ENERGY AND CIVILIZATION A HISTORY

VACIAV SNIL

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4 Preindustrial Prime Movers and Fuels

Most people in preindustrial societies had to spend their lives as peasants, laboring in ways that in some societies remained largely unchanged for millennia. But the inconsistent food surpluses that they produced with the aid of a few simple tools and the exertion of their muscles and the draft of their animals sufficed to support the unevenly advancing complexity of urban societies. Physically, these achievements were reflected above all in the construction of remarkable structures (ranging from ancient Egypt's pyramids to the Baroque churches of the early modern era), the rising capacities and increasing reach of transportation (ranging from slow wheeled transfers on land to faster ships capable of circumnavigating the planet), and improvements in a multitude of manufacturing techniques, spearheaded above all by advances in metallurgy.

The prime movers and fuels energizing these advances remained unchanged for millennia, but human ingenuity improved their performance in many remarkable ways. Eventually, some of these conversions became so powerful and so efficient that they were able to energize the initial stages of modern industrialization. Two principal roads led to higher outputs and better efficiencies. The first one was multiplication of small forces, primarily a matter of superior organization, especially with the application of animate energies. The second one was technical innovation, which introduced new energy conversions or increased the efficiencies of established processes. In practice, the two approaches often melded. For example, monumental structures built by virtually every old high culture demanded both massed labor and extensive applications of labor-easing devices, starting with simple levers and inclined planes and eventually including pulleys, cranes, windlasses, and treadwheels.

The differences between the first documented mechanical energy converters and their successors, used at the beginning of the industrial era, are often quite remarkable. Early designs of spoon tilt-hammers, the simplest machines powered by falling water, did not even involve continuous rotary motion; they were just repeatedly actuated simple levers (fig. 4.1). Later, vertical waterwheels turned trip hammers into reliable helpers in Asian and European forges, and some nineteenth-century water-powered forge hammers were impressive, complex, high-performance pieces of machinery (fig. 4.1).

Similar comparisons can be made for every class of water- and windpowered prime movers. What a difference there is between rough-hewn medieval horizontal wooden waterwheels, whose power was just a few hundred watts (less than half a horsepower), the much better built seventeenthcentury vertical machines, with power ratings easily ten times higher, and the Lady Isabella, England's largest iron overshot wheel, capable of delivering more than 400 kW, power equivalent to that of nearly 600 strong horses! Or between inefficient and heavy European medieval post mills that had to be laboriously turned into the wind, only to lose more than 80% of their potential power to poor sails and rough gearing, and their automatically regulated nineteenth-century American counterparts with spring sails and smooth transmissions, whose operation—they were often used to pump water—helped open up the Great Plains.

Contrasts are no less impressive for animate conversions and the combustion of phytomass fuels. A nineteenth-century heavy draft horse with iron horseshoes and a collar harness hitched to a light flat-top wagon on a hard-top road could easily pull a load 20 times as heavy as its much lighter, unshod, breast-harnessed ancestor linked to a heavy wooden cart on a muddy road could. And an eighteenth-century blast iron furnace consumed less than one-tenth the charcoal per unit of hot metal output than was needed by its early medieval predecessor (Smil 2016). The human capacity for heavy work, however, changed little between antiquity and the onset of industrialization. Even in those societies where average body weight increased over time, such a gain had only a marginal effect on maximum

Figure 4.1

Flowing water powered these three hammers, but their complexity and performance were vastly different. The primitive Chinese spoon tilt-hammer of the early four-teenth century was a simple lever actuated by falling water (top). European forge hammers of the late sixteenth century were energized by waterwheels whose rotary power was transferred by connecting rods (middle). Tilt-hammers at a nineteenth-century English foundry were high-performance, adjustable machines (bottom). Reproduced from drawings in Needham (1965) and Reynolds (1970).







muscular exertion, and heavy exertions have always required the combined power of many individuals.

To move a 327 t Egyptian obelisk from the site where it was left by the Romans (Caligula had it placed at the central *spina* of his circus, the spot that is now just south of San Pietro) 269 m eastward, Domenico Fontana used huge (up to 15 m long) wooden levers and pulleys to lift it from its ancient base, and on September 10, 1586, when he raised it in the center of St. Peter's Square in Rome, he relied on 900 men and 75 horses to pull pulley-guided ropes and set it on a new foundation (Fontana 1590; Hemphill 1990). The entire project was accomplished in 13 months and the erection took one day. Later famous relocations of obelisks included the structures now standing at Place de la Concorde in Paris (completed in 1833), on the Thames Embankment (1878), and (since 1881) in New York's Central Park (Petroski 2011).

When the world's heaviest column—604 t of red Finnish granite erected to commemorate Russia's victory over Napoleon's invading army—was raised in Saint Petersburg on August 30, 1832, the French architect Auguste de Montferrand relied on 2,400 men (1,700 engaged in the actual pulling), who did the job in less than two hours (box 4.1). And the two essential devices that provided the necessary mechanical advantage for these two lifts and that have allowed men to execute many prodigious moves and lifts and emplacements, inclined planes and levers, have been with us not only since the time of ancient empires but, necessarily, long before that—or how else did Stonehenge's 40 t outer stones get raised?

In this chapter I first appraise the kinds, capacities, and limits of all traditional prime movers—human and animal muscles, wind, and water—as well as the combustion of phytomass fuels, mostly wood and charcoal made from it, but in deforested regions also many kinds of crop residues (particularly cereal straw) and on grasslands also dried dung. Afterward I look in some detail at the uses of prime movers and fuels in critical segments of traditional economies: in food preparation, in the provision of heat and light, in land and waterborne transportation, in construction, and in color and ferrous metallurgy.

Prime Movers

Animate labor and conversions of the kinetic energies of water and wind (by sails and mills) were the only prime movers in traditional societies before the diffusion of steam engines. Although the subsequent retreat of traditional prime movers was relatively rapid, waterwheels and windmills

Box 4.1 Raising Alexander's column

The large piece of red granite that became Alexander's Column was quarried at Virolahti in Finland, rolled onto a purpose-built barge able to carry 1,100 t (the column nearly fell into the water during loading), shipped about 190 km to the Neva's embankment in Saint Petersburg, offloaded onto a solid wood deck, moved up 10.5 m on an inclined plane, and positioned on a platform at a right angle to the pedestal in the center of Palace Square. A solid wooden scaffolding erected above the pedestal was 47 m tall, with pulley blocks hanging from five double oak beams. Montferrand built a 1/12 scale model of the scaffolding to guide the carpenters in its construction (Luknatskii 1936). Lifting was accomplished by 60 capstans mounted on the scaffolding in two staggered rows. Ratchets were iron drums mounted in a wooden frame, the upper blocks were hung from the double oak beams, and 522 ropes, each tested to lift 75 kg (triple the actual load), were attached to the shaft of the column. The total mass of the monolith with all devices was 757 t.

Lifting the column was done on August 30, 1832, and employed directly 1,700 soldiers and 75 officers, supervised by foremen who coordinated speed and a steady pace depending on the tension on the rope. Montferrand's assistants stood at the four corners of the scaffolding with 100 sailors who watched the blocks and ropes and kept them straight; 60 workers stood on the tower itself; and carpenters, stonecutters, and other craftsmen also stood in reserve. The total labor force for the lift was about 2,400 people, and the task was completed in just 105 minutes. Remarkably, the column has kept its upright position without being fastened to the pedestal: the 25.45 m tall, slightly conical (3.6 m diameter at the bottom, 3.15 m at the top) mass simply rests on its foundations.

retained (or even increased) their importance during the first half of the nineteenth century, sail ships became marginal means of ocean transportation only after 1880, and draft animals dominated even the most advanced Western agricultures until after World War I. The early phases of industrialization had actually increased the demand for human labor, ranging from some extremely heavy exertions in coal mining and the iron and steel industry to the myriad tiresome tasks involved in manufacturing, with child labor common in Western countries even at the beginning of the twentieth century: in 1900 about 26% of boys aged 10–15 years worked, and the percentage of children in agricultural employment was as high as 75% for girls (Whaples 2005). And heavy exertions and child labor are still common in most rural areas of sub-Saharan African countries and in the poorest regions of Asia: in Africa, women carry heavy head loads of firewood; in India, women break stones with small hammers; in India, Pakistan, and Bangladesh, men dismantle massive ships on hot beaches (Rousmaniere and Raj 2007); in China, peasants dig coal in small rural mines. And millions of people are still subjected to different forms of forced and slave labor and human trafficking (International Labour Organization 2015). A continuing reliance on human labor (including its most offensive variants) is one of the most obvious marks of the great divide between the rich and poor worlds. But even in the West, heavy exertions (in underground coal mining, steelmaking, forestry, fishing) were not uncommon until the 1960s, and the use of animate prime movers is more than a matter of historical interest: it is the not so distant foundation of our present affluence.

This account of preindustrial prime movers would be incomplete without noting the medieval invention, diffusion, and historical importance of gunpowder. Awe of thunder and lightning can be seen in every old high culture. The aspiration to emulate their destructive power recurs in many narratives and fantasies (Lindsay 1975). But for millennia the only pale imitation was to attach incendiary materials to arrowheads, or to hurl them in containers from catapults. Sulfur, petroleum, asphalt, and quicklime were used in these incendiary mixtures. Only the invention of gunpowder combined the propulsive force with great explosive and inflammatory power.

Animate Power

Animate energies remained the most important prime mover for most of humanity until the middle of the twentieth century. Their limited power, circumscribed by the metabolic requirements and mechanical properties of animal and human bodies, restricted the reach of preindustrial civilizations. Societies that derived their kinetic energy almost solely (as in the case of ancient Mesopotamia or Egypt, with sail ships being the only exception) or largely from animate power—medieval Europe is an excellent example, with water and wind power limited only to certain tasks, and in rural China that was the case until two generations ago—could not provide a reliable food supply and material affluence to most of their inhabitants.

There were only two practical ways in which the delivery of useful animate power could be increased: either by concentrating individual inputs or by using mechanical devices to redirect and amplify muscular exertions. The first approach soon runs into practical limitations, especially with the direct deployment of human muscles. Even unlimited labor force is of little use for directly grasping and moving a relatively small but very heavy object as only a limited number of people can fit around its perimeter. And while a group of people can carry a heavy object, lifting it first in order to insert slings or poles could be a challenging problem. Human capacities in lifting and moving loads are limited to weights substantially smaller than their body mass. Traditional sedan chairs (litters), used by most of the Old World societies, were carried by two men, each bearing at least 25 kg and up to 40 kg, with heavier loads supported by poles resting on their shoulders.

