CHAPTER 6

TECHNOLOGY

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I ANCIENT TECHNOLOGY IN MODERN HISTORIOGRAPHY

Ancient technology has been a subject of controversial scholarly debate since the beginning of the twentieth century. So far, a consensus has proved unattainable, whether about the issues and topics of a modern history of ancient technology, about the criteria of evaluation of technological developments in pre-industrial societies, or about the actual spread of technological innovations. In such circumstances, this chapter must begin by taking up a position in relation to the views expressed in earlier research, and at the same time offering some methodological justification for my own view.

Almost all work on the history of technology published before 1984 espoused the opinion that technological development in antiquity never implemented advances that were actually quite possible; that ancient technology had, on the whole, been characterized by stagnation; and that it had only few inventions to show which could be compared in importance to the accomplishments of the ancient civilizations in such areas as literature, art, philosophy, mathematics or medicine. It was further held that those few technological innovations which are documented had scarcely been put to economic use, and had therefore only had scant influence on work, production, and productivity. Various reasons were given for the perceived primitive and backward nature of ancient technology, such as a reverence for nature that was rooted in religion, the preponderance of thought structures shaped by rhetoric and therefore unsuitable for the understanding of technical facts, or the elitist self-perception of ancient scholars who had had no interest in making practical use of their scientific knowledge. Economic factors were also brought into play, such as the lack of markets for the yields of mass-production based on the mechanization of work processes, the lack of capital for the building up of industries, the lack of suitable energy sources for industrial production and, not least, the existence of slavery, which had

Translation by Annemarie Künzl-Snodgrass, with the help of Anthony Snodgrass.

supplied the ancient economy with sufficient cheap labor, so as to make the use of labor-saving machinery superfluous.[1]

This critical view of ancient technology is in many cases based less on a comprehensive evaluation of the sources for the history of technology in antiquity, than on generalized statements that can hardly be adequately substantiated. A characteristic example of this can be found in Finley's observations at the beginning of his much-cited 1965 essay on "Technical innovation and economic progress in the ancient world." His statement "it is a commonplace that the Greeks and Romans together added little to the world's store of technical knowledge and equipment," an older position in scholarship, which should have been critically evaluated, is instead accepted as a *communis opinio* and used as the starting point for the deliberations on ancient technology which follow. In this same context it is significant that Finley, after giving a (by no means comprehensive, yet still impressive) list of technical innovations, comprising amongst others the cog wheel, screw, rotary and water mill, screw press, glass production, concrete, hollow-cast bronzes and torsion catapult, comments on this list by saying that "it adds up to not very much for a great civilisation over fifteen hundred years."[2] The criteria for such an evaluation of ancient technology remain unclear; the question arises whether, in the light of the inventions listed by Finley, it would not be more appropriate to credit ancient society with a considerable potential for technological innovation and to analyze the causes of the technological development achieved, rather than to postulate a technological backwardness in antiquity and then discuss the reasons for the perceived stagnation.

Behind much of the work published in the twentieth century on ancient technology lies an understanding of technology which is, to a high degree, shaped by technological progress in the age of industrialization. Since the beginning of the Industrial Revolution, an acceleration in technological change has taken place, which through the mechanization of work processes and the use of machinery led, from the first, to a fundamental change of production and thus to a hitherto unimagined increase in productivity. The interdependency of technological progress and economic growth, so characteristic for modern industrialized societies, is reflected in the fact that inventions are very swiftly put to economic use. From early on, industry went over to pushing technological developments ahead in their own research laboratories, in order to secure advantages for themselves in the competition of the markets. Through competition between businesses as well as between nation states, through patency laws which guaranteed

[1] Lombroso-Ferrero 1920; Lämmli 1968: 44–9, 58–67; Kiechle 1969; Vernant 1974; Gille 1980: 170–95; Greene 1990; Schneider 1992: 22–30; Wilson 2002; compare also the criticism of such positions in Persson 1988.

[2] Finley 1965b: 29.

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the economic utilization of inventions, and through the development of joint-stock companies, these processes were still further accelerated, so that innovations followed each other in ever quicker succession. Railways, motor cars, and aeroplanes revolutionized transport in the nineteenth and early twentieth centuries, as did telephone and radio with communication systems and electricity and power stations with power supply. Technological change spread beyond industry into agriculture, private households and, with electronic data-processing in the past two decades, into office work as well as the whole area of communication. Far-reaching social change sprang from industrialization: while the number of workers in farming decreased strongly, the number of industrial and office workers increased, production came to be concentrated in industrial cities, which developed into conurbations with millions of inhabitants; in the longer term, the supply of food and consumer goods to the population improved.

Impressed by the technological progress of the nineteenth and twentieth centuries, ancient historians had to grant the superiority of modern technology over ancient; yet at the same time it was held that it had been in principle possible for antiquity to anticipate modern technological developments. It was pointed out in this context that the principle of steam power had been known in antiquity and that the building of steam engines had thus been a possibility.[3] On this premise, it needed to be explained why technological progress comparable with that of the Industrial Revolution had not taken place in the Roman empire, although the empire had at its disposal considerable technical means and great progress had been made in the understanding of nature.

Such argumentation understands industrialization as the model for a technological development which can serve as a yardstick for other epochs and societies; every deviation from this model therefore needed an explanation. What was not taken into account was the fact that the Industrial Revolution was based on specific economic and technological, not to mention social, scientific and political, conditions which only became present in the eighteenth and nineteenth centuries; it is impossible to detach industrialization from the context of European, and particularly British, history of that time.

The conditions for technological development changed fundamentally with the Industrial Revolution; therefore, when describing the technology of pre-modern agricultural societies, it makes little sense to take as a starting point the expectations and horizons of modern industrialized societies. Rather, the attempt should be made to understand technological development and the potential for innovation in agricultural societies from the standpoint of their own conditions. One part of this is the examination of

[3] Diels 1920: 29–33; Kiechle 1969: 148–55.

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individual inventions or minor improvements precisely in terms of their importance in the context of agriculture and craft.

A new view of ancient technology was formulated in 1984 by White and Wikander. In a longish section of his *Greek and Roman Technology*, White gives an impressive overview of "Innovation and Development" in antiquity, taking into account all areas of technology ranging from agriculture and craftsmanship to the military sector. Independently of White, Wikander addressed the problem of "technological stagnation" in a study of the diffusion of the water mill in antiquity, contradicting the accepted opinion that water power had scarcely been put to economic use in the Roman empire, even though the principle of constructing a water mill had already been known in Augustan times. Lately, Greene and Wilson have pointed in a series of articles to the technological advances of Roman times especially, decisively supporting the view that ancient technology must be freshly evaluated.[4]

More recent studies of the history of technology increasingly take as their theme, besides invention, the transfer of technology, that is the adoption of technological knowledge from other societies or the transfer of one's own technology to other regions. This aspect is of considerable importance for the history of antiquity, in as much as the development of Greek civilization in archaic times was to a high degree based on the appropriation of the technological achievements of Egypt and Mesopotamia; while the historically relevant process of Romanization, especially in the western Mediterranean and in north-western Europe, also included the spread of Roman technology in the provinces.

One of the most important results of modern research in the history of technology is, without doubt, the insight into the interdependency of technological and economic developments. Economic activities are, on the one hand, dependent on the technological equipment of a society; on the other, they favor innovation and thus create the conditions for technological progress. This by no means applies to modern industrial societies only, but also – within limits – to pre-modern agricultural societies. Economic development in antiquity can only be understood when studies of economic history sufficiently take into consideration the technological levels reached in Greece and in the Roman empire. The production and distribution of goods depended on the use of tools, equipment, and means of transport, as well as on the application of technological procedures in the production and transformation of substances; the use of certain tools and equipment shaped the work processes, and the productivity of agriculture and craft had a considerable influence on the prosperity of urban centers.

