water mill. (*P. Haase & Son*)

which was set in a stream of water. When turned by manpower, the buckets picked up water from the stream and carried it to the top of the wheel radius, where it was dumped into a reservoir or pipe. At some point it must have occurred to someone that by adding paddles to the buckets, the wheel could be turned by the power of the flowing water itself and thus perform the work of the man.

The next step was to put a gear wheel on the axle of the paddle-wheel and make it turn a vertical axle that carried a millstone. These first gear wheels had round pegs for teeth, which were fitted to the gear wheels set at right angles.

The water mill developed quickly. Rome was provided with ten aqueducts that carried water from mountain springs to reservoirs in the city; the water ran day and night, and the surplus went to rinse the sewers. Where the water came down the Janiculum, one of the seven hills on which Rome was built, it was used for turning mills.

Mills now appeared throughout the Roman Empire, and were applied to several tools, including saws for cutting marble. Although the substitution of water for muscle power represented an enormous stride forward, the new mills had considerable limitations. The most obvious and critical was that they were tied to the geographical accident of sufficient water power. The lack of adequate transportation from the sites of water power (and therefore mill sites) to cities was a drawback which severely limited the wide use of mills. The result was that water mills, while first employed near the beginning of the Christian era, were not to achieve wide use until many centuries later; thus the development of the hammer mill during the early Middle Ages was due to the finding of ore near water power, so that the ore did not have to be transported.

The idea of the water wheel could, of course, be reversed, and the ancients developed a device to that end. It will be recalled that about 150 B.C. the hour-glass shaped mills had appeared whose upper grindstones were attached to a pole; animals were harnessed to the pole and thus turned the mill by going around and around. Since the gearing used in the water mill changes the rotation from vertical to horizontal, the ancients perceived that the horizontal rotation of the horse-walk could be converted to the vertical rotation of a bucket chain, and that animal power could thus be used to perform the laborious task of lifting water. Our earliest evidence of the animal-driven bucket chain for lifting water is to be found in a mural painting dated somewhere between 100 B.C. and 100 A.D., which shows such a device driven by oxen. This device, still in use in Mediterranean countries and the Near East, is now known as a *saqija* (in Spanish, *noria*); it is a striking example of the wish to substitute animal power for human power.

The windmill was not known till many centuries after the Roman Empire. Although a chapter in Heron's *Pneumatics* describes an organ whose air pump is driven by a sort of wind motor, this was just a sketch for a toy, and nothing came of the air pump until the Middle Ages, when a greater variety of power sources was required. Like so much of Heron's work, it remains only a historical curiosity.

MILITARY TECHNOLOGY OF GRECO-ROMAN TIMES

Military needs have frequently stimulated technological developments throughout history. Man's paramount need for security has meant that he lavished care, time, and energy on his weapons. With the Greek city-states constantly engaging in warfare with one another, and with Rome later conquering and maintaining a vast empire, it is not surprising that improvements and some innovations occurred in military technology during this period.

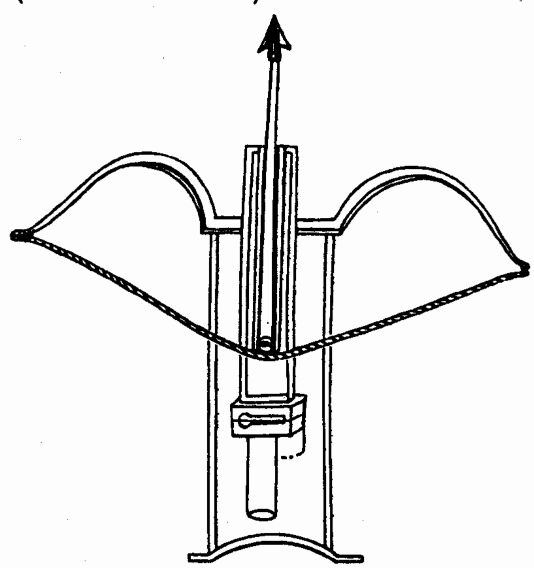
The ordinary hand-weapons—spear, javelin, sword, bow and arrow—had been known, of course, since prehistoric times. Apart from the sword, these were all hunting weapons, which were used also against human enemies. The javelin, or the "hand-flung spear," was greatly improved by the Romans for military purposes, by making it difficult for the enemy to extract it from his shield. Upon attacking, the Roman soldiers first threw their javelins at the enemy, and then closed in upon him with their swords. When the javelin pierced the enemy's shield, its shaft turned at right angles to the point; while this then made the javelin useless as a weapon, it also meant that the shield was useless till the javelin had been removed. While the enemy was thus encumbered, the Roman soldier was upon him. In a later development, the point of the javelin was firmly fixed to the shaft, but it was made partly of soft iron, so that it bent when it struck.