When unloading and loading ships and wagons, Roman *saccarii* lifted and carried (over short distances) sacks of 28 kg (Utley 1925). Heavier burdens were manageable only with the help of simple devices that conferred significant mechanical advantage, usually by deploying a lesser force over a longer distance. Five such devices were widely used during the Old World's antiquity: Philo (during the third century BCE) listed them as a wheel and axle, a lever, a system of pulleys, a wedge (an inclined plane), and an endless screw. Their common variations and combinations ranged from screws to treadwheels. By using these tools and simple machines, people could deploy smaller forces over longer distances, thereby enlarging the scope of human action (box 4.2). The three simplest aids providing mechanical advantage—levers, inclined planes, and pulleys—were used by virtually all old high cultures (Lacey 1935; Usher 1954; Needham 1965; Burstall 1968; Cotterell and Kamminga 1990; Wei 2012).

Levers are rigid, slender pieces of wood or metal. As they pivot around a fulcrum they convey an mechanical advantage that is easily calculated as a quotient of effort-arm and load-arm lengths (measured from the pivot point; the higher the number, the easier and faster the task). The ancient use of levers ranged from driving oared ships to moving heavy loads (fig. 4.2). Levers are classified according to the position of fulcrum (fig. 4.2). In the first class of lever the fulcrum is between the load and the applied force, which acts in the opposite direction to a displaced load. In the second class of lever the fulcrum is at one end and the force acts in the same direction as the load. Levers of the third class do not provide any mechanical advantage but increase the load's speed, as is clear from the operation of catapults, hoes, and scythes.

Common hand tools using levers of the first class are crowbars, scissors, and (a double lever) pliers. Wheelbarrows have been among the most often used levers of the second class (Needham 1965; Lewis 1994). Chinese

Box 4.2 Work, force, and distance

Work is done when a force—no matter whether provided by animate or inanimate prime movers—changes a body's state of motion. Its magnitude is equal to the product of exerted force and the displacement in the direction in which the force acts. In formal terms, a force of one newton and the displacement of one meter will require the energy of one joule (J = Nm). Just to get the feel for relevant orders of magnitude: lifting a 1 kg book from a desk (0.7 m above the floor) and placing it on a shelf (1.6 m above the floor) requires work of almost 9 J. Lifting an average stone (about 2.5 t) of Khufu's pyramid one course higher (about 75 cm) required about 18,000 J (18 kJ), or 2,000 times more energy than shelving the book.

Naturally, the same amount of work can be accomplished by applying a greater force over a shorter distance or a smaller force over a longer distance: any device that converts a small input force into a larger output force provides a mechanical advantage whose magnitude is measured simply as a dimension-less ratio of the two forces. This mechanical advantage has been exploited since the prehistoric era by using levers and inclined planes, and later also by deploying pulleys. There are countless examples of these actions in everyday life, from opening locks with a key (a row of wedges, that is, inclined planes, moving the pins inside a lock) to pulling a nail from a piece of wood by using a claw hammer (a lever action).

barrows, used since the Han dynasty, usually had a large (90 cm diameter) central wheel surrounded by a wooden framework. With the load right above the axle they could carry large loads (commonly 150 kg); they were used by peasants to take products to markets and sometimes also to transport people, who sat on the sides (Hommel 1937). Little sails could be erected to ease propulsion. European barrows are first convincingly documented during the high Middle Ages (late twelfth and early thirteenth centuries) and subsequently were used mostly in England and France, usually in construction and mining. Their fulcrum was at the end, which put more strain on people pushing them, but they still offered a considerable (typically threefold) mechanical advantage.

The wheel and axle form a circular lever, with the long arm being the distance between the axle and the wheel's outer rim and the short arm being the axle's radius, which produces a large mechanical advantage, even for heavy wheels on a rough surface. The first wheels (used in Mesopotamia before 3000 BCE) had solid wooden wheels; spoked wheels appeared about



Three classes of levers are distinguished by the point at which the force is applied in relation to the object (whose weight, *W*, always acts in a downward direction) and the fulcrum (*F*). In levers of the first class, the force moves in a direction opposite to that of the object. In levers of the second class, the force moves in the same direction as the object, but both levers confer the same mechanical advantage: they gain power at the expense of distance. In levers of the third class, the force moves over a shorter distance than the object, resulting in a velocity gain. The first two classes of levers have had countless applications in lifting and moving objects and in machinery construction. A detail from a partially reconstructed Assyrian bas-relief at Kuyunjik (about 700 BCE) shows a large lever used to move a giant statue of a winged bull with a man's head. Reproduced from Layard (1853).

1,000 years later, first on chariots, and friction was reduced by iron rims. The wheel's enormous importance in the Old World can be seen in the rapid diffusion of the invention of wheeled vehicles and in their countless mechanical uses ever since. Curiously, the Americas had no native wheels, and the desert environments in many Muslim lands made pack camels more important than wheeled transport pulled by oxen (Bulliet 1975, 2016).

Neglecting friction, the mechanical advantage of an inclined plane is equal to the quotient of the length of slope and the height to which an object is raised. Friction can reduce this gain quite substantially, and that is why smooth surfaces and some form of lubrication (water being the easiest obtainable and the cheapest lubricant) were needed for the best practical performance. According to Herodotus, an inclined plane was the principal means of conveying heavy stones from the Nile shore to the building site of the great pyramids, and there has been much speculation on its further use during their actual construction (later in this chapter I explain why we should discount that choice). The most common modern use of inclined planes is as ramps, ranging from strong metal plates to load cargo on vehicles and ships to soft plastic surfaces to offload airplane passengers in an emergency.

Wedges are just double inclined planes exerting large sideways forces across small distances. They have commonly been used for splitting rocks, by means of pieces of wood inserted into stone cracks and wetted, and as the cutting edges of adzes and axes. Screws, first used in ancient Greek olive and grape presses, are nothing but circular inclined planes wrapped around a central cylinder. As already noted in the previous chapter, a screw design was also used for shallow water lifts. Their large mechanical advantage means that workers are able to exert high pressure with minimal effort. In many applications small screws (now mass-produced and usually tightened with a clockwise rotation) are used as irreplaceable fasteners.

A simple pulley, consisting of a grooved wheel guiding a rope or a cable, invented during the eighth century BCE, makes the handling of loads easier by redirecting the force, but it confers no mechanical advantage, and its use can result in accidental load falls. Ratchet and pawl take care of the last problem and multiple pulleys address the first deficiency, as the force required to lift an object is nearly inversely proportional to the number of deployed pulleys (fig. 4.3). *Mechanica*, attributed to but not written by Aristotle (Winter 2007), shows a clear understanding of the mechanical advantage afforded by such devices.

The ancient Chinese were such frequent users of pulleys that even palace entertainments could not do without them, and once a whole corps de ballet of 220 girls in boats was pulled up a slope from a lake (Needham 1965). But certainly the most famous ancient testimony to the efficacy of compound pulleys is Archimedes' demonstration to King Hiero, recorded in Plutarch's *Lives*. When Archimedes "declared that, if there were another world, and he could go to it, he could move this," Hiero asked him for a suitable demonstration of such powers.

Archimedes therefore fixed upon a three-masted merchantman of the royal fleet, which had been dragged ashore by the great labours of many men, and after putting on board many passengers and the customary freight, he seated himself at a distance from her, and without any great effort, but quietly setting in motion with



Equilibrium forces in pulleys are determined by the number of suspension cords. There is no mechanical advantage in A. In B the weight *P* is suspended by two parallel cords and hence the free end needs to be loaded only by P/2 to be in equilibrium, in C by P/6, and so on. A worker raising building materials with Archimedean potential pulley (D) could lift (ignoring friction) a 200 kg stone with a force of only 25 kg, but a lift of 10 m will require pulling 80 m of the counterweight cord. A ratchet and pawl can be used to interrupt this effort anytime.

his hand a system of compound pulleys, drew her towards him smoothly and evenly, as though she were gliding through the water. (Plutarch 1961, iv:78–79)

Three classes of mechanical devices—windlasses and capstans, treadwheels, and gearwheels—became critical for applying continuous human power, needed in lifting, grinding, crushing, and pounding (Ramelli 1976 [1588]). Windlasses were commonly used not only in lifting water from wells and raising building materials with cranes but also in winding the most destructive stationary weapons of antiquity, the large catapults used in besieging towns and fortresses (Soedel and Foley 1979). Horizontal windlasses (winches), requiring the grip to be shifted four times during each revolution (fig. 4.4, left side), and vertical capstans (fig. 4.5) made it possible to transmit power by ropes or chains through simple rotary motion. Cranks, first used in China during the second century CE and introduced to Europe seven centuries later (fig. 4.4, right side), made this even easier, except that the speed of hand cranking (or foot treading) had to match the speed of a driven machine (often a lathe).

This limitation was eliminated by using a crank to power a large wooden or iron wheel (the great wheel) that was independently mounted on a



Figure 4.4

Miners using both a horizontal windlass (left) and a crank (right) to lift water from a shaft. A heavy wooden wheel, sometimes with pieces of lead fastened to its spokes, helped to conserve the momentum and make the lifting easier. Reproduced from Agricola, *De re metallica* (1912 [1556]).



Eight men rotating a large vertical capstan in a mid-eighteenth-century French workshop. The capstan winds a cord fastened to pincers, drawing a gold wire through a die. Reproduced from the *Encyclopédie* (Diderot and d'Alembert 1769–1772).

heavy shaft and whose rotation was transmitted to a lathe by a crossed belt. This allowed the use of many gear ratios, and the momentum of a large wheel helped maintain even revolutions even as muscular exertion rose and faded. This medieval innovation enabled accurate machining of wood and metal parts, used to construct a wide variety of precise mechanisms ranging from clocks to the first steam engines, but it could not eliminate the hard work needed when cutting hard metals (fig. 4.6). George Stephenson's workers, who used a great wheel to make parts for the first steam locomotive, had to rest every five minutes (Burstall 1968).



The great wheel powered by a crank, used to turn a metalworking lathe. The smaller wheel was used for working with larger diameters, and vice versa. In the background of this image a man works on a foot-powered lathe machining wood. Reproduced from the *Encyclopédie* (Diderot and d'Alembert 1769–1772).

Deployment of the body's largest back and leg muscles on treadwheels delivered much more useful power than hand-turned rotaries. The largest treadwheels (also called, confusingly, great wheels) were two wheels whose rims, connected by planking, formed a pavement trodden by men. A bas-relief in the Roman tomb of the Haterii (100 CE) is the first extant image of a large internal treadwheel (Greek *polyspaston*). Roman treadwheels could lift up to 6 t, and such large machines became a common sight during medieval and early modern Europe at major construction sites and docks and also at mines, where they were used to pump water (fig. 4.7).