[4] White 1984: 27–48; Wikander 1984: 5–15; Greene 2000; Wilson 2002.

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II THE TECHNOLOGICAL SYSTEMS IN ANTIQUITY: AGRICULTURAL TECHNOLOGY, TOOLS, ENERGY

Agricultural technology, mining, the various branches of craftsmanship and transport represent areas of technology by no means independent of each other, but showing numerous mutual dependencies and thus forming a technological system.[5] For example, the level of metal-working is of decisive importance for building, the working of wood for ship-building. Plato already clearly sees this connection: he points out that craftsmen produce the tools for other crafts – thus a carpenter produces a loom for a weaver – and emphasizes the specialization of the individual craftsman. Thus, in a bigger city, craftsmanship is directed not only to goods for consumption, but also to tools and equipment for production.[6]

For an adequate and comprehensive description of a technological system it is necessary, first to establish the economic significance of the various branches of the economy; then to work out the characteristics of the means of production typical for the system; finally to record the energy sources at the disposal of the economy. For the technological system of antiquity, three fundamental facts call for notice:

1 Ancient societies were agricultural societies: agriculture was their economic basis. This means that particular weight must be given to agricultural technology in the description of ancient technology.
2 Ancient technology must primarily be characterized as a tool-based technology; the use of tools was indispensable for all important processes of work and production.
3 Human and animal muscle power remained the crucial sources of power until the end of antiquity. The thermal energy needed for the preparation of food, as well as for metal-working or for the production of glass or ceramics, was delivered by wood or charcoal. From Augustan times, water power was used for the grinding of grain; for late antiquity it is also documented for the sawing of marble.

Agriculture had as its primary function the production of food, with the cultivation of grain, wine and olive trees being prominent; fruit and vegetable growing also played an important part. The mainly vegetarian diet was supplemented by products of animal husbandry, in particular cheese and pork. It must not be overlooked here that agriculture also delivered the raw materials for the production of textiles – wool and flax – and that animal breeding supplied both agriculture and transport with work animals – oxen, mules, and donkeys – and the army with horses for the cavalry. The most important aim of cattle husbandry was the rearing of oxen.[7]

[5] Gille 1978: 19. [6] Pl. *Cra.* 387d–389d; *Resp.* 370c–e; *Leg.* 678c–679b.
[7] Isager-Skydsgaard 1992; White 1970b; White 1984: 58–72.

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In ancient agriculture there existed not only farmsteads where farmers farmed either their own or leased land, but also bigger estates specializing in a market-oriented production with particular products, and gigantic *latifundia*, which were normally managed extensively. While small farmers usually clung to traditional equipment and procedures and hardly had the economic scope for experimentation with new technologies, the owners of big estates in Roman times were really interested in using new or improved equipment and adopting new methods of cultivation or animal husbandry; they had financial resources at their disposal to increase the output of their estates through the acquisition and use of new or improved equipment.

In ancient agriculture, certainly, much of the work hardly changed over long periods of time: for example, ploughing with a pair of oxen, hoeing of the ground to eliminate weeds, harvesting the grain with a simple sickle, winnowing, or harvesting olives with long sticks. Numerous innovations are however attested, for example in the threshing of grain; in many estates in Italy, grain was not trodden out by animals, but rotating sledges were used. At the same time, threshing with threshing sticks was common. Wine- and oil-presses were significantly improved in Roman times. Yet in many cases, innovations in agricultural technology were not established throughout the empire, but only in individual regions. Moreover, inventions did not at all always result in the immediate suppression of the older technology. This is especially true of wine- and olive-presses: they were expensive acquisitions and had a relatively long life-span; therefore they were not replaced immediately even when construction had been partially improved. Thus it was possible to have various types of press simultaneously in use.

For ancient craftsmanship, working with a tool was characteristic; both Plato and Aristotle analyzed the function of tools and described it in precise terms. According to Aristotle, it is his soul, which already bears in itself the form of the product, and his knowledge that move the hands of the craftsman; his hands in turn move the tool which has an effect on the material.[8] Thus the structure of craft-production can be understood in its essence: the craftsman directs a tool with his hand and so shapes the material; the work of the craftsman is based on a clear idea of the object which is to be produced, on knowledge of the properties of the material used for working and not least on manual dexterity. Craftsmanship of this kind dominated many branches of manual work in antiquity.

Under ancient technological conditions, a mechanization of production, that is the transfer of individual steps in the course of the work to a machine, could be realized only within certain limits. Besides tools, use was also made of mechanical equipment, which either made certain work easier or else made it possible at all. In an illuminating section, Vitruvius differentiates

[8] Arist., *Gen. an.* 730b.

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between tools (*organa*) and mechanical equipment (*machinae*), which in his opinion differ from each other in that *machinae* are moved by several workers and by bigger forces, whereas a tool is used by a single craftsman in a intelligent way.[9] So the operation of mechanical equipment did not need the technical expertise of a craftsman, and was therefore not comparable with the use of a tool. The effectiveness of mechanical equipment was based on the use of mechanical instruments such as the roller, the pulley, the lever, the winch or the screw; examples are on the one hand lifting equipment, which enabled heavy stone blocks to be lifted on building sites; on the other, the big wine- and oil-presses. This by no means rendered superfluous the use of human labor; rather, the physical force needed for certain work was reduced through the use of mechanical equipment. The analysis of simple mechanical instruments such as roller, pulley, lever, winch or screw, and the construction of mechanical equipment needed a kind of competence which far exceeded the knowledge and experience of a craftsman: a new scientific discipline emerged in mechanics, which employed mathematical methods to enable the most efficient use of mechanical instruments.

Under the conditions of ancient technology, human muscle power remained one of the most important energy sources.[10] Agricultural work in particular was highly physical work, done with simple tools such as hoe, sickle, or scythe. Craftsmen use muscle power to handle their tools: this is true for all branches of craft, for the working of metal or ceramics as well as for textile production; in a similar way, the mechanical crushing of ore, the forging of iron by hammering the piece, the shaping of silver or bronze objects by cold-working, the shaping of clay vessels, the weaving or fulling of cloth all demanded the use of human labor. On top of that, human muscle power served as driving-force: thus the potter's wheel was driven by an assistant while the potter shaped the vessel, and the big water-sluicing installations in Roman mines were operated by manpower, as were the Archimedean screws used for irrigation in Egypt. As is shown on Roman reliefs, the big cranes used to lift big loads on building sites were equipped with tread-wheels, set in motion by manpower.

Above all, the part played by human labor in the transport of goods should not be underestimated; in particular, it was people who carried the loads at harbors or in the middle of cities – amphoras filled with wine or oil as well as sacks of grain. The distances were usually fairly short, but such transports made up a substantial portion of the whole. Even in the transport of human beings, people as carriers played a considerable part: the sedan-chair carried by slaves served as a normal means of transport for the members of the upper classes in the cities, but also in rural districts.

[9] Vitr. *De arch.* 10. 1. 3. [10] Halleux 1977; Landels 1978: 9–33; Casson 1984a; White 1984: 49–57.

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After human labor, animal muscle power was the second most important source of energy in antiquity. In the ancient economy, the prime function of animals was that of supporting people in their work, and many of the domesticated animals were work animals.[11] Oxen were used in agriculture above all for ploughing, for the necessary preparation of the soil for sowing; oxen also pulled heavy, mostly two-wheeled carts and thus transported loads such as the monumental stone blocks which had to be carried from the quarries to the building sites. Donkeys carried loads with the help of pack saddles and baskets; they brought agricultural products from the hinterland to the cities on a daily basis, as Libanios describes for Antioch; in particular, the transport of wood for fuel by donkeys is also widely attested.[12] Mules, which were better suited to certain tasks than horses or donkeys, were harnessed to light carts or even ploughs and were also valued as riding or transport animals. In the eastern parts of the Roman empire the camel, which is superbly suited to the climatic conditions of desert regions, became quite important for transport.