One important invention—the catapult—dates entirely from Classical times. Whereas the ordinary bow sends out its arrow only with the force given it by the strength of the arm of the man who shoots it, the catapult multiplied by many times the power of the bow or the sling. Invented by the Greeks in Sicily shortly after 400 B.C., the first step in the development of the catapult was the *gastraphetes*, or "stomach-bow." This was a crossbow, strung by the archer leaning his weight against the stock while it rested on the ground. In this way a sliding board was driven into the stock, taking the bow string with it; the string was caught by a hook and released by a trigger.

Next came the catapult proper. Instead of a bow made of wood or horn, it was provided with two strong arms whose outer ends carried the bow string, while the inner ends went through two bundles of sinews which possessed great elasticity. The bow string was drawn back by a winch, and the whole device stood on a wooden base. Some catapults shot arrows, others hurled stones. Although the arrow catapults did not work swiftly, they made it possible to shoot at enemies from a safe distance. The stone-throwers were not strong enough to knock down a solidly built wall, but were useful to the besieged for destroying the attacking siege-engineers.

The power of the catapult resided in the two bundles of sinews that activated the arms; their strength depended on their circumference. To build a catapult to a given specification, the diameter of the hole for the sinews was calculated from the length of the arrow or the weight of the stone, and the dimensions of all the other parts of the catapult were given with this diameter as the basic measure-

Fig. 4-9. Gastraphetes, or "stomach-bow."
(*P. Haase & Son*)



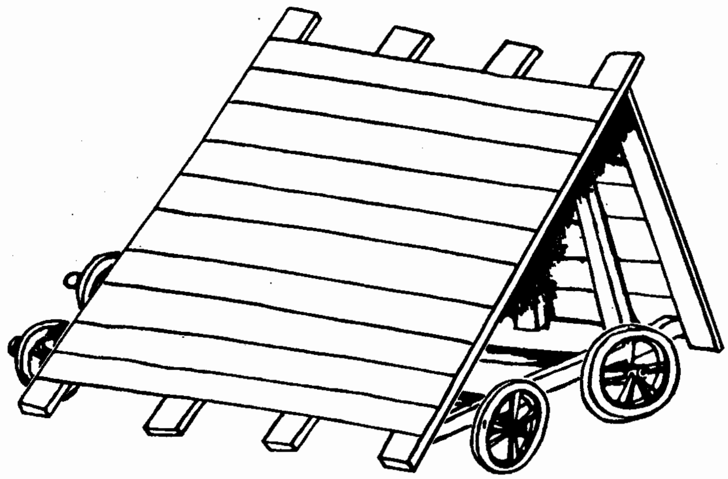


Fig. 4-10. Tortoise. (*P. Haase & Son*)

ment. This is one of the oldest examples of the use of a basic measurement to provide the ratios of the other parts, and it shows that mathematical knowledge had its part in the technical progress of the times.

Pitched battles were the exception rather than the rule in ancient warfare. Most wars involved lengthy sieges against fortified places. The attack against a fortified town was made by "tortoises," battering rams, scaling ladders, and siege towers.