The difference between the radius of the wheel and the radius of the axle drum gave these treadwheels a large mechanical advantage, and they could lift such heavy burdens as keystones, massive timbers, or bells to the tops of cathedrals and other tall buildings. In 1563 Pieter Bruegel the Elder painted such a crane lifting a large stone to the second level of his imaginary Tower of Babel (Parrott 1955; Klein 1978). His device, with





Details of treadwheels with different torque. a. Internal treadwheel. b. External treadwheel (maximum torque). c. Inclined treadwheel. Reproduced from Agricola, *De re metallica* (1912 [1556]).

treadwheels on both sides, was powered by six to eight men. Externally driven vertical wheels were less common, but they allowed the maximum torque when treading on a level with the axle (fig. 4.7). There were also inclined treadwheels, with laborers leaning against a bar (fig. 4.7), and in English prisons treadmills became common in the early nineteenth century (box 4.3, fig. 4.8).

All types of treadwheels could be also designed or adjusted for animal operation. All drumlike devices had the added advantage of relatively easy mobility: they could go from job to job by rolling along on a fairly flat surface. Until the introduction of steam-powered railway cranes they were the only practical way of tackling heavy lifting. Maximum power inputs on treadwheels were limited by their size and design. With a single worker the power output would be no more than 150–200 W during brief spells of hard effort, and no more than 50–80 W during episodes of sustained effort with tired muscles, while the largest treadwheels, powered by eight men, could operate briefly at about 1,500 W.

On the end of the exertion spectrum were the tasks powered by a single worker using cranks, treadles, pedals, or screws. This hand- or footwork-powered machines ranged from small wood-turning lathes and printing presses to sewing machines, whose first commercial models came during the 1830s but whose widespread use (both hand-turned and treadle-oper-ated designs) began during the 1850s (Godfrey 1982). During the same period, large numbers of boys and men continued to flap (using pulleys) *punkha (pangkha* in Hindi), cloth or palm frond ceiling fans, the only means of making India's monsoon heat a bit more bearable for all those who could afford to pay a *punkhawallah*, who operated the fan.

The question of how much useful work a man could do in a single day remained unsettled for long time, and comparisons of the man-day effort with the work of horses had ranged widely, with extreme values differing as much as sevenfold (Ferguson 1971). Watt's definition of horsepower—equal to 33,000 pound-feet per minute, or 745.7 W (Dickinson 1939)—implied an equivalent of about seven workers. The first reliably measured rate was by Guillaume Amontons (1663–1705), who equated the work of glass polishers during a 10-hour shift with raising continuously a weight of 25 pounds at a speed of 3 ft/s (Amontons 1699). In modern scientific units that would amount to total useful work of 3.66 MJ at a rate of 102 W.

How powerful are people as prime movers, and how efficient? The first question was answered quite accurately long before the beginning of systematic energy studies of the nineteenth century. The early estimates

Box 4.3 Working on a treadmill

The largest treading devices operated during the nineteenth century in English prisons, where William Cubitt (1785–861) introduced them as a means of punishment, but soon they were deployed to grind grain and pump water, and sometimes were used simply for exercise (Mayhew and Binney 1862). These long inclined penal treadmills had wooden steps around a cylindrical iron frame and could accommodate as many as 40 prisoners standing side by side, holding on to a horizontal handrail for stability and being forced to step up at the same time. The use of penal treadmills was banned only in 1898.

But writing in 1823, a Devon prison governor, in answer to an inquiry, replied, "I consider the labour at the Tread Mill not as injurious, but conducive to the health of prisoners" (Hippisley 1823, 127). Millions of enthusiastic modern treadmill users might agree, and Landels (1980, 11–12), while noting that we cannot talk or even think about these machines unemotionally, stressed nevertheless that a well-designed treadwheel was not only a highly efficient mechanical device but also one most comfortable for the operator "in so far as any continuous, monotonous physical work can be comfortable."



Figure 4.8 Prisoners on a treadmill at the Brixton House of Correction (Corbis).

ranged from equating the labor of one horse with the exertion of just two to as many as 14 men (Ferguson 1971). Before 1800, rates converged on the correct maxima of 70–150 W for most adults steadily working for many hours. When working steadily at a rate of 75 W, ten men would be needed to equal the power of one standard horse.

In 1798, Charles-Augustin de Coulomb (1736–1806) took a more systematic look at the different ways in which men used their strength during their daily work (Coulomb 1799). These experiences ranged from climbing Tenerife (2,923 m) in the Canaries in a bit less than 8 hours to a day's work by wood carriers ascending 12 m 66 times a day with burdens of 68 kg. The former effort adds to a total work of 2 MJ and a power of 75 W, the latter to about 1.1 MJ and a power of about 120 W. All subsequent evaluations could only confirm the power range established by Coulomb's investigations: most adult men can sustain useful work at 75–120 W (Smil 2008a). During the early twentieth century, studies of human basal metabolic rate (BMR), led by Francis G. Benedict (1870–1957) of the Carnegie Institution in Boston, made it possible to formulate equations of expected energy expenditures and establish typical BMR multipliers for different levels of physical activity (Harris and Benedict 1919), and both are valid for a wide range of body types and ages (Frankenfield, Muth, and Rowe 1998).

As already noted, comparing the exertions of people and animals yields a wide range of men-to-horse ratios. Nicholson (1825, 55) concluded that "the worst way of applying the force of a horse, is to make him carry or draw up hill; for if the hill be steep, three men will do more than a horse. … On the other hand, … in a horizontal direction … a man … cannot exert above one-seventh part of the force of a horse employed to the same purpose." And employing animals was not always practical. As Coulomb (1799) noted, people require less space to work than animals and are easier to transport, and their efforts may be easier to combine.

The performance of small, often poorly fed beasts of antiquity and the early Middle Ages was much closer to human exertion than was the effort of powerful nineteenth-century draft horses. Animals were usually blindfolded (or blind) and harnessed directly to the beams, which were fastened to a central axle whose rotation would be used to mill (mostly grains, but also clays for tiles), extract (oil from seeds, juice from cane and fruits), or wind up a rope tied to a burden (when raising water, coal, ore, or men from mines). In some enterprises animals also rotated whims attached to geared assemblies to multiply the mechanical advantage.

Poor feeding and abuse of these animals forced to walk for hours in a small circle were common, as attested by Lucius Apuleius in his *Golden Ass*

(second century CE, here in a classic William Adlington translation from 1566):

But how should I speake of the horses my companions, how they being old and weake, thrust their heads into the manger: they had their neckes all wounded and worne away: they rated their nosethrilles with a continuall cough, their sides were bare with their harnesse and great travell, their ribs were broken with beating, their hooves were battered broad with incessant labour, and their skinne rugged by reason of their lancknesse. When I saw this dreadfull sight, I began to feare, least I should come to the like state.

This use of horses continued well into the nineteenth century: by the 1870s horses were powering thousands of whims (sweeps) in Appalachian states and throughout the U.S. South, both on farms (grinding grain, extracting oil, compacting cotton bales) and in water pumping and hoisting loads from mines (Hunter and Bryant 1991). They walked in circles often less than 6 m in diameter (see fig. 1.3; 8–10 m was more comfortable), and before the adoption of electric streetcars Western cities had many urban horses harnessed to omnibuses and carts (box 4.4; see also fig. 4.18).

The use of horses for transportation or in construction was constrained by the same factors that limited their employment as draft animals in farming. Neither good pastures nor a sufficient supply of feed grains were available in dry Mediterranean countries or in the densely populated lowlands of Asia, while poor harnessing converted their power quite inefficiently. In Eurasia's arid regions, much less demanding camels were used for many of the tasks done by oxen and horses in Atlantic Europe, but in Asia domesticated elephants (used in harvesting heavy timber, in construction, and in war) also put a considerable strain on feed resources (Schmidt 1996). A classic Indian source of elephant lore extols their effectiveness, but it also prescribes expensive feeding of newly caught elephants in training with boiled rice and plantains mixed with milk and sugar cane (Choudhury 1976). If the animals stayed healthy, such high energy costs were well compensated by their power and remarkable longevity.

Animals used for transport and stationary work ranged from small donkeys to massive elephants, and in some places dogs turned spits over kitchen fires or pulled small carts or wheelbarrows. But, not surprisingly, the modest nutritional demands of bovines—oxen and water buffaloes and yaks—made them the leading working animals both on farms and elsewhere. Yaks were invaluable as pack animals not because of any extraordinary power but because of their ability to walk in high mountains and in snow. The typical draft performance of bovines in transportation was at

Box 4.4 Draft horses in urban transportation

Draft horses were employed in cities to deliver food, fuel, and materials (pulling carts of different sizes) and for personal transport, pulling hackney carriages and, since 1834, their modernized versions, cabs patented by Joseph Hansom (1803–1882) and widely known as hansoms. But as Western cities grew, the need for more efficient public transportation led to the introduction of horse-drawn omnibuses (horse-buses). Their use began in 1828 in Paris; a year later they appeared in London and in 1833 in New York, and then in most of America's large eastern cities (McShane and Tarr 2007). In New York their number peaked at 683 vehicles in 1853.

Horsecars (streetcars drawn by horses) on tracks made transport more efficient, and such lines were common before the introduction of electric street cars during the 1880s. Light omnibuses (with just a dozen passengers) were drawn by just two horses, but four horses were common, and carriages made for up to 28 passengers were often overcrowded. There were hourly departures, and many lines followed established suburban coach stages, reaching destinations 8–10 km from downtowns in about one hour. Hard-working horses had to be well fed, and data collected by McShane and Tarr (2007) show that typical daily rations per animal were 5–8 kg of oats and a similar mass of hay. Supplying urban horses with this feed was an important service in all large nineteenth-century cities.

best moderate. For short spells on good roads they could pull loads as much as three or four times their body weight, but their steady work delivered no more than 300 W. Old and weak horses, which were often used for turning a whim, a beam attached to a central axle for work in small manufactures requiring steady rotary power, could not deliver much more, and before the introduction of steam engines many of them were replaced by much more powerful waterwheels and windmills.

Water Power

Antipater of Thessalonica, writing during the first century BCE, left the first literary reference to a simple water mill doing away with the hard work of manual grain milling (translated in Brunck 1776, 119):

Set not your hands to the mill, O women that turn the millstone! Sleep sound though the cock's crow announces the dawn, for Ceres has charged the nymphs with the labours which employed your arms. These, dashing from the summit of a wheel, make its axle revolve, which by the help of moving radii, sets in action

the weight of four hollow mills. We taste anew the life of the first men, since we have learnt to enjoy, without fatigue, the produce of Ceres.

And with the notable exception of ancient sailing ships, the harnessing of wind started even later. Al-Masudi's report, dated 947, is one of the first reliable records of simple vertical shaft windmills (Forbes 1965; Harverson 1991). His description portrayed Seistan (in today's eastern Iran) as a land of winds and sand where the wind drove the mills and raised water from streams to irrigate gardens. The barely changed successors of these early mills—with plaited reed sails behind narrow openings in high mud walls creating faster wind flow—could be seen in the region well into the twentieth century. Both kinds of machines diffused fairly rapidly throughout the medieval world, but water mills were far more abundant.