Although horses are more powerful than oxen, their use in ancient economies remained problematic: not because the type of ancient harness presented a decisive obstacle, as an older thesis held, but because of the difficult temperament of the horse, and in addition its susceptibility to injury and illness, as well as the need for high-quality food. Only when overland transport in the north-western provinces grew commoner and wider inland regions were increasingly opened up to carriage-roads did the use of the horse as a draught animal catch on.[13]

In many cases animal power was confined to the simple function of driving a mill or raising water. The grinding of grain is widely documented, and represented in images too, as the work of donkeys, mules and, above all, horses. Harnessed to a rotary mill, the blindfolded animal had to drive the heavy millstone in the narrowest of circles and with extreme flexion of its body; in addition, the use of oxen for the scooping of water is documented for Roman Egypt.[14]

Thermal energy was as necessary for the preparation of food, the baking of bread, or the cooking of meat as for the smelting of ore, the forging of iron, the casting of bronze, the firing of lime, bricks or ceramics, or for glass production. The fuel most used in the Mediterranean lands was wood and charcoal, the use of coal being widespread only in the Roman province of Britannia. Charcoal has several advantages in comparison with wood; its calorific value is higher than that of wood, so that higher temperatures can be reached, and it burns more or less smoke-free. Since charcoal kilns were

[11] Xen. *Mem.* 4.3.10; Pl. *Resp.* 370d–e; Cic. *Nat. D.* 3.159.
[12] Lib. 50; Dem. 42.7; Apul. *Met.* 7.17f. [13] Amouretti 1991; Raepsaet 2002.
[14] Moritz 1958: 74–102.

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often situated in remote forest areas, charcoal had to be transported over longish distances to the consumers. Charcoal from different woods was used for different purposes; young trees were mostly used for the production of charcoal, which could have negative consequences on forestation.[15]

Wind power was used only for shipping: Greek merchantmen had a high mast and a square-rigged sail, which offered a big enough surface to the wind to drive the ship. Merchantmen made use of rowers only in exceptional cases; there was a type of fast ship which could deliver wares to their destination even when the wind failed. Warships, on the other hand, having to remain capable of maneuver even when the winds were unfavorable, were driven by crews of oarsmen during military operations.[16]

The use of water power is without doubt to be considered as a breakthrough in technological history; it was probably the construction of water-wheels that constituted the first use of machines driven by running water. A transmitting mechanism then made it possible to transfer the rotary movement of the water-wheel to the grindstone. With the mill driven by water power, which according to recent research was in widespread use throughout the Roman empire, the foundation for the technological system of the Middle Ages was created.[17]

III AREAS OF TECHNOLOGICAL PROGRESS

Technical advances that were of economic relevance can be substantiated in various areas of the ancient economy: these at times changed fundamentally the processes of production, the kinds of work and the products themselves, or generated new products. In building, technological innovations such as the use of concrete (*opus caementicium*) and the superior command of the construction of the arch had opened up completely new possibilities for architecture and had, more especially, made possible an accelerated development of the infrastructure of the Roman empire. The sources may not allow us to follow these processes in detail; but a few examples can nevertheless well demonstrate the characteristics, the economic consequences and the limitations of technological change in antiquity.

(a) *The development of the grain mill*

Since grain, containing in sufficient quantity almost all the nutritional elements needed by human beings, plays a decisive role in ancient nutrition, the grinding of corn, along with ploughing, sowing, and harvesting, was part of the agricultural work necessary for sustaining life. The machine

[15] Reece 1969: 43–6. [16] Casson 1971; Landels 1978: 133–66.
[17] Landels 1978: 16–26; Wikander 1981; 1984.

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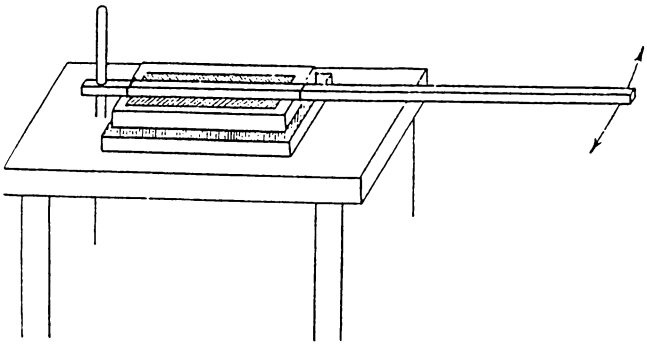

Figure 6.1 Olynthian grain mill with upper stone and long handle
Source: Moritz 1958: 45

used for this was the mill, which underwent several significant changes in the course of antiquity. For any evaluation of ancient technology, it is indispensable to describe these changes, together with their effects on the work process and work productivity, with precision.[18] The earliest reference in Greek literature to the grinding of corn is in Homer: in Odysseus' palace on Ithaca, twelve women work on the mills;[19] these would be saddle querns, which had a firmly fixed lower stone and a smaller moveable upper stone. The upper surface of the lower stone was inclined at about 25 degrees; the corn was usually ground by women who knelt at the upper end of the lower stone, moving the upper stone forwards and backwards; this procedure had to be interrupted frequently to remove the flour and to put more corn grains between the millstones. Corn-grinding was labour-intensive, and tiring and monotonous work for those who undertook it.

Millstones found at Olynthus, which was destroyed in 348 BC, show that in classical times the grain mill was considerably improved by two innovations. The upper millstone was now fitted with a large funnel, so that grains fed into it while grinding could run slowly down into the space between the millstones. The lower, horizontal millstone rested on a table, while a long horizontal pole was fixed to the upper millstone, which was attached at one end to a vertical upright, while the other end, protruding beyond the upper stone, served as a handle. With this device, efficient use could be made of leverage in the grinding operation.

The rotary mill probably originated in the western Mediterranean, through the use of two circular millstones; a rotary movement now replaced the backward-and-forward one. This type of mill was probably first used

[18] Moritz 1958; Maróti 1975; Wikander 1981; Wikander 2000: 371–400; Wilson 2002: 9–15.
[19] Hom. *Od.* 20.106–11.

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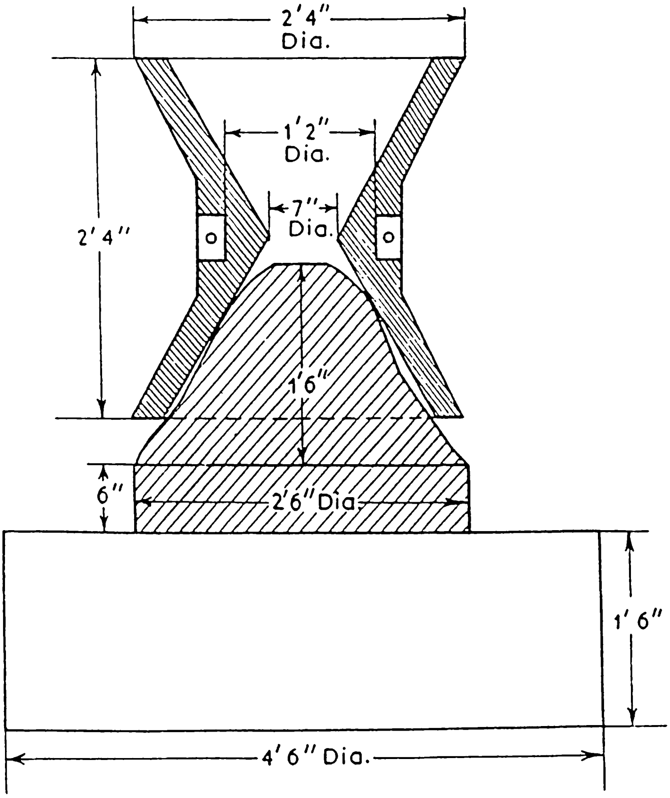