The tortoise was a solid shelter, like the roof of a house, which was moved on wheels toward the wall of the fortress. Under its protection soldiers could demolish or undermine the wall. The battering ram was a huge wooden beam with a bronze head. It was hung from a tall timber structure by chains, so that it could be swung forward against the wall. The scaling ladder was a long ladder wheeled against the wall, and the seige tower was a solid wooden building at least as tall as the wall against which it was wheeled.

All these seige engines had been invented by the Greeks. The Romans merely took them over and improved them.

ROADS

The greatest contribution to military technology in Classical times, however, and perhaps to the advance of civilization itself, was the system of roads developed by the Romans. In Greece the roads had been mere paths or tracks, on which such deep ruts were made by the two-wheeled carts that they could pass each other only with difficulty. Only for the religious processions to the great temples were short paved roads laid down.

The Romans, on the other hand, wanted to move their army to the place it was needed as swiftly as possible, and they built roads everywhere. The roads followed as far as possible a straight line: small hills were cut through, tunnels were made through mountains, ways were cut through forests, and on swampy ground the roads were laid on planks carried by posts rammed down into the mud. The surface of the road was paved with stones, and drainage ditches were dug along it; in some places there were even sidewalks. Rivers were crossed by bridges, some of which still exist and carry modern traffic. All in all, the Romans built some 44,000 miles of road.

These roads made possible swift communication and transportation throughout the vast empire, enabling Rome to maintain its military domination and to administer a large territory. Commerce and culture also benefitted by the roads, many of which are still in use. The roads were the Romans' most valuable contribution to material civilization.

HYGIENE

The Romans also were interested in hygiene, not only personal hygiene but also public health. Life in large cities would have been impossible without adequate water supplies and a sewage system.

A big sewer, the *cloaca maxima,* was built in Rome about 600 B.C., and in 312 B.C. the Censor Appius Claudius built the first aqueduct to carry pure water from a small mountain river to Rome. From that time on, no one in Rome drank from or bathed in the Tiber, which received the water from the sewers. The aqueducts were multiplied, and in 226 A.D. no less than eleven aqueducts carried water to the city. Many of them are still in use.

Most of our knowledge about the Roman water system comes to us from a treatise, *On the Water Supply of the City of Rome,* written by Sextus Julius Frontinus (*c.* 35–103 A.D.). Considered by some scholars to be the greatest engineer in antiquity, Frontinus was commissioner of water works in Rome during the last half-dozen years of his life. His book is a detailed description of the Roman water-works system, including information about the construction of the aqueducts which supplied the city, the breakdown of the distribution of the water, the problems of construction and maintenance, and the laws applicable to the water system. Frontinus proved to be an efficient administrator of the water system, doing away with much fraud and corruption, such as the practice of water-works employees to take on private jobs while on the public payroll and the illegal tapping of water mains by householders. In his treatise, Frontinus pointed with pride to the utility of the aqueducts as compared with the "useless" works of the Egyptian and Greek engineers.

Wherever the Romans occupied or built a town, they took care of the water supply and the sewers, with beneficial effects on the health of the inhabitants. This practice however, fell into disuse during the early Middle Ages, surviving only in a few favored places. As late as the end of the 19th century, epidemics occurred in those European countries where people drank river water contaminated by sewers.

Both the Greeks and Romans were fond of athletics, and the public sports grounds were provided with baths. In the Roman Empire no town was complete without its public bath; in Rome itself they were developed into veritable palaces, with central heating and luxurious appointments, so they became favorite meeting places. During the Middle Ages bathing was frowned upon, and the personal cleanliness that characterized both Greeks and Romans did not come into its own again until our time.

CONSTRUCTION

The great baths and other Roman construction works were built of stone and cement. By a fortunate accident, the Romans discovered and made use of hydraulic cement (that is, cement that hardens under water and is not dissolved by water). Cement until that time had had only a limited use because it could not stand up to the elements, but the Romans fortunately had a supply of *pozzalana* sand nearby, which, when mixed with limestone, formed a cement which was impervious to water. The Romans did not know why this particular sand made such superior cement, but nevertheless they used it in their construction works. After Roman times hydraulic cement disappeared from history, only to be invented in the 19th century. We know it today as Portland cement.