Their ubiquity is attested by the Domesday Book count of 1086, when there were 5,624 mills in southern and eastern England, or one for every 350 people (Holt 1988). The earliest horizontal waterwheels are often referred to as either Greek or Norse wheels, but the origin of their design remains uncertain. They became common in many regions of Europe and everywhere east of Syria. The impact of flowing water, usually directed through a sloping wooden trough onto wooden paddles that were often fitted to a hub at an incline, rotated a sturdy shaft that could be directly attached to a millstone rotating above (fig. 4.9). This simple and relatively inefficient design was best suited for small-scale milling. Later designs, with water led through a wooden trough with a tapered bore (Wulff 1966), had efficiencies above 50% and a maximum power above 3.5 kW.

Vertical wheels supplanted the horizontal machines because of their superior efficiency. They turned the millstones by right-angle gears, and in the Western literature they became known as Vitruvian mills, after the Roman builder gave the first clear description of *hydraletae*, dated to 27 BCE. But Lewis (1997) thought the water mill originated during the first half of the third century BCE, most likely in the Ptolemaic Alexandria, and that by the first century CE water power was already in more common use. In any case, because of their eventual ubiquity and persistence we have a large body of literature dealing with their history, design, performance, and uses (Bresse 1876; Müller 1939; Moritz 1958; Forbes 1965; Hindle 1975; Meyer 1975; White 1978; Reynolds 1983; Wölfel 1987; Walton 2006; Denny 2007).

But one thing that is impossible to do is to estimate reliably the contribution of waterwheels to the overall primary energy supply of ancient and medieval societies. Wikander (1983) showed that waterwheels were more common during the Roman era than is usually assumed, and although only



The horizontal waterwheel, also called the Greek or Norse wheel. The wheel was powered by the impact of running water and rotated directly the runner stone above. Reproduced from Ramelli (1976 [1588]). 20 early medieval water mill sites have been identified, about 6,500 localities had mills in eleventh-century England (Holt 1988). But my estimates show that even with very liberal assumptions regarding the unit power and adoption of waterwheels throughout the Roman Empire, water power contributed only a fraction of 1% of the useful mechanical energy supplied by people and draft animals (Smil 2010c).

Vertical waterwheels are classified according to the point of impact. Undershot wheels were propelled by the kinetic energy of moving water (fig. 4.10). They worked well in a slow but steady flow, but location on swift-flowing streams was especially desirable because the maximum theoretical power of undershot wheels is proportional to the cube of the water speed: doubling the speed boosts the capacity eightfold (box 4.5). Where the stream flow was first impounded, undershots were used only with low heads of between 1.5 and 3 m. Radial boards were later fitted with backs to prevent water shooting over the floats.

The efficiency of undershot wheels could be further improved by forming the base below the waterwheel rim into a closely fitting breast over a 30° arc at the bottom center to increase the water retention. Their most efficient design, introduced around 1800 by Jean-Victor Poncelet (1788–1867), had curved blades and could convert about 20% of water's kinetic energy into useful power; later in the century the best performance rose to 35–45%. Wheel diameters were roughly three times as large as the head for paddle wheels and two to four times for Poncelet wheels.

Breast wheels were powered by a combination of water flow and gravity fall in streams with heads between 2 and 5 m. Close-fitting breastworks, preventing premature water spillage, were essential for good performance.

Box 4.5 Power of undershot wheels

The kinetic energy of flowing water (in joules) is $0.5\rho v^2$, one-half the product of its density ($\rho = 1,000 \text{ kg/m}^3$) and squared velocity (v in m/s). The number of unit volumes of water impacting at waterwheel paddles per unit of time equals the flow speed, and hence the theoretical power of the stream is equal to its energy multiplied by velocity. Water flowing at a speed of 1.5 m/s and turning vanes with a cross section of about 0.15 m² (roughly 50 × 50 cm) could ideally develop just over 400 W of power—but an inefficient wooden medieval undershot could actually deliver no more than a fifth of this rate, or about 80 W, as useful rotary motion.



Engravings of a large undershot wheel running a French royal paper mill (top) and of an overshot wheel powering ore-washing machinery in a French forge (bottom). Reproduced from the *Encyclopédie* (Diderot and d'Alembert 1769–1772).

Low breast designs, with water entering below the elevation of the center shaft, had efficiencies no better than those of well-designed undershot wheels. High breast machines, with water impacting above the elevation of the center shaft, approached the outputs of overshot wheels. Traditional overshot wheels, powered largely by gravitational potential energy, operated with heads over 3 m, and their diameters were usually equal to about three quarters of the head (fig. 4.10). Water was fed through troughs or flumes into bucketlike compartments at rates of less than 100 L/s to more than 1,000 L/s and at speeds of 4–12 rpm. Because most of the rotary power was generated by the weight of the descending water, overshot wheels could be placed on slowly flowing streams (box 4.6).

This advantage was partially negated by the need for a well-directed and carefully regulated water supply, which required the frequent building of storage ponds and races. Overshot wheels operating with excess carrying capacity, that is, with reduced spillage from buckets, could be more efficient, though less powerful, than machines under full flow. Until the early decades of the eighteenth century, overshot wheels were considered to be less efficient than the undershots (Reynolds 1979). This error was disproved during the 1750s in the writings of Antoine de Parcieux, and Johann Albrecht Euler, and above all by careful experiments with scale models conducted by John Smeaton (1724–1792), who compared the waterwheel capacities with those of other prime movers (Smeaton 1759).

Smeaton's subsequent promotion of efficient overshot wheels helped slow down the diffusion of steam engines, and his experiments (when he correctly concluded that a wheel's power rises with the cube of the water's velocity) set an efficiency range for overshot wheels at 52–76% (average 66%), compared to 32% for the best undershot wheels (Smeaton 1759).

Box 4.6

Power of overshot waterwheels

The potential energy of water (in joules) is equal to *mgh*, the product of its mass (in kg), gravitational acceleration (9.8 m/s²), and head (height in m). Consequently, an overshot wheel bucket containing 0.2 m³ of water (200 kg) poised 3 m above the discharge channel has a potential energy of roughly 6 kJ. With a water flow rate of 400 kg/s, the wheel would have a theoretical power of nearly 12 kW. The useful mechanical power of such a machine would have ranged from less than 4 kW for a heavy wooden wheel to well over 9 kW for a carefully crafted and properly lubricated nineteenth-century metal machine.

Denny's (2004) modern theoretical analysis of waterwheel efficiency produced very similar results: 71% for overshot wheels, 30% for undershot wheels (and about 50% for Poncelet wheels). In practice, properly designed and well-maintained twentieth-century overshot wheels had potential shaft efficiencies of nearly 90% and could convert up to 85% of water's kinetic energy to useful work (Muller and Kauppert 2004), but a generally achievable rate was 60–70%, while the best German all-metal undershot wheels, designed and made during the 1930s, were up to 76% efficient (Müller 1939).

Undershot wheels could be placed directly in a stream, but such a location naturally increased the chances of flood damages. Breast wheels and overshot wheels needed a regulated water supply. The water bypass usually consisted of a weir across a stream and a channel diverting the flow to the wheel. In regions of low or irregular rainfall it was common to impound water in ponds or behind low dams. No less attention had to be paid to returning water to the stream. Backed-up water would have impeded wheel rotation, and smooth tail races were also needed to prevent channel silting. Even in England, wheels, shafts, and gears were almost completely wooden until the beginning of the eighteenth century. Afterward came a growing use of cast iron for hubs and shafts. The first all-iron wheel was built early in the nineteenth century (Crossley 1990). Besides fixed stream waterwheels there were also the much less common floating wheels, installed on barges, and tidal mills. Floating grain mills were successfully used for the first time on the Tiber in the year 537 when Rome was besieged by the Goths, who cut off the aqueduct water turning the milling wheels.

They were a common sight in or near cities and towns in medieval Europe, with many remaining until the eighteenth century. The use of intermittent power from the sea was first documented in Basra during the tenth century. During the Middle Ages small tidal mills were built in England, the Netherlands, Brittany, and on the Atlantic coast of the Iberian Peninsula; later came the installations in North America and the Caribbean (Minchinton and Meigs 1980). Perhaps the most important and long-lived tide-powered machinery supplied drinking water for London. The first large vertical tidal waterwheels, built after 1582, were destroyed by the 1666 fire, but their replacements operated until 1822 (Jenkins 1936). Three wheels, driven by water passing through the narrowed arches of the old London Bridge, turned in either direction (other wheels usually worked only with the ebbing tide) and powered 52 water pumps forcing 600,000 L of water to a height of 36 m.

Grain milling remained the dominant use of water power: in medieval England it accounted for about 90% of all milling activity, with most of the rest used for cloth fulling (fluffing up and thickening woolens) and only 1% for other industrial activities (Lucas 2005). The late Middle Ages saw the widespread use of water power in ore crushing and smelting (blast furnace bellows) and in stone and wood sawing, wood turning, oil pressing, papermaking, tanning, wire pulling, stamping, cutting, metal grinding, blacksmithing, majolica glazing, and polishing. English waterwheels were also used for winding and water pumping in underground mines (Woodall 1982; Clavering 1995).

All of these tasks were done by waterwheels with a higher efficiency than people or animals could provide, and hence also with much increased labor productivity. Moreover, the unprecedented magnitude, continuity, and reliability of power provided by waterwheels opened up new productive possibilities. This was especially true in mining and metallurgy. Indeed, the energy foundations of Western industrialization rest to a significant degree on these specialized uses of waterwheels. Human and animal muscles could never convert energy at such high, concentrated, continuous, and reliable rates—but only such deliveries could increase the scale, speed, and quality of countless food-processing and industrial tasks. Yet it took a long time for typical waterwheels to reach capacities surpassing the power of large harnessed animal teams.

For centuries, the only way to achieve larger power outputs was to install a series of smaller units in a suitable location. The best-known example of this concentration is the famous Roman mill line at Barbegal, near Arles, which had 16 wheels, each with about 2 kW of capacity, for a total of just over 30 kW (Sellin 1983). Greene (2000, 39) called it "the greatest known concentration of mechanical power in the ancient world," and Hodge (1990, 106) described it as "something that, according to all the textbooks, never existed at all—an authentic, ancient Roman, power-driven, massproduction, assembly-line factory." A closer look shows a less impressive reality (box 4.7).