Figure 6.2 Pompeian mill with *meta* and *catillus*, the upper stone
Source: Moritz 1958: 75

as a hand mill. Soon it proved possible to have an animal carry out the continuous rotary movement. Portrayals of this donkey mill can be found on several Roman reliefs, while numerous actual mills have survived in Pompeii. It consisted of a bell-shaped lower stone and a hollow, hour-glass shaped upper stone. This was not in direct contact with the lower stone, but was suspended on a wooden frame, whose center rested on a vertical iron axis. In this way, the mill could be adjusted exactly to different types of flour, while abraded stone was prevented from getting mixed in with the flour. In comparison with the saddle quern and the rotary hand mill, which were above all for domestic use, the Pompeian donkey mill was a complex appliance, which brought a higher level of mechanization to grain milling and was used mainly by commercial bakeries to produce flour for bread production. The donkey mill freed people from a monotonous labor which was now loaded on to animals.

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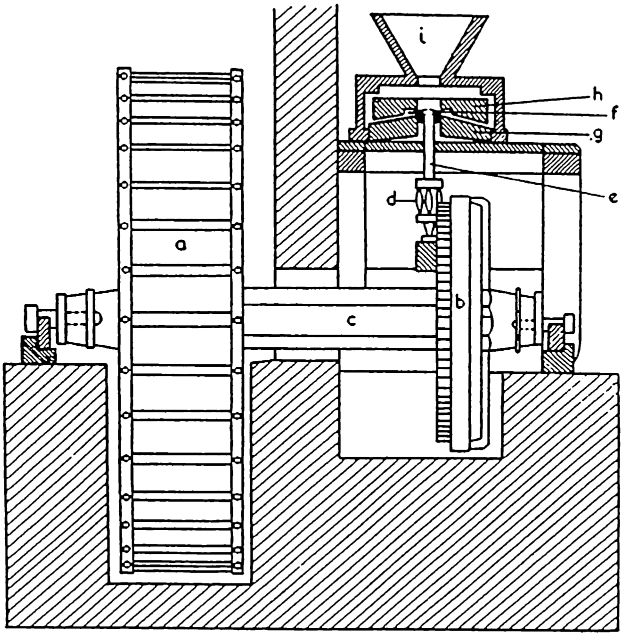

Figure 6.3 Water mill as described by Vitruvius (10.5.2)
Source: Moritz 1958: 123

From the first century BC on, water power generated by water mills was used for the grinding of grain; knowledge of the cog wheel was the prerequisite for the mechanism of transmission by which the rotary movement of the water wheel was brought to bear on the millstone.

Besides single water mills in various provinces of the Roman empire, large mill complexes, which were erected on slopes and had several milling stations, are documented in archaeological remains and literary sources; water was supplied by aqueducts. One such facility near Barbegal, in the vicinity of Arles, has now been dated to the period of Trajan.[20]

In fourth-century Rome, the mills on the Janiculan hill delivered the flour for the city's population.[21] When the Goths at the siege of Rome interrupted the water supply for these mills, Belisarius in AD 537 had mills installed on ships moored by a bridge over the Tiber. The ship mill, originating in a military crisis, has been shown to have existed in many European cities down to early modern times. Its advantage lay above all in the fact that the water wheel could be adapted without difficulty to the changing water level of the river.[22]

[20] Leveau 1996. [21] *Cod. Theod.* 14.15.4. [22] Procop. *Goth.* 1.19.8–29.

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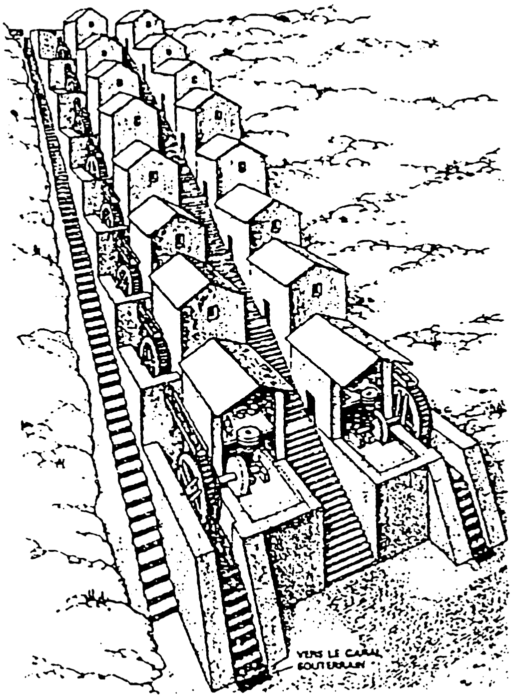

Figure 6.4 Barbegal multiple system with 16 wheels
Reproduced from Sagui 1948: 225–31

An overview of the development of the mill, from the primitive saddle quern to the water mill and then the ship mill, makes it clear that the step-by-step improvement of this invention had achieved a notable lightening of the work necessary for everyday subsistence. People were relieved from heavy physical labor; human labor as the driving force was replaced first by animal muscle power and then by water power. The transition from backward-and-forward to rotary movement was a precondition for the mechanization of the mill. For the construction of the water mill, a transfer from one area of technology to another was necessary: the water wheel driven by running water, which combined the functions of a driving wheel and scooping wheel, was now used, by the transmission of power through cog wheels, as the drive for the mill.

(b) *Oil and wine presses*

For the production of olive oil and wine, which together with grain were an important component of the ancient diet, equipment was needed for

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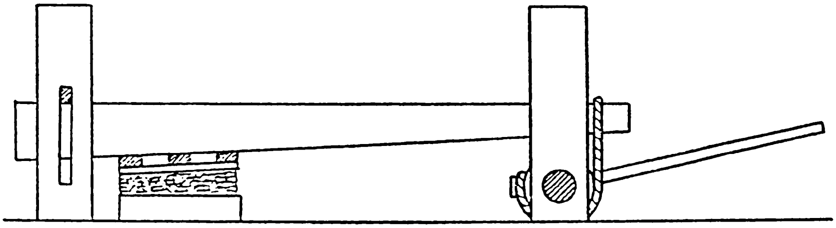

Figure 6.5 Roman lever-press as described by Cato the Elder
Reproduced from Drachmann 1967: 31

the pressing of the olives or the grapes. Although it was not at all unusual to tread grapes with the feet, from archaic times use was also made of the lever-press, whose press-beams were pulled down by weights, such as large stones, so that continuous pressure was put on the material to be pressed. The improvements made to this press were generally aimed at increasing the efficiency of the pressing process by technical means and, at the same time, decreasing the danger of injury to the people working with the press; in addition, it was desirable to save as much space as possible when setting up the press-beam, so as to limit the size of the press-rooms.[23]

While the press-beams of the early Roman presses were pulled down by a rope winch and a long lever, attempts were made in the ensuing period to construct a press in which continuous pressure could be applied to the material, without the need to employ uninterrupted human labor. For that purpose, a heavy stone was used as weight, but the rope winch was retained. This was now used to lift the stone, which in turn pulled down the press-beam by its weight. There were, however, serious disadvantages to this construction: the long levers turning the winch could break or jump out of their fastenings; the rope, too did not always run smoothly over the roller. These problems were only overcome when the rope winch had been replaced by a big wooden screw, which was fitted into a thread on the press-beam and had the weight at its lower end.

Through rotation of the screw the weight, which to start with was on the floor, could be lifted up, and the press-beam lowered accordingly. There were various types of screw-press, amongst them also presses without a stone weight, where the press-beam was pulled down by a screw fixed to the floor.