Cement was used both for casting in blocks and as mortar; for common masonry made of sun-dried bricks, ordinary mortar of slaked lime was used. Although hydraulic cement enabled the Romans to bind together the stones of their buildings, bridges, and aqueducts without the need for elaborate mortising of joints, they still bound marble blocks together with iron cramps imbedded in lead, as in the famous Colosseum in Rome.

In addition to the new material of hydraulic cement, the Romans also exploited a new structural device—the arch. Certain forms of the arch and the vault (an extended arch) had been known in Mesopotamia about 4000 B.C.; and a true arch, dating from the 5th century B.C., has been found in the Greek town of Palaera. Although the arch was not invented by the Romans, they developed it and used it, so that it became the characteristic structural member in Roman architecture.

Previous stone construction, under the Greeks, for example, had always employed post-and-lintel construction, that is, columns (posts) supporting a beam (lintel) across them, similar to the way children build with playing cards. Though the Greeks achieved beautifully proportioned buildings (e.g., the Parthenon) with this type of construction, it had its limitations, chiefly the need for many columns to support any long beam, thus making it impossible to roof over any large area without the obstruction of many columns. As we will see later, the arch overcame this limitation; the stress and the thrust of the weight of the roofing was dispersed laterally to the base of the arches. The arch enabled the Romans to cover large areas without columnar obstruction. So successful a solution was this to the problem of spanning large areas that at the beginning of the 20th century the ancient Baths of Caracalla in Rome were copied for the Pennsylvania Station in New York City.

A Roman architect and engineer, Marcus Vitruvius Pollio wrote (25 B.C.) a comprehensive treatise on Roman architecture and building techniques, entitled *De architectura* (On Architecture), and dedicated it to Augustus. The book contains discussions of astronomy, sundials, and others materials, but its language indicates that Viruvius was probably not a highly educated man. Vitruvius' attempts to deal with the scientific principles underlying architectural theory are not convincing, but his detailed description of constructional matters reveals him to be unequalled as a practical builder. In the period following the decline of the Roman Empire, the work of Vitruvius was lost. When the study of Latin authors was revived in the 15th century, a manuscript of *De architectura* was discovered and Vitruvius' instructions on how to build a fortress, a temple, a theater, a seaport, or a house exerted an enormous influence on Renaissance architecture.

"Architect" at Vitruvius' time meant builder, contractor, and engineer, and the two last books of the ten that constitute his work deal with instruments and engines that today would not be considered within the province of the architect. Thus, Vitruvius describes clocks, cranes, and catapults, as well as buildings. So it is not surprising that Vitruvius is our main source of knowledge of the technical achievements of his time.

In the Middle Ages the arched vault of the Romans which developed into the pointed Gothic arch was employed successfully in the great cathedrals of Northern Europe. The dome, another development from the arch (simply an arch turning on its axis throughout its entire circumference), became characteristic of Byzantine architecture; and much modern concrete architecture employs the principles of the Roman arch. Thus the Romans have lasting monuments not only in their own buildings but in the design and techniques of future buildings.

TECHNOLOGY AND SOCIETY

During the thirteen centuries (*c.* 900 B.C.–*c.* 400 A.D.) which we assign to the Greco-Roman period, Western society changed from a conglomeration of small agricultural communities to a worldwide state with great cities and an extensive trade. These cities demanded aqueducts and sewers and the transportation of goods by land and sea. They also required a division of labor, which led to the rise of a class of artisans: smiths, weavers, fullers, bakers, and the like.

There still remained much unskilled, heavy labor to be done, and this was the task of slaves; though slaves were also used for the lighter work of servants, secretaries, or accountants, according to their ability. A slave was not recognized as a legal person, but was the personal property of his owner. Yet, to be a slave was not an inexorable fate, for a slave was sometimes allowed to save up money to buy his freedom, which, in Rome about 50 B.C., might take him some seven years. Once freed, the slave would become a Roman citizen with all the rights belonging to this rank.