In any case, larger water mills remained rare for centuries to come. Even during the early decades of the eighteenth century European waterwheels averaged less than 4 kW. Only a few machines surpassed 7 kW, and crude finishing and poor (high-friction) gearing resulted in low conversion efficiencies. Even the most admired machines of that time—14 large waterwheels (12 m in diameter) built on the Seine at Marly between 1680 and 1688—fell short of the intended task of pumping water for 1,400 fountains and cascades in Versailles. The site's potential was nearly 750 kW,

Box 4.7 Barbegal waterwheels

Water for the Barbegal's 16 overshot wheels (most likely built during the early second century CE) was diverted from a nearby aqueduct into two parallel channels on 30° slope (Benoit 1940). Sagui (1948) used highly unrealistic assumptions (a water flow of 1,000 L/s, a speed of 2.5 m/s, an average productivity of 24 t of flour a day) to conclude that the establishment produced enough flour to make bread for about 80,000 people. But Sellin (1983) used more realistic numbers (a water flow of 300 L/s, a speed around 1 m/s), and estimated that each wheel had about 2 kW of useful power, hence a total of 32 kW and (with a 50% capacity factor) a daily output of 4.5 t of flour.

But Sellin adopted Sagui's assumption of 65% of the kinetic energy of water getting converted to kinetic energy of a rotating millstone—while Smeaton's (1759) careful calculations showed 63% to be the maximum efficiency of far better-designed eighteenth-century overshot wheels. The combination of a lower flow—Leveau (2006) argued for 240 or 260 L/s—and a lower efficiency (say, 55%) would translate to 1.5 kW/unit. That would be equal to the combined power of three (or four weak) Roman horses harnessed to a whim, and enough to produce daily about 3.4 t of flour to feed about 11,000 people: certainly a much higher performance than for typical mills of the second century CE but less than a prototype of mass production.

but inefficient transmission of rotary motion (through the use of long reciprocating rods) reduced the useful output to only about 52 kW, not enough to supply every fountain (Brandstetter 2005).

But even small waterwheels had a major economic impact. Even when assuming that flour supplied half of an average person's daily food energy intake, a small water mill, manned by fewer than 10 workers, would grind enough in a day (10 hours of milling) to feed some 3,500 people, a fair-sized medieval town, while hand milling would have required at least 250 laborers. And when combined with innovative machine design, the late eighteenth-century waterwheels made an enormous difference in productivity. A perfect example is the introduction of water-powered machinery for cutting and heading 200,000 nails a day, patented in the United States in 1795 (Rosenberg 1975). The widespread use of these machines brought nail prices down by nearly 90% during the next 50 years.

Waterwheels were the most efficient traditional energy converters. Their efficiencies were superior even when compared to the best steam engines, whose operation converted less than 2% of coal into useful power by 1780,

and usually no more than 15% even by the end of the nineteenth century (Smil 2005). No other traditional prime mover could deliver so much continuous power. Waterwheels were indispensable during the early stages of both European and North American industrialization. Waterwheels reached their apogee—whether evaluated in terms of individual or total capacities or in terms of efficiency of design—during the nineteenth century, at the same time that steam engines were being adopted for new stationary and transportation uses, and the rise and eventual dominance of the new prime mover overshadowed the importance of water power.

But more water power capacity was added during the first six decades of the nineteenth century than ever before, and most of these machines continued to operate even as steam power, and later electricity, were conquering the prime mover markets. Daugherty (1927) estimated that in the United States in 1849, total installed capacity in waterwheels was nearly 500 MW (<7% of all prime movers, including working animals but excluding human labor) compared to about 920 MW installed capacity in steam engines. Comparing actual work performed is more revealing: Schurr and Netschert (1960) calculated that in 1850, U.S. waterwheels delivered about 2.4 PJ, or 2.25 times the total for coal-powered steam engines; that they were still ahead (by about 30%) in 1860; and that their useful work was surpassed by steam power only during the late 1860s. As recently as 1925, 33,500 waterwheels were in operation in Germany (Muller and Kauppert 2004), and some European wheels worked even after 1950.

The new nineteenth-century large textile plants were especially dependent on water power. For example, the Merrimack Manufacturing Company, America's first fully integrated clothmaker (mainly of calico fabrics), opened in 1823 in Lowell, Massachusetts, and relied on about 2 MW of water power from a large (10 m) drop in the Merrimack River (Malone 2009). By 1840 the largest British installation—the 1.5 MW Shaw's waterworks at Greenock, near Glasgow, on the Clyde—had 30 wheels built in two rows on a steep slope and fed from a large reservoir. The largest individual waterwheels had diameters around 20 m, a width of 4–6 m, and capacities well above 50 kW (Woodall 1982).

The world's largest wheel was the Lady Isabella, designed by Robert Casement and built in 1854 by the Great Laxey Mining Company on the Isle of Man to pump water from the Laxey mines. The wheel was a pitchback overshot machine (2.5 rpm) with a diameter of 21.9 m and a width of 1.85 m; its 48 spokes (9.75 m long) were wooden, but the axle and diagonal drawing rods were made of cast iron (Reynolds 1970). All the streams on the slope above the wheel were channeled into the collecting tanks, and the water was then piped into the base of the masonry tower and rose into a wooden flume. The power was transmitted to the pump rod, reaching 451 m to the bottom of the lead-zinc mine shaft, by the main-axle crank and by 180 m of timber connecting rods. The wheel's theoretical peak power was about 427 kW. In normal operation it generated about 200 kW of useful power. The wheel worked until 1926 and was restored after 1965 (Manx National Heritage 2015) (fig. 4.11).

But the era of giant waterwheels was short-lived. Just as these machines were being built during the first half of the nineteenth century, the development of water turbines brought the first radical improvement in waterdriven prime movers since the introduction of vertical wheels centuries earlier. Benoît Fourneyron's first reaction turbine with radial outward flow was built in 1832 to power forge hammers in Fraisans. Even with a very low head of just 1.3 m and a rotor diameter of 2.4 m, it had a capacity of 38 kW. Five years later two improved machines working at the Saint Blaisien spinning mill rated at about 45 kW under heads of 108 and 114 m (Smith 1980).



Figure 4.11 The Great Laxey waterwheel after restoration (Corbis).

The performance of Fourneyron's machine was soon surpassed by an innovative design of an inward-flow turbine, a product that Layton (1979) called a prototypical industrial research product but now is generally known as the Francis turbine, named after James B. Francis (1815–1892), a British American engineer. Later came the jet-driven turbines of Lester A. Pelton (patented in 1889) and the axial flow turbines of the Viktor Kaplan type (in 1920). New turbine designs replaced waterwheels as the prime movers in many industries. For example, in Massachusetts they accounted for 80% of installed power by 1875. That was also the time of the greatest importance of water-driven machines in a rapidly industrializing society.

For example, each of the three leading textile mill centers on the lower Merrimack River in Massachusetts and southern New Hampshire, Lowell, Lawrence, and Manchester, had water machines totaling about 7.2 MW. The whole river basin had about 60 MW of installed capacity, averaging some 66 kW per manufacturing establishment (Hunter 1975). Even in the mid-1850s steam was still about three times more expensive as a prime mover in New England than water. The era of water turbines as direct prime movers rotating geared and belted shafts ended rather abruptly. By 1880 large-scale coal mining and more efficient engines had made steam cheaper than water power virtually anywhere in the United States. Before the end of the nineteenth century most water turbines had stopped delivering direct power and had started to turn electricity generators instead.

Wind Power

The history of harnessing wind for stationary power (as opposed to the much longer history of converting wind into motion through the clever use of sails) and the evolution of windmill designs toward complex and powerful machines of the early industrial era have been well covered by both general and specific national reviews. Notable contributions in the first category are those of Freese (1957), Needham (1965), Reynolds (1970), Minchinton (1980), and Denny (2007). Important national surveys are Skilton (1947) and Wailes (1975) on British mills, Boonenburg (1952), Stockhuyzen (1963), and Husslage (1965) on the much-talked-about Dutch designs, and Wolff (1900), Torrey (1976), Baker (2006), and Righter (2008) on the American machines, which played such a key but underappreciated role in opening the West. Windmills became the most powerful prime movers of the preindustrial era in flatlands where almost nonexistent water heads precluded the construction of small waterwheels (in the Netherlands,

Denmark, and parts of England) and in a number of arid Asian and European regions with seasonally strong winds.

The contribution of windmills to worldwide economic intensification was less decisive than that of waterwheels, mainly because their use eventually became common only in parts of Atlantic Europe. The first clear records of European windmills come from the last decades of the twelfth century. According to Lewis (1993), their use spread first from Persia to the Byzantine territory, where they were transformed into vertical machines, encountered by the Crusaders. Unlike the Eastern machines, whose sails rotated in a horizontal plane around a vertical axis, these mills were vertically mounted rotaries on a horizontal axis whose driving shafts could be turned into the wind. With the exception of Iberian octagonal sail mills working with with triangular cloth (an import from the eastern Mediterranean), early European machines were all post mills. Their wooden structure, housing gears, and millstones pivoted on a massive central post that was supported by four diagonal quarter-bars (fig. 4.12). Because they could not realign themselves once the wind direction changed, they had to be turned to face the wind. They were also unstable in high winds and vulnerable to storm damage, and their relatively low height limited their highest performance (box 4.8).

While post mills continued to work in parts of Eastern Europe until the twentieth century, in Western Europe they were gradually replaced by tower mills and smock mills. In both these designs only the top cap was turned into the wind, either from the ground or, with tall towers, from galleries. Smock mills had a wooden frame, usually octagonal, that was covered with clapboards or shingles. Tower mills were typically rounded, tapering stone structures. Only after 1745 did the English introduction of a fantail to power a winding gear start to turn the sails automatically into the wind. Curiously, the Dutch, with the largest number of windmills in Europe, adopted this innovation only in the early nineteenth century.

But Dutch millers were the first ones to introduce more efficient blade designs. They started to add canted leading-edge boards to previously flat blades around 1600. The resulting arching (camber) gave blades more lift while reducing drag. Later innovations included improvements in sail mounting, cast-metal gearings, and a centrifugal regulating governor. This device did away with the difficult and often dangerous task of adjusting the canvas to different wind speeds. By the end of the nineteenth century the English were starting to install true airfoils, aerodynamically contoured blades with thick leading edges. Grain milling and water pumping (also on ships, with small portable machines) were the most common applications.



Post windmill. The main wooden, almost always oaken, post on which the whole structure was balanced was held up by four quarter-bars attached to massive cross-trees. Windmill rotations were transferred to the millstone by a lantern-and-crown gear and the only access was by ladder. Reproduced from the *Encyclopédie* (Diderot and d'Alembert 1769–1772).