Towards the middle of the first century AD a new type of press emerged, where direct pressure was put on the material to be pressed by the rotation of a screw fitted vertically into a wooden frame. There were several advantages

[23] Drachmann 1932; Rossiter 1981; White 1984: 67–72; Brun 1986; Amouretti 1986: 166–75; Cato, *Agr.*18–22; Vitr. *De arch.* 6.6.3; Plin. *HN.* 18.317; Heron, *Mechanica* 3.13–21.

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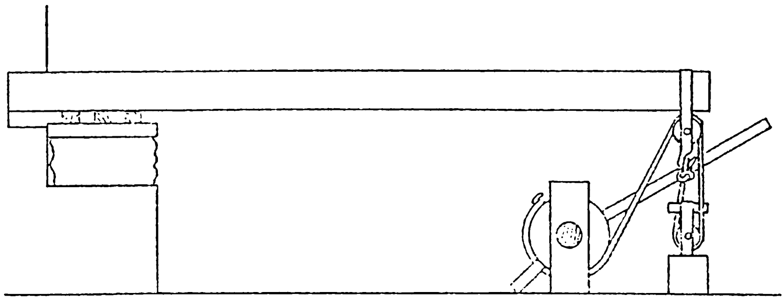

Figure 6.6 Lever-and-stone press according to Heron's *Mechanika* (3.13f.)
Source: Drachmann 1967: 32 (top)

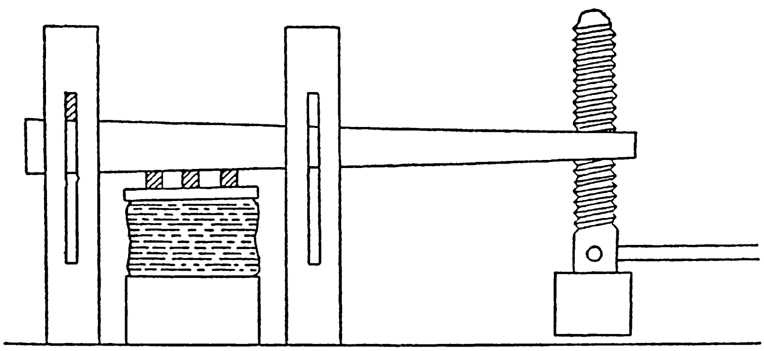

Figure 6.7 Lever-and-screw press according to Pliny the Elder (18.317)
Source: Drachmann 1967: 33

to this type of press: since there was no need for a long press-beam, this press needed very little space and could be easily transported.

This type of screw press appears relatively quickly in the urban context; it is remarkable that it was already used as a cloth press in Pompeii, that is before AD 79. The conditions of ancient technology clearly made it quite possible for equipment designed for agricultural use to be employed in craft production.[24]

Ancient presses proved to be so efficient that it was not possible to make fundamental improvements in them in the Middle Ages and in early modern times. In the Mediterranean lands, presses with press-beams and wooden screws were used until the early twentieth century; the screw press

[24] Moeller 1976: 25–7.

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which put direct pressure on the material to be pressed was used in trade for other purposes, such as the book press for the printed book.

The development of the mill and the press is exemplary for technical change in antiquity: equipment that was important for production was improved; new mechanisms, such as the transmission of power through cog wheels or the generation of pressure through the turning of a screw, were introduced. Such technological progress is hardly to be rated as marginal.

(c) *Innovations in the production of ceramics and glass*

The commercial production of ceramics supplied many families and households in antiquity with vessels and dishes of high quality; production of one's own clay pots for domestic use seems to have continued to be of importance only in remote rural regions. In these conditions, the potters produced large quantities of ceramic vessels for local and inter-regional markets from archaic times onwards. Technical innovations in ceramic production thus involved a trade which was of some economic importance.[25]

Already in archaic and classical times, the production of black- and red-figure Attic vases was based on considerable technical and manual skills: the clay had to be prepared diligently before the shaping of the pots, and the firing process required exact regulation of the temperature in the kiln and the oxygen supply during the separate phases of firing. In traditional ceramic production, the potter's work was limited to the shaping of the pot on the potter's wheel, while a vase painter painted the pots before firing. In Roman times, this working process was fundamentally changed for the production of the relief-decorated *terra sigillata* vessels, with the employment of moulds. Smooth *terra sigillata* pots, shaped without a mould, were still in mass production at the time of the Principate but, in addition, relief-decorated vessels from the pottery centers of Southern Gaul were marketed in many parts of the Empire during the first century AD. The thick-walled shaping bowls used as moulds carried on their inner side decoration in relief, executed by pressure with an incising tool (*poicon*). The production of relief-decorated ceramics was thus separated into three stages of work: first, the burins were cut; then the shaping bowl was prepared, with the hollow relief on its inner side; lastly, the mould was fired and used to shape the relief-decorated vessels. The potter put the mould at the center of his wheel, pressed the clay into the inside of the shaping bowl with the wheel turning, and thus drew up the wall of the pot. While the pot was being shaped, the relief decoration was simultaneously created, and the individual vessel did not require separate and time-consuming decoration. Once the clay had dried (and simultaneously shrunk), the pot was taken from the

[25] Peacock 1982; Bémont and Jacob 1986; Noble 1988.

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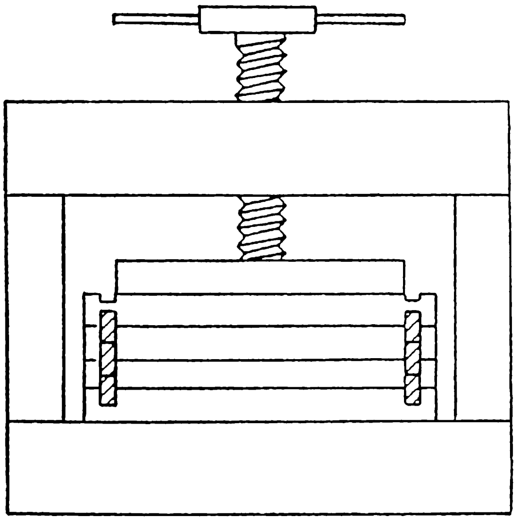

Figure 6.8 Screw-press according to Heron (3.20)
Source: Drachmann 1967: 36

shaping bowl, which then could be used again. In this way it was possible to produce identical pots in great numbers; relief-decorated ceramics became an article of mass production.

In the pottery centers of Gaul, big kilns were erected for the firing of ceramics, which can hardly be compared with the kilns in Greek potteries. At La Graufesenque, such kilns were 4 meters wide and 3 meters high, and had a capacity of approximately 30,000 pots; lists, preserved as graffiti on bowls and plates, show that several potters delivered their products for simultaneous firing.[26]

In certain pottery centers, the existence of big installations for clay preparation can be demonstrated: it seems to have been already then appreciated that productivity in ceramic production could be increased by wider cooperation at the stages of clay preparation and firing.

Glass production provides a further example of the way in which technological innovations could have far-reaching economic consequences. Glass is a material which does not occur in nature, but has to be produced from various natural components (quartz sand, soda, lime); it was used, before the first century AD, primarily for the production of small containers. This glass was colored and opaque; small bottles were shaped by the sand-core method, in which a solid sand core was immersed into the molten glass. Two technological innovations made it possible to open up completely new

[26] Marichal 1988.