Since the owner had to feed and clothe his slaves anyway, he was interested in getting as much work done as possible with the fewest slaves, and undoubtedly some inventions had saving labor as their purpose. Archimedes invented his water snail, differential gear, and endless screw on the strength of his mathematical studies, but they all aimed at making human muscle power more effective. The screw press had the same effect. The water wheel, invented for lifting water, was used for grinding grain and for other purposes.

Thus there was incentive to save human muscle power in antiquity, despite the abundance and cheapness of slave labor. Indeed, the invention of the water wheel—while not fully exploited until the Middle Ages—was a turning point in technical progress, for it introduced the idea of using another source of power in place of muscles. Nevertheless, the chief energy source of antiquity continued to be human and animal muscles; the basic materials continued to be stone, wood, and brick, with metal used chiefly for weapons and sometimes for tools. With the exception of the Roman roads, transportation and communication remained much the same as they had been since the beginnings of historic times. However, the Hellenistic inventors had devised some very ingenious machines, so that the mechanical equipment of Classical antiquity was more than simply a refinement of the tools and implements of pre-Classical times. Thus most of the elements of machinery used to improve technical devices after 500 A.D. had actually been invented before the fall of the Roman Empire.

The Romans are known to history as great engineers. Why is this so? Partly this is owing to the large number and monumentality of their construction works—the great aqueducts, roads, buildings, and bridges which have withstood the ravages of time and still bear testimony to the strength and solidity with which the Romans built. Partly too it is owing to the organizational abilities of the Romans. For engineering consists of more than machines and processes; the task of the engineer is to marshal effectively the resources at his command, to understand the limitations and potentialities of his tools and materials, and to organize his human as well as material resources for the accomplishment of the task at hand. It is perhaps in this last category that the Romans truly excelled.

Using the basic tools which had come to them from previous times and the improvements invented by the Greeks, the Romans nevertheless succeeded in accomplishing engineering feats which had no counterparts until relatively modern times. Roman engineering skill represents a triumph of human organization, and the Romans displayed the same organizing skill in law, government, and military matters. And, while the Roman Empire declined and eventually disintegrated, its engineering constructions remained as a source of wonder and amazement for future generations, a constant reminder of "the grandeur that was Rome."

5 / Technology in the Middle Ages

LYNN WHITE, JR.

The traditional historical picture of the Middle Ages (roughly from the 5th century A.D. to the mid-15th century) has been one of cultural decline, particularly in the early Middle Ages. These centuries, from the 5th to the 9th, have therefore sometimes been called the Dark Ages. Yet such a view of the Middle Ages, and even of its early period, is false when viewed from the standpoint of the history of technology.

Medieval technology continued that of the Roman world. In the eastern half of the Roman Empire, Byzantium, the New Rome established in 330 by Constantine, enjoyed an amazing prosperity and vigor for a thousand years and more. Even when, in the 7th century A.D., the Arabs wrested Syria and Egypt from Byzantium, there was no "decline and fall": on the contrary, the very creative new Islamic civilization incorporated and perpetuated the technical achievements of Greece and Rome.

The idea of the so-called Dark Ages is therefore applicable only to the western portion of the Roman Empire, but again, it is not in terms of technology. In the West the turmoil of the Germanic invasions led to a technological slump only in a few areas. The Romanized Celts of Britain, for example, were pushed into Wales and Cornwall by the fairly primitive Angles and Saxons (who were, however, superb goldsmiths), where they lived in such difficult circumstances that technical rejuvenation could not be spontaneous. Eventually it came from the Continent, where culture never sank so low, despite instability, depopulation, and economic depression. A symbol of the general maintenance of skills in the barbarian kingdoms is the tomb of Theodoric the Ostrogoth (d. 526) at Ravenna: it is capped by a monolithic dome weighing 276 tons which was barged some one hundred miles from Istria and lowered with razor-edge precision onto a masonry drum.

When Roman inventions did pass out of use there was always a good reason. Roman roads were so costly to maintain that even the wealthy Byzantine and