Box 4.8 Wind energy and power

Average wind speed increases roughly with one-seventh the power of height. This means, for example, that it will be about 22% higher 20 m above the ground than at a height of 5 m. The kinetic energy of 1 m³ of air (in joules) is equal to $0.5\rho v^2$, where ρ is air density (about 0.12 kg/m^3 near the ground) and v is its average wind speed (in m/s). Wind power (in watts) is the product of wind energy, an area perpendicular to the wind direction swept by the machine's blades (A, in m²), and wind speed cubed: $0.5\rho AV^3$. As the wind power goes up with the cube of the average speed, doubling the speed increases the available power eightfold. Early (relatively heavy and poorly geared) wind-mills also needed winds of at least 25 km/h (7 m/s) in order to start milling or pumping; at lower speeds they just turned slowly, but sails had to be trimmed at wind speeds above 10 m/s (and furled at speeds above 12 m/s), providing only a narrow window (5–7 hours of daily rotation) for useful work (Denny 2007).

These realities obviously favored locations with sustained brisk winds. Later, more efficient, smoothly geared, and properly lubricated designs would work well with winds above 4 m/s, delivering 10–12 hours of useful operation a day. Preindustrial societies could capture only wind flowing near the ground, with the spans of most of the windmills being less than 10 m. Wind flows also have large temporal and spatial variation. Even in windy places the annual wind speed means fluctuate by up to 30%, and shifting a machine's location by just 30-50 m may cut or increase the average speed easily by half. The limited capacities of preindustrial land transport precluded location at the windiest sites, and the mills were often motionless. No wind machine can extract all of the available wind power: this would require a complete stopping of the airstream! The maximum extractable power is equal to 16/27, or nearly 60%, of the kinetic energy flux (Betz 1926). The actual performance was 20-30% for preindustrial windmills. An eighteenth-century tower mill with a blade diameter of 20 m thus had a theoretical power of about 189 kW with a velocity of 10 m/s-but it delivered less than 50 kW.

Windmills were also used both in Europe and in the Islamic world in grinding and crushing (of chalk, sugar cane, mustard, cocoa), papermaking, sawing, and metalworking (Hill 1984).

In the Netherlands they did all of these things, but their greatest contribution was in draining the country's low-lying land and reclaiming polders for crop fields. The first Dutch drainage mills date from the early fifteenth century, but they became common only in the sixteenth century. Hollow-post *wipmolen* turned big wooden wheels with scoops, and smaller mobile *tjasker* rotated Archimedean screws, but only efficient smock mills could deliver the power required for large-scale reclamation of polders. Zaanse Schans in North Holland had 600 windmills built after 1574, a few of them preserved (Zaanse Schans 2015). The tallest Dutch windmills (33 m) were in Schiedam (five of the original 30 are still standing), grinding grain for the production of jenever (Dutch gin).

Old American windmills, such as those in coastal Massachusetts, were often used for salt extraction, but their numbers remained low. New American windmills appeared right after the middle of the nineteenth century with the westward expansion across the Great Plains, where the scarcity of small streams and the erratic rainfall precluded use of small waterwheels but where the shortage of natural springs required pumping water from wells. Rather than extracting the power in the manner of heavy (and expensive) Dutch mills (that is, by using a few large and wide sails), American windmills were smaller, simple, affordable and yet efficient machines serving individual railway stations and farms.

They consisted usually of a large number of fairly narrow blades or slats that were fastened to solid or sectional wheels and were equipped either with the centrifugal or the side-vane governor and independent rudders. Placed on top of lattice towers 6–25 m tall, they were used to pump water for households, cattle, or steam locomotives (fig. 4.13). These windmills, barbed wire, and railroads were the iconic artifacts that helped open up the Great Plains (Wilson 1999). Daugherty's (1927) estimates show the U.S. nationwide capacity of windmills rising from about 320 MW in 1849 to nearly 500 MW in 1899 and peaking at 625 MW in 1919.

We have no information on the capacities of early windmills. The first reliable experimental measurements date from the late 1750s, when John Smeaton put the power of a common Dutch mill with 9 m sails equal to the power of ten men or two horses (Smeaton 1759). This calculation, based on measurements with a small model, was corroborated by actual performance in oilseed pressing. While the windmill-powered runners turned seven times a minute, two horses made scarcely 3.5 turns in the same time. A


Halladay windmill. During the last decade of the nineteenth century, Halladay windmills were the most popular American brand. They were a common sight at western railway stations, where they pumped water for steam locomotives. Reproduced from Wolff (1900).

typical large eighteenth-century Dutch mill with a 30 m span could develop about 7.5 kW (Forbes 1958). Modern measurements at a well-preserved 1648 Dutch drainage mill capable of lifting 35 m³ with 8–9 m/s winds indicated a windshaft power of about 30 kW, but large transmission losses lowered the useful output to less than 12 kW.

All of these results confirm Rankine's comparison of traditional prime movers. He credited post windmills with 1.5–6 kW of useful power and tower mills with 4.5–10.5 kW (Rankine 1866). Measurements of American windmills put their useful power from a mere 30 W for 2.5 m mills to as much as 1,000 W for large 7.6 m machines (Wolff 1900). Typical ratings (in terms of useful power) were 0.1–1 kW for the nineteenth-century American designs, 1–2 kW for small and 2–5 kW for large post mills, 4–8 kW for common smock and tower mills, and 8–12 kW for the largest nineteenth-century machines. This means that typical medieval windmills were as powerful as contemporaneous waterwheels, but by the early nineteenth century many waterwheels were up to five times more powerful than the largest tower mills, and that difference only grew with the subsequent development of water turbines.

As in the case of waterwheels, the contribution of windmills as providers of stationary power peaked during the nineteenth century. In the UK their total reached 10,000 in 1800; during the late nineteenth century 12,000 worked in the Netherlands while18,000 worked in Germany; and by 1900 about 30,000 mills (with a total capacity of 100 MW) were installed in countries around the North Sea (De Zeeuw 1978). In the United States, several million units were erected between 1860 and 1900 during the country's westward expansion, and their numbers began to decline only in the early 1920s. By 1889 there were 77 manufacturers, with Halladay, Adams, and Buchanan being the leading brands (Baker 2006). Large numbers of American-type water-pumping windmills were used during the twentieth century in Australia, South Africa, and Argentina.

Biomass Fuels

Nearly all traditional societies could produce heat and light only by burning biomass fuels. Woody phytomass, the charcoal derived from it, crop residues, and dried dung provided all the energy needed for household heating, cooking, and lighting and for small-scale artisanal manufactures; later, in larger proto-industrial enterprises, those fuels were used in firing relatively large quantities of bricks and ceramics, making glass, and smelting and shaping metals. The only notable exceptions were found in ancient China, where coal was used in the north in iron making and natural gas was burned in Sichuan to evaporate brines and produce salt (Adshead 1997), and in medieval England (Nef 1932).

The provision of biomass fuels could be as easy as making an everyday short trip to a nearby forest or bush or mountainside to collect fallen branches and break off dry twigs, or to gather dry grasses, or to gather some dry straw after the grain harvest and store it under house eaves. More often, however, it could entail long walks, mostly by women and children, to gather combustible biomass; laborious tree cutting; exhausting charcoal making; and the long-distance transport of the fuel in ox-drawn carts or in camel caravans to cities in the middle of long-deforested plains or in desert regions. The abundance or scarcity of fuel affected house design, as well as dressing and cooking practices. Provision of these energies was one of the principal reasons for traditional deforestation.

In West European countries this dependence diminished rapidly after 1850. The best reconstructions of the primary energy supply show that in France, coal began to provide more than half of all fuel energy by the mid-1870s, and in the United States, coal and oil (and a small volume of natural gas) surpassed the energy content of fuelwood by 1884 (Smil 2010a). But elsewhere the dependence on phytomass fuels continued well into the twentieth century: in the most populous nations of Asia it remained dominant until the 1960s or 1970s, and in sub-Saharan Africa it remains the single largest source of primary energy.

This ongoing use has allowed us to study the modalities and consequences of the inefficient combustion of traditional fuels and its widespread health impact, and observations and analyses done in recent decades (Earl 1973; Smil 1983; RWEDP 2000; Tomaselli 2007; Smith 2013) thus help us understand the long history of preindustrial biomass combustion. Many of these recent findings are perfectly applicable to preindustrial settings because the basic needs have not changed: for most people in traditional societies, energy needs have always amounted just to cooking two or three meals a day, in cold climates heating at least one room, and in some regions also preparing feed for animals and drying food.

Wood and Charcoal

Wood was used in any available form: as fallen, broken, or lopped-off branches, twigs, bark, and roots—but chopped stem wood became available only where good cutting tools—adzes, axes, later saws—were common. Wood variety made surprisingly little difference. There are thousands of woody plants, and though their physical differences are substantial—the specific density of some oaks is almost twice as high as that of some poplars—their chemical composition is remarkably uniform (Smil 2013a). Wood is about two-fifths cellulose, roughly one-third hemicelluloses, and the rest is lignin; in elemental terms, carbon accounts for 45–56% and oxygen for 40–42% of the total mass. The energy content of wood rises with shares of lignin and resins (these contain, respectively, 26.5 MJ/kg and up to 35 MJ/kg, compared to 17.5 MJ/kg for cellulose), but the differences among common woody species are fairly small, mostly 17.5–20 MJ/kg for hardwoods and, because of their higher resin content, 19–21 MJ/kg for softwoods (box 4.9).

The energy density of wood should always refer to absolutely dry matter, but wood burned in traditional societies had a widely varying moisture content. Freshly cut mature hardwoods (leafy trees) are typically 30% water, while softwoods (conifers) are well over 40%. Such wood burns inefficiently as a significant part of the released heat goes into vaporizing released moisture rather than heating a cooking pot or a room. When wood has more than 67% of moisture it will not ignite. That is why dry fallen branches and twigs or hacked-off pieces of dead trees were always preferable to fresh wood, and why wood was usually air-dried before combustion. Cut wood was stacked, sheltered, and let dry for at least a few months, but even in dry climates it still retained about 15% moisture. In contrast, charcoal contains only a trace of moisture, and it was a biomass fuel always preferred by those who could afford its price.

This high-quality fuel is virtually smokeless, and its energy content, equal to that of good bituminous coal, is roughly 50% higher than that of

Energy content of biomass fuels		
		Energy content of
Biomass fuel	Water content (%)	dry matter (MJ/kg)
Hardwoods	15–50	16–19
Softwoods	15-50	21–23
Charcoal	<1	28-30
Crop residues	5-60	15–19
Dry straws	7–15	17–18
Dried dung	10-20	8-14

air-dried wood. Charcoal's other main advantage is its high purity. Because it is virtually pure carbon, it contains hardly any sulfur or phosphorus. This makes it the best possible fuel not only for indoor uses but also in kilns producing bricks, tiles, and lime and in the smelting of ores. A further advantage for smelting is charcoal's high porosity (with a specific density of merely 0.13–0.20 g/cm³), facilitating the ascent of reducing gases in furnaces (Sexton 1897). But traditional production of this excellent fuel was very wasteful.