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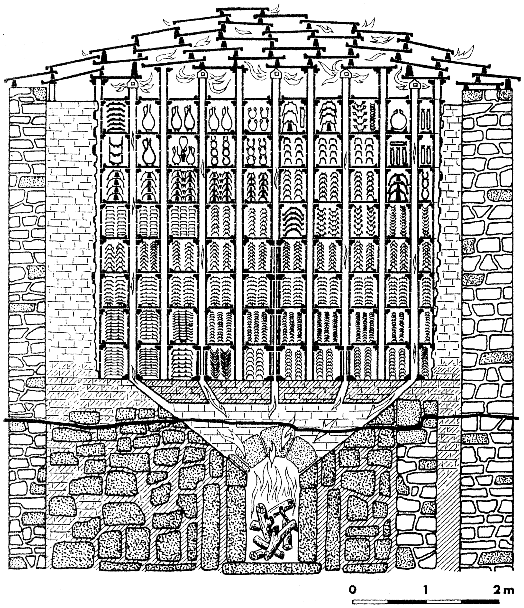

Figure 6.9 A large pottery-kiln at La Graufesenque
Reproduced from Vernhet 1981: 38

production possibilities for glass as a material: with the glass-blowing pipe, bigger vessels could be shaped through glass bubbles, and certain additional ingredients made it possible to produce colorless, transparent glass. Thus the glassmakers were able to produce bottles, glasses, little jugs, and bowls which displayed their content for all to see. An anecdote about a glassmaker in Rome at the time of Tiberius and the representations of glass vessels on murals in Pompeii show that this new material exercised widespread fascination. Glass objects were soon distributed widely, and glass production in the western Mediterranean and the north-western provinces was accordingly soon on the increase. The gravestone in Lyon of the glassmaker Julius Alexander, who was of African origin, is testimony to the fact that this craft offered the opportunity for a certain prosperity. New techniques were repeatedly developed in ancient glass production: at the time of the early Principate, two-colored and two-layered glasses were created, with the use of moulds making it possible to decorate bottles in relief or shape vessels in the form of fruits. In late antiquity *diatreta* glass, with the appearance of being enveloped in a net, was created by intricate cutting methods. Finally, even glass plates with applied figural images made of gold were produced. Besides the plain glassware for domestic use, the products of glassmakers included precious luxury items. The development of Roman

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glass production proves the craftsmen's ability to innovate and to be in total command of new techniques. In addition, it is clear that technical innovations spread and put to economic use fairly rapidly.[27]

(d) *New building techniques: Arch construction and* opus caementicum

Ancient architecture underwent a complete change during the Hellenistic age and the early Principate, thanks to two technological changes; this transition was not limited to the aesthetic dimension, but opened up entirely new possibilities for creating large interior spaces, without the use of many supports, and for bridging large spans. Arch construction undoubtedly had an effect on the design of façades, in particular of Roman monumental architecture; but its wider use was in the construction of installations for the infrastructure, for instance in the building of the bridges so important for the network of Roman roads. Similarly, aqueducts were led across wide valleys on top of high arches, as for example in the Pont du Gard in the south of France. In order to bring water to Rome in an open channel at the highest possible level, arched stretches more than 9 km in length were in several cases constructed in the plains outside the city.

From the second century BC a new building material, *opus caementicium*, came into use. This was a kind of liquid concrete which could be poured into wooden boarding and which, when it dried, was of such firmness that it was also suitable for the building of vaults and domes. Examples of this new building technique are the Pantheon, constructed at the time of Hadrian, which has a dome bigger than that of St. Peter in Rome or the Duomo in Florence, and the Frigidarium of the Baths of Diocletian (today S. Maria degli Angeli). In particular, utilitarian buildings used for trade, such as the market halls at Ferentinum or in Trajan's Forum in Rome, had large vaults made of *opus caementicium*. During the early Principate, in particular after the fire in Rome at the time of Nero, fired brick came into wide use as a building material for walls; the walls of larger buildings were often furnished with a core of *opus caementicium*, with the brick walls having the function of a boarding. Since *opus caementicium* retained its firmness even under water, it could also be used for the building of harbors.[28]

The construction of building complexes for inner-city trade, as well as the intensified improvements in the infrastructure of transport and traffic, were without a doubt of considerable importance for the Roman economy. In the big inland spaces of the western and north-western provinces especially, the transport of goods was dependent on a network of good and passable

[27] Strong and Brown 1976: 111–25; Newby and Painter 1991; Schneider 1992: 108–19; Plin. *HN.* 36.189–99; Strabo 16.2.23; Petron. *Sat.* 51; Sen. *Ep.* 90.31; Dessau, *ILS* 7648.

[28] White 1984: 73–90; Adam 1984; Hodge 1992; O'Connor 1993; Vitr. *De arch.* 2.6.

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roads; bridges made river crossings possible without passing through fords. Improvements in Mediterranean harbors, such as the construction of the mole at Puteoli or of the harbor basin at the mouth of the Tiber, supported long-distance trade and thus secured the supply of the big cities.

(e) *Shipping and land transport*

There were numerous innovations in shipping in antiquity, closely connected with the expansion and intensification of trade and the exchange of goods in the Mediterranean. Already in the archaic period, the long, slim galleys were no longer adequate for the demands of longer trading journeys. From the sixth century, therefore, ships were built with a thick-set body, high sides, high masts and a big square-rig sail. These ships were wind driven and therefore no longer needed rowers; because of their bigger loading capacity, they could be used for the transport of mass-produced goods such as grain, wine, and oil. In the time of the early Principate, grain for the city of Rome was transported from Egypt to central Italy by ships that could carry loads of over 450 tonnes in weight. One problem with such ships was that they often had only one sail; in order to increase the size, some Roman trading ships had two further masts installed at the bow and at the stern, besides the mainmast in the middle of the ship; and a triangular upper sail was fixed above the mainsail on the central mast. At the same time, the rigging and thus the maneuverability of the ships was improved. In figural representations, the lateen sail appears besides the square rig: its main use was probably for coastal shipping in the eastern Mediterranean. Ancient ships were perfectly capable of navigating the high seas: after the discovery of the monsoon winds, Roman ships traveling in convoy took the direct route to India by the Red Sea and across the Indian Ocean. The lighthouse of Brigantium (La Coruña) in north-western Spain proves the existence of Roman seafaring on the Atlantic.[29]

The construction of the boats used for the transport of goods on the rivers of the north-western provinces also underwent a series of technical changes. As is demonstrated by the finds of wrecks at Mainz, the Romans on the Rhine went over from the shell construction common in the Mediterranean, to skeleton construction, which made the building of the hull noticeably easier. Another characteristic of these boats is that the single rudder is firmly fixed to the stern post; this is clearly visible on several reliefs.

In the Mediterranean world until late antiquity, overland transport of heavy loads was mostly carried on in the traditional manner, that is, with pack animals or two-wheeled ox-carts; but at the same time, the fundamental change in overland transport in the north-western provinces, and

[29] Casson 1971; Landels 1978: 133–66; White 1984: 141–56.

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also in northern Italy, should not be overlooked. Strabo already appreciated the close connection between improvements in traffic infrastructure and technological developments in transport; in comparing Roman and Greek building activities, he notes that Roman roads were constructed in such a way as to allow the transport of entire ship's cargoes by cart. As is documented by numerous reliefs and mosaics, new methods of harnessing were experimented with, especially in Gaul and northern Italy; at the same time, carts were constructed which were better suited to the long-distance transport of heavy loads than the usual ox-carts with their big disc-wheels. While in archaic and classical Greece two oxen – more rarely two mules – were normally harnessed to a yoke fixed to the cart's shaft, during the Principate horses began to be increasingly used for overland transport. The harness was now adapted to the horse's anatomy, so that the animals were not handicapped when pulling. In Roman Gaul, heavy carts with two axels and spoked wheels were used for the transport of goods. They were usually pulled by two horses: a relief from Langres even shows a team of horses harnessed in couples behind each other. It was also possible to harness a single horse to a two-wheeled cart; the horse then walked between two poles, which were connected to the harness around the horse's neck.[30]

From Augustan times, wooden barrels were used in Gaul and northern Italy as containers for wine; their decisive advantage over amphoras was the better ratio between the weight of the container and the weight of the fluid; moreover, since vats did not have to be carried like amphoras but could be rolled, the transport of fluids, for example when loading or unloading ships, was made considerably easier. While smaller barrels were used for river transport, bigger carts were sometimes loaded with a single barrel of considerable capacity.[31]

(f) *Water-lifting equipment*

In ancient Egypt as well as in archaic Greece, devices for the lifting of water already existed: the *shaduf*, a swing-beam to which a scooping container and a counterweight were fastened, was used in Egypt for the irrigation of fields and gardens; with the *shaduf*, water could be taken from a river or canal and led to a field higher up. In Greece, such swing-beams were fixed directly to the well, in order to make the lifting of the water-filled clay vessels easier.

Two new devices for the raising of water were the scoop-wheel and the Archimedean screw. The scoop-wheel was either fitted at its circumference with boxes to take up the water, or else had containers attached there, which

[30] Landels 1978: 170–85; White 1984: 127–40; Raepsaet 2002.
[31] Plin. *HN* 14.132; Strabo 5.1.8; 5.1.12; White 1984: 133; Zimmer 1982: 218–19; 229–30.

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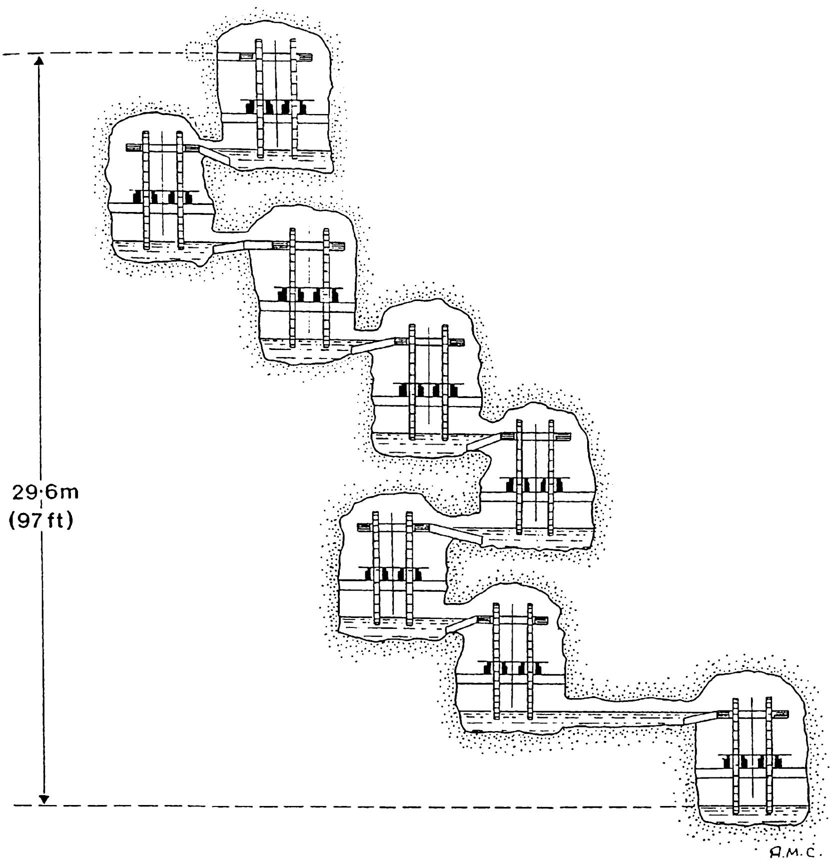

Figure 6.10 Water wheels used for drainage at Rio Tinto
Source: Wacher 1987: vol. II, 621

were then emptied at the highest point of the wheel. If the scoop-wheel was located on a river with strong enough currents, it could be driven by water power. The Archimedean screw, on the other hand, set up in a slanting position, had to be turned by human power; it could lift water only over a small vertical interval, but was an efficient device for the irrigation of agricultural land in Egypt.[32]

But the preeminent economic importance of water-lifting equipment lay in its use in Roman mines, much more than in its agricultural uses. When the Romans in Spain started to mine precious metals below ground-water level, they had to tackle the problems of drainage. For this, water-lifting

[32] Oleson 1984; Landels 1978: 58–83; Wikander 2000: 217–302; Vitruvius, *De arch.* 10.4–6.

equipment, long since used for the irrigation of fields, was installed in the mines. The contemporaries of the Romans were much impressed by their ability to pump whole streams of water out of mines with the help of the Archimedean screw: it was a precondition for the mining of gold and silver. Besides Archimedean screws, scoop-wheels were also set up in mines; since their size made it impossible to take them to their final position through the narrow shafts and galleries, they were put together from their components underground.

Only through the Roman solution of the technical problem of water containment in the silver and gold mines could sufficient quantities of precious metal be mined for the minting of coins under the late Republic and the early Principate.[33]

IV TECHNICAL KNOWLEDGE AND ECONOMIC DEVELOPMENT

At many levels in ancient societies, technical knowledge was passed on orally: experiences and knowledge were handed down from the older to the younger generation in the context of the rural family, without the need to record them. Similarly, in the field of craftsmanship, apprentices gained the necessary competence for the practice of their craft through direct contact with an older craftsman.[34] Apart from this knowledge gained through experience by farmers and craftsmen, a body of technological knowledge grew up in classical Greece, which was used to employ mechanical instruments with maximum efficiency, or to construct equipment designed for certain purposes. Architects in particular faced grave problems with the construction of monumental buildings, and needed a great deal of technological creativity to solve them. Examples are the lifting of heavy ashlar blocks, the transport of stone blocks from the quarry to the building site, or the laying of foundations in soft ground. Already in early classical times architects self-consciously recorded their achievements in their own writings. Later, Vitruvius systematically summarized the specialist knowledge of architecture, with technical aspects taking up a substantial part of his work.[35]

In the field of engineering, the aim of specialist knowledge was to understand exactly the causes behind the effectiveness of mechanical instruments; for example, much attention was paid to the lever and its effects. A specialist literature developed in the fourth century BC for this area of ancient technology, which was by no means confined to theoretical knowledge, but was quite attuned to practical application, for example, the *Mechanica* of Heron

[33] Diod. Sic. 5.37.3f.; Healy 1978: 93–100; Domergue 1990: 443–60.
[34] Meissner 1999. [35] Vitr. *De arch.* 10.2.11f.; cf. 7, *Praefatio* 12; Plin. *HN* 36.95–8.

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of Alexandria. Heron was interested in the improvement of presses, and was able to expound exactly the advantages and disadvantages of the various types of press, taking also the safety of the workers into consideration. It was specifically in the field of engineering that considerable progress, of importance for general technology and consequently for the economy, was made. A precise description of the transmission of power by cog-wheel, or the use of a combination of rollers (block and tackle) for the lifting of heavy loads, was achieved; the screw and the advantages of the screw press are also the subject of longish explanations.[36]

An enlightened attitude towards technological innovation is clearly expressed in the Roman literature on agriculture, by Cato, Varro, and Columella; fairly long treatises are devoted to the devices for pressing olives, the equipment used for threshing, or the methods of fertilization. Pliny likewise mentions, in his *Natural History*, new devices such as the heavy plough pulled by four oxen, the mowing machine used in Gaul, or the screw press.[37] The work of Pliny undoubtedly contributed to the spread of technological knowledge. The recording of technological knowledge in writing did not, however, lead to a permanent process of technological innovation; technological change remained in many cases spasmodic and dependent on specific contexts.