Partial combustion of the heaped wood inside primitive earth or pit kilns generates the heat necessary for carbonization. Consequently, there is no need for additional fuel, but both the quality and the quantity of the final products are difficult to control. Typical charcoal yields in such kilns were only between 15% and 25% those of air-dried wood. This means that about 60% of the original energy was lost in making charcoal, and in volumetric terms up to 24 m³ of wood (and no less than 9–10 m³) were required to make 1 t of charcoal (fig. 4.14). But the payoff was in the fuel's quality: its combustion could produce temperature of 900°C, and with a supplementary air supply, achieved most efficiently by using bellows, that could be raised to nearly 2000°C, more than enough to melt even iron ores (Smil 2013a).

The harvesting of wood for fuel (as well as for construction and shipbuilding) led to widespread deforestation, and the cumulative effect reached worrisome levels in previously heavily wooded regions. At the beginning of the eighteenth century about 85% of Massachusetts was covered by forests, but by 1870 only about 30% of the state was covered by trees (Foster and Aber 2004). Not surprisingly, on March 6, 1855, Henry David Thoreau (1817–1862) wrote in his *Journals* that

our woods are now so reduced that the chopping this winter has been a cutting to the quick. At least we walkers feel it as such. There is hardly a wood-lot of any consequence left but the chopper's axe has been heard in it this season. They have even infringed fatally on White Pond, on the south of Fair Haven Pond, shaved off the top-knot of the Cliffs, the Colburn farm, Beck Stow's, etc., etc. (Thoreau 1906, 231)

Studies of traditional societies that remained dependent on biomass fuels into the second half of twentieth century indicate annual fuel requirements of less than 500 kg/capita in the poorest villages of tropical regions. Up to five times as much biomass was used in latitudes with pronounced winters and with a substantial wood-based production of bricks, glass, tiles, and metals and evaporation of brines. In Germany up to 2 t of wood (almost



Charcoal production started with leveling the ground and setting up the central pole; cut wood was stacked around it and covered up by clay before ignition. Reproduced from the *Encyclopédie* (Diderot and d'Alembert 1769–1772).

all of it burned to obtain potassium rather than to produce heat) were needed for to make 1 kg of glass, while evaporation of brines in large wood-heated iron pans consumed up to 40 kg of wood per 1 kg of salt (Sieferle 2001).

There are no records of typical biomass fuel consumption during antiquity, and only a few reliable quantities were recorded for some medieval societies. I estimated that average annual energy requirements in the Roman Empire around 200 CE added up to 650 kg/capita, that is, roughly 10 GJ, or about 1.8 kg/day (box 4.10). The best available reconstruction of firewood demand in medieval London (around 1300) resulted in an annual mean of about 1.75 t of wood, or roughly 30 GJ/capita (Galloway, Keene, and Murphy 1996). Estimates for Western Europe and North America just before their switch to coal show even higher average needs.

Those nineteenth-century northern European, New England, Midwestern, or Canadian communities heating and cooking only with

Box 4.10

Wood consumption in the Roman Empire

My conservative estimate accounts for all major wood consumption categories (Smil 2010c). Bread and stews were the Roman staple, and urban *pistrinae* and *tabernae* needed at least 1 kg of wood per day per capita. At least 500 kg of wood per year were needed for space heating, which was required for the roughly one-third of the empire's population that lived beyond the warm Mediterranean in temperate climates. To this must be added an average annual per capita consumption of 2 kg of metals, which required about 60 kg of wood per kilogram of metal. This adds up to 650 kg/capita (roughly 10 GJ, about 1.8 kg/day), but as the Roman combustion efficiencies were uniformly low (<15%), useful energy derived from burning that wood was only on the order of 1.5 GJ/year, an equivalent of nearly 50 L, or one tankful, of gasoline.

For comparison, when Allen (2007) constructed his two Roman household consumption baskets, he assumed an average consumption of nearly 1 kg of wood per capita per day for what he called a respectable alternative, and just 0.4 kg/capita for a bare-bones budget, but his rates excluded fuel used for metallurgy and artisanal manufacturing. And Malanima (2013a) put the average per capita wood consumption in the early Roman Empire at 4.6–9.2 GJ/year, half of the total energy use, with the other half split roughly 2:1 between food and fodder energy. His higher total was 16.8 GJ/capita, while my estimate for food, fodder, and wood was 18–19 GJ/capita (Smil 2010c). wood consumed annually anywhere between 3 and 6 t of the fuel per capita. That was the range of German household consumption during the eighteenth century (Sieferle 2001). The Austrian mean in 1830 was close to 5 t/capita (Krausmann and Haberl 2002), and so was the American nationwide average in the middle of the nineteenth century (Schurr and Netschert 1960). Although that figure also included growing industrial (mainly metallurgical charcoal) and transportation uses, household combustion was still the leading consumer of American wood during the 1850s.

Crop Residues and Dung

Crop residues were indispensable fuels on deforested, densely settled agricultural plains and in arid, sparsely treed regions. Cereal straws and stalks were usually the most abundant, but many other residues were locally and regionally important. These included legume straws and tuber vines, cotton stalks and roots, jute sticks, sugar cane leaves, and branches and twigs pruned from fruit trees. Some crop residues needed drying before combustion. Ripe straws are only between 7% and 15% water, and their energy content is comparable to that of deciduous trees (hardwood).

But their density is obviously much lower, and so storing enough straw to last through the winter could never be as easy as stacking chopped wood. The low density of crop residues also meant that open fires and simple stoves had to be stoked almost constantly. Because of a number of competitive nonenergy uses, crop residues were often in short supply. Legume residues were an excellent high-protein feed and fertilizer. Cereal straw makes a good ruminant food and animal bedding; many societies (including England and Japan) used it for thatching house roofs, and it was also a raw material for manufacturing simple tools and domestic articles.

Consequently, every bit of combustible phytomass was often gathered for household use. Throughout the Middle East thorny shrubs were often burned, and date kernels were used to make charcoal. On the North China Plain women and children with rakes, sickles, baskets, and bags collected fallen twigs, leaves, and dry grasses (King 1927). And in the interior of Asia, as well as throughout the Indian subcontinent, parts of the Middle East, Africa, and both Americas, dried dung was the most important source of heat for cooking. Air-dried dung's heat value is comparable to that of crop residues or grasses (box 4.9).

A little-appreciated reality is dung's essential contribution to America's westward expansion (Welsch 1980). Wild buffalo and cattle dung made possible the early continental crossings and the subsequent colonization of the Great Plains during the nineteenth century. Travelers on the Oregon

and Mormon Trails collected "buffalo wood," and the early settlers stacked winter supplies in igloo shapes or against house walls. Known as cow wood or Nebraska oak, the fuel burned evenly and with little smoke and odor, but its rapid combustion required almost continuous stoking. In South America llama dung was the principal fuel on the altiplano of the Andes, the core of the Inca Empire in southern Peru, eastern Bolivia, and northern Chile and Argentina (Winterhalder, Larsen, and Thomas 1974). Cattle and camel dung was used in the Sahelian region of Africa, as well as in Egyptian villages. Cattle dung was gathered in largest quantities in both arid and monsoonal Asia, and Tibetans always relied on yak dung. Only sheep dung has generally been avoided because its burning produces acrid smoke.

In India, where dung use is still common in many rural areas, both cow and water buffalo droppings are gathered regularly, mostly by *harijan* (untouchable) children and women, both for their own household use and for sale (Patwardhan 1973). Dung was (and is) collected either as dry chips or as a fresh biomass. Fresh dung is mixed with straw or chaff, hand-molded into patties and cakes, and sun-dried in rows, plastered on house walls, or stacked in piles (fig. 4.15). A recent survey of rural energy use in South Asia found that 75% of Indian, 50% of Nepali, and 47% of



Figure 4.15 Rows and piles of cow patties left to dry in Varanasi, Uttar Pradesh, India (Corbis).

Bangladeshi households are still using dung for cooking (Behera et al. 2015).

Household Needs

An ancient Chinese proverb had the right order of things that people cannot do without every day: firewood, rice, oil, salt, sauce, vinegar, and tea. In traditional agricultural societies where grains supplied most of the food energy, their cooking (by steaming, boiling, or baking) was necessary to make the hard seeds edible. But before the grains (stored in baskets, jars, or bins) could be cooked, they had to be processed, and grain milling has been a virtually universal, and also historically almost always the first, processing step; the extraction of oils by pressing a variety of seeds, fruits, and nuts came later. Tubers were processed to remove antinutritive factors or to enable their long-term storage, and sugar cane was crushed to express its sweet juice. In all of these tasks, human energy was only gradually augmented by animal labor.

As already noted, the first use of inanimate power in grain milling horizontal waterwheels rotating small millstones—is about two millennia old.

Cooking required relatively little heat energy in East Asian stir-frying and steaming. In contrast, considerable fuel inputs were needed for baking bread, the staple throughout the rest of the Old World, and for the roasting done commonly in the Middle East, Europe, and Africa. In some societies fuel was also required to prepare feed for domestic animals, above all for pigs. Seasonal heating was necessary in the midlatitudes, but (save for sub-Arctic locations) preindustrial houses were usually heated only for short periods and to relatively low temperatures.

In some fuel-short regions there was no winter heating at all despite months of cold weather: there was no heating in the deforested lowlands of Ming and Qing China south of the Yangzi. But the northernmost parts of the Jiangnan (China south of the Yangzi) have mean January and February temperatures just between 2 and 4°C, with minima going below –10°C. And the chill of traditional English interiors, even after the introduction of coal stoves, is proverbial. The total household energy needs of East Asian or Middle Eastern societies were thus very low. The absolute fuel demand of some northern European and colonial North American societies was rather high, but low combustion efficiencies resulted in relatively low shares of useful heat. Consequently, even in nineteenth-century America, endowed with plenty of fuelwood, an average household claimed only a small fraction of the useful energy flows that became available to its twentiethcentury counterpart.

Food Preparation

In light of the dominance of cereals in the nutrition of all high cultures, milling of grains was certainly the most important food-processing need in history. Whole grain is not very palatable; it is difficult to digest and, obviously, it could not be used for baking. Milling produces flours of various fineness that could be used for the preparation of highly digestible foods, above all breads and noodles. The evolutionary sequence of grain milling started with slightly hollowed rubbing stones and stone pestles and mortars. An oblong, oval saddlestone worked from a kneeling position was common in ancient Middle Eastern societies, as well as in preclassical Europe.