V CONCLUSION

The recent debate on the ancient economy distinguishes clearly between two forms of economic growth in pre-industrial societies: on the one hand, with the level of productivity remaining stable, growth depends on the extension of the land available for agriculture, on the opening up of new mines, or on an increase in the number of workshops. A precondition for this type of growth (extensive or aggregate growth) is a numerical increase in the labor force. Per capita growth, on the other hand, is dependent on an increase in work productivity; its prerequisites are normally technological innovation and an increase in financial expenditure on technical provision at production sites.[38]

In the debates of economic history, two fundamental facts are perhaps beyond dispute: on the one hand, that in antiquity as in other pre-industrial societies, considerable extensive growth took place, visibly represented by urbanization, the growth of urban settlements and the foundation of new cities, the development of wider regions for intensive agricultural use and

[36] Arist. [*Mech.*]; Heron, *Mechanica*; Drachmann 1963; Gille 1980.

[37] Cato, *Agr.* 18–22; Varro, *Rust.* 1.29.1; 1.52; Columella, *Rust.* 12.52.6f.; Plin. *HN* 18.171–3; 18.296; 18.317.

[38] Saller 2002.

the extension of mining activities; on the other hand, that economic growth since the beginning of the Industrial Revolution has essentially been attributed to an increase in work productivity, which in turn is highly dependent on increasing division of labor, technological innovation and rising capital investment.

The question that faces ancient historians is whether, and if so to what degree, technological innovation in antiquity contributed to a growth in productivity, and thus generally to intensive economic or per capita growth. First, the way in which working processes in agriculture, craft, and building were changed through technological development must be clarified. In antiquity, there were various possibilities for increasing the productivity of work processes: the introduction of new tools, the improvement of known tools and equipment, or the construction of complex mechanical devices. An example of the introduction of a new tool is the use of handled shears for sheep shearing in Roman Italy.[39] The importance of improvements in the details of technical equipment is often underrated. This is true for the vertical loom, which in Roman times had an upper and a lower beam, while the Greek loom possessed only the upper cloth-beam, the warp-threads being held taut by weights. At first glance, this change seems insignificant, but it made it possible to push the weft-thread downwards on to the already woven fabric and to weave sitting down, while with older looms the women had to work standing, and with raised arms. In this case, technological improvement certainly led to a considerable reduction in physical exertion. As is demonstrated by the development of the grain mill, there was even the possibility of a partial mechanization of work processes, resulting in the use of animal muscle power and finally of water power as the driving force. Mill complexes such as those near Arles and on the Janiculan hill in Rome had a high capacity of output and could meet the demands of several thousand people. A targeted use of the laws of mechanics also characterizes the construction of oil- and wine-presses or water lifting equipment, and the use of block-and-tackle for lifting heavy loads in the construction of large buildings. The Romans were also capable of adapting traditional technology to new conditions: many technological innovations can be traced in Gaul, for instance the wheeled plough mentioned by Pliny, which was better suited to the heavy soil of the regions north of the Alps than the Mediterranean plough; or the mower specific to Gaul, which allowed the harvest to be brought in in the quickest possible way and with little expenditure of labor.[40] By comparison with the archaic epoch, such technological developments certainly increased the productivity of work processes in Hellenistic and Roman times.

39 Varro, *Rust.* 2.11.9. 40 Pliny, *HN* 18.171–3; 18.296.

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But at the same time the limitations of technological development in antiquity must be emphasized. In the area of craftsmanship, manual tools were never replaced by machines nor, by and large, was manual production ever pushed aside. Such a division of labor as is described by Adam Smith in the famous first chapter of *The Wealth of Nations* was therefore hardly possible in the ancient sites of production. In contrast with the factories of the Industrial Revolution, the introduction of larger workshops barely influenced working processes. Such workshops were therefore essentially no more productive than the small ones in which one craftsman worked with his assistants. Normally, the workshops were not elaborately fitted out and it was quite cheap to set up a workshop; a craftsman usually needed only a few tools for his craft and often practiced it in a shop connected with his living quarters. There were some crafts, however, which were dependent on bigger production sites with more expensive equipment: bakeries had their ovens and mills, smithies their forges for bringing iron to red heat, and fulling plants their big water basins for the working of cloth. Bakers and fullers in particular were sometimes quite well-off: the baker Eurysaces, for example, was able to have erected for himself a pretentious monument at the Porta Maggiore in Rome, and the fullers of Pompeii were able to donate money for a statue for Eumachia.

In such conditions as these, it hardly made sense for the members of the upper classes to invest part of their wealth in large-scale enterprises for commercial production: the chances of obtaining high returns from craft-based production were clearly lower than in agriculture or in money-lending. One of the few exceptions, from the time of the early Principate, was brick production: here, some big land-owners made economic use of the clay from their estates by setting up brickworks, which delivered building materials even to distant cities. The chances of a profitable return arose from the building boom in Rome and in other cities, such as Carthage, ensuring the sale of large amounts of brick.

The dominant feature of urban trade continued to be the small workshop, and even production centers that were of inter-regional importance comprised not large-scale concerns, but a multitude of small businesses.[41] In special cases a number of craftsmen, each working in their own small workshop, were able to use certain production facilities in common, for example at La Graufesenque, where many potters were able to fire their pots simultaneously in the big kilns. Ancient craftsmanship achieved its highest possible quality and productivity by the specialization of individual craftsmen or workshops in certain products; production and products were crucially governed by the experience and practice of the individual craftsman. Antiquity was characterized not by the large concern, where

[41] Manning 1987: 587.

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the work process would be divided (vertical specialization) into a multitude of individual operations with a marked division of labor, but by a specialization, as far-reaching as was possible, of craftsmen and workshops (horizontal specialization). The degree of specialization was dependent on the size of particular markets: a small rural settlement undoubtedly offered fewer opportunities for craft specialization than a bigger town with an affluent group of consumers.[42] That specialization in individual trades and professions makes economic sense and leads to a better supply of goods for a *polis* was a claim already recognized, and extensively supported through theory, by Plato.[43]

In any analysis of the role which technological innovation played in economic growth, it must be borne in mind that productivity could be increased not only through technological progress, but also through improvement in the organization of labor. This is especially true for the big estates of Hellenistic and Roman times: the control over slaves, the exact listing of individual duties, the establishment of work norms, the motivation of the slaves through rewards, even the fixing of food rations aimed at securing the highest possible income for the owners of the big estates. Labor organization and technological advance complemented each other nicely in estate management: estate owners like Cato paid attention to both.

But technological progress should not only be seen from the point of view of increase in productivity: the new possibilities of arch construction and of *opus caementicium* were employed in architecture in order to create an efficient infrastructure for transport, trade and exchange, both in the cities and in rural regions; water supply for urban populations was secured by the building of aqueducts; in this way, technological change also has an effect on health and welfare. The effects of an efficient infrastructure on the economic growth of pre-industrial societies are difficult to evaluate, but it can safely be assumed that the infrastructure of the Roman empire contributed substantially to the standard of living and the prosperity of Roman society. Urbanization in the Mediterranean lands had been possible only on the condition that agriculture and craft were able to provide the growing urban populations with food and consumer goods, and that the erection of public buildings, which served the benefit of the population, was technically and financially possible.

Technological change in the ancient Mediterranean never changed production in agriculture and craft as fundamentally as did the Industrial Revolution, and never increased productivity to a degree that would have resulted in change to the economic or social structure. On the contrary,

[42] Xen. *Cyr.* 8.2.5.

[43] Pl. *Resp.* 369d–371e; 374a; 397e; Harris 2002; compare with Rome also Treggiari 1980.

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technological progress in antiquity always took place within the framework of the agricultural society and never achieved the same dynamic as the innovatory processes of modern industrial societies. To point out the technological innovations of antiquity and their economic effects is by no means to express agreement with a modernist view of ancient technology and economics; rather, it is meant to contribute to an adequate recording of the importance of technological change for ancient agricultural societies.

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