Push mills with hoppers and grooved bedstones were the first major innovation. The Greek hourglass mill had a cone-shaped hopper and a conical grinder. The productivity of muscle-driven processing was very low (Moritz 1958). Tedious labor with rubbing stones or mortars and pestles would yield no more than 2–3 kg of roughly ground flour per hour Two Roman slaves laboriously grinding flour with rotary *mola manualis* (used since the third century BCE) could produce less than 7 kg of coarse flour per hour. The more efficient *mola asinalis* (known as the Pompeian mill, confined to cities and towns) was made from rough volcanic rock, with the *meta* (the lower cylindrical part) covered by the hourglass *catillus*, which was rotated by a harnessed donkey walking in a tight circle, though in confined places slaves were commonly used, and slaves also powered dough-kneading machines in large bakeries: the empire's staple was paid for by terrible suffering (box 4.11).

Box 4.11

Lucius Apuleius (Metamorphoses IX, 12, 3.4) on Roman mill slaves

Ye gods, what a set of men I saw! Their skins were seamed all over with marks of the lash, their scarred backs were shaded rather than covered with tattered frocks. Some wore only aprons, all were so poorly clothed that their skin was visible through the rents in their rags! Their foreheads were branded with letters, their heads were half-shaved. They had irons on their legs. They were hideously sallow. Their eyes were bleared, sore, and raw, from the smoke of the ovens. They were covered with flour as athletes with dust! (J. A. Hanson translation)

A donkey-powered mill (energy input at the rate of 300 W) produced from less than 10 kg/h to 25 kg/h (Forbes 1965), while millstones driven by a small waterwheel (1.5 kW) would grind flour at rates between 80 and 100 kg/h. Flour would have been used to bake bread supplying at least half of all food energy in average dietary intake (but bread's share was often more than 70%). Consequently, a single mill would have produced enough flour in a 10-hour shift to feed 2,500–3,000 people, a fair-sized medieval town. Millstones could be rotated directly by horizontal waterwheels, but all vertical waterwheels and all windmills required the reasonably efficient transmission of rotary power by wooden gears. And no mill could produce good flour without accurately set and well-dressed millstones, the top runner and the stationary bedstone (Freese 1957). By the eighteenth century the stones were usually 1–1.5 m in diameter, up to 30 cm thick, weighed close to 1 t, and rotated 125-150 times a minute. Grain was fed from the hopper into the opening (eye) of the runner, and it was crushed and milled between lands, the stones' flat surfaces.

These massive stones had to be precisely balanced. If they rubbed against each other they could be badly damaged, and they could also spark a fire. If they were too far apart they produced rough meal rather than fine flour. Tolerance requirements were no more than the thickness of a heavy brown paper between the stones at the eye-and that of a tissue paper at the edge. Ground flour and milling by-products were channeled outward along incised grooves (furrows). Skilled craftsmen used sharp tools (mill bills) to deepen these furrows (dress the stone). They did this at regular intervals determined by the quality of the stone and the rate of milling, usually every two to three weeks. Solid granites or hard sandstones, or pieces of cellular quartz (buhrstones) cemented together and held by iron hoops, were the most common millstone choices, and none could do a perfect job in a single run. After the coarse bran was separated from the fine flour the intermediate particles were reground. The whole process could be repeated several times. Final sieving (bolting) separated flour from bran and the flours into different grades.

For centuries, milling with water or wind still required a great deal of heavy labor. Grain had to be unloaded and hoisted with pulleys to hoppers; the freshly milled flour had to be cooled by raking, sorted by sieving, and bagged. Sieves driven by water power were introduced during the sixteenth century. A fully automatic flour mill was first designed only in 1785 by an American engineer, Oliver Evans, who proposed using endless bucketed belts to lift grain and augers (Archimedean screws) to transport it horizontally and to spread the freshly ground flour for cooling. Evans's invention was not an immediate commercial success, but his self-published book on milling became a classic of the genre (Evans 1795).

The history of cooking shows remarkably few advances until the onset of the industrial era. Open hearths and fireplaces were used for roasting (in the fire or on spits, skewers, or gridirons), boiling, frying, and stewing. Braziers were used for boiling water and for grilling, and simple clay or stone ovens were used for baking. Flat breads were stuck to the sides of clay ovens (still the only way to bake proper Indian naan) and leavened breads were placed on flat surfaces. Fuel shortages contributed to the introduction of low-energy cooking methods. The Chinese used cooking pots on three hollow legs (*li*) already before 1500 BCE. Shallow sloping pans—Indian and Southeast Asian *kuali*, and the Chinese *kuo*, better known in the West as the Cantonese wok—sped up frying, stewing, and steaming (E. N. Anderson 1988).

The origin of kitchen stoves remains uncertain, but their wide acceptance obviously required the construction of chimneys. Even in the richest parts of Europe they were uncommon before the beginning of the fifteenth century as people continued to rely on smoky, inefficient fireplaces (Edgerton 1961). Many Chinese clay or brick stoves still did not have chimneys during the first decades of the twentieth century (Hommel 1937). Iron stoves fully enclosing the fire started to replace open fireplaces for cooking and heating only during the eighteenth century. Benjamin Franklin's famous stove, conceived in 1740, was not a self-standing device but rather a stove within a fireplace, able to cook and heat with a much higher efficiency (Cohen 1990). In 1798 Benjamin Thompson (Count Rumford, 1753–1814) designed a brick range with top openings for placing the pots and with a cylindrical oven; the range was first adopted by large kitchens (Brown 1999).

Heat and Light

The primitive nature and inefficiency of traditional heating and lighting are especially remarkable when contrasted with the often impressive mechanical inventions of ancient civilizations. The contrast is even greater in the context of the wide range of technical advances in post-Renaissance Europe. Open fires and simple fireplaces supplied generally inadequate heat during most of the early modern era (1500–1800). The glow of the fire and the flickering, weak flames of the (often smoking) oil lamps and of (mostly expensive) candles provided poor illumination for millennia of preindustrial evolution.

In heating, the much-needed transition from wasteful, unregulated open fires to more efficient arrangements was very slow. Merely moving an open fire into a three-sided fireplace brought only a marginal efficiency gain. Well-stoked fireplaces could keep an unattended fire overnight, but their heating efficiencies were poor. The best rates were close to 10%, but more typical performances were just around 5%. And often a working fireplace, warming its immediate vicinity with radiated heat but drawing the warm inside air outside, was actually causing an overall heat loss in the room. When this draft was impeded the combustion could produce dangerous, even lethal, levels of carbon monoxide.

The efficiencies of traditional brick or clay stoves varied not only with design (often mandated by cooking preferences) but also with the dominant fuel. Modern measurements of Asian rural stoves, whose design has not changed for centuries, make it possible to fix the highest practical efficiencies. Grated, massive brick stoves with long flues and tightly fitting tops, fueled with chopped wood, had efficiencies mostly around 20%. In less massive, drafty stoves with short flues, fueled with straw or grasses, the typical performance was closer to 15%, or even just 10%. But not all traditional heating arrangements were wasteful. At least three spaceheating systems used wood and crop residues in ingeniously efficient ways while providing a great degree of comfort.

They were the Roman *hypocaust*, the Korean *ondol*, and the Chinese *kang*. The first two designs led hot combustion gases through raised room floors before exhausting them through a chimney. The hypocaust was a Greek invention, with the oldest remains found in Greece and Magna Graecia, the coastal areas of southern Italy settled by the Greeks, and dating to the third century BCE (Ginouvès 1962); the Romans used it first in the hot rooms (*caldaria*) of their public baths (*thermae*) and then to heat stone houses in colder provinces of the empire (fig. 4.16). Trials with a preserved hypocaust showed that just 1 kg of charcoal per hour could maintain a temperature of 22°C in a room $5 \times 4 \times 3$ m when the outside temperature was 0°C (Forbes 1966). The third traditional heating setup is still found throughout North China. The kang, a large brick platform (at least 2×2 m and 75 cm tall) is warmed by the waste heat from the adjacent stove; it serves as a bed at night and as a resting place during the day (Hommel 1937).

Yates (2012) did a detailed engineering analysis of this traditional bedstove (or heat exchanger) and offered suggestions for improving its efficiency. These arrangements conducted heat slowly over relatively large areas. In contrast, brazier heaters, common in most Old World societies,



Part of a Roman hypocaust (with the skeleton of a dog killed by fumes) displayed at Homburg-Schwarzenacker Roman Museum in Saarland. Photograph courtesy of Barbara F. McManus.

offered only limited point sources of warmth but could produce high concentrations of carbon monoxide. Japanese, great exploiters of Chinese and Korean inventions, could not introduce the ondol or kang into their flimsy wooden houses. They relied instead on charcoal braziers (*hibachi*) and on foot warmers (*kotatsu*). These small containers of charcoal, set into the floor and covered with wadded cloth, were used well into the twentieth century. They survive even today in the form of an electric kotatsu, a small heater built into a low table. And even the British House of Commons was heated by large charcoal pots until 1791.

Biomass fuels were also the principal sources of traditional lighting in all preindustrial societies. Fire glow, torches of resinous wood, and burning splinters were the simplest but also the least efficient and the least convenient solutions. The first fat-burning oil lamps appeared in Europe during the Upper Paleolithic, nearly 40,000 years ago (de Beaune and White 1993). Candles were used in the Middle East only after 800 BCE. Both oil lamps

and candles offered inefficient, weak, and smoky illumination, but they were at least easily portable and safer to use. They burned a variety of animal and plant fats and waxes—olive, castor, rapeseed, and linseed oils and whale oil, beef tallow, and beeswax—with papyrus, rush pith, flaxen, or hempen wicks. Until the end of the eighteenth century artificial indoor light came only in units of one candle. Bright illumination was possible only through the massive multiplication of these tiny sources.

Candles convert only about 0.01% of their chemical energy into light. The bright spot in their flame has an average irradiance (rate of energy falling on a unit area) just 20% higher than clear sky. The invention of matches, dating to China of the late sixth century, made kindling fires and lighting lamps much easier than igniting tinder. The earliest matches were slender pinewood sticks impregnated with sulfur; they reached Europe only in the early sixteenth century. Modern safety matches, incorporating red phosphorus in the striking surface, were first introduced in 1844, and soon captured most of the market (Taylor 1972). In 1794, Aimé Argand introduced lamps that could be regulated for maximum luminosity using wick holders, with a central air supply and chimneys to draw in the air (McCloy 1952).

Soon afterward came the first lighting gas made from coal. Outside large cities, tens of millions of households around the world continued to depend for their light for more than half of the nineteenth century on an exotic biomass fuel, oil rendered from the blubber of sperm whales. The poorly paid, wearying, and dangerous hunt for these giant mammals—portrayed so unforgettably in Herman Melville's great book, *Moby-Dick* (1851)—reached its peak just before 1850 (Francis 1990). The American whaling fleet, by far the world's largest, had a record total of more than 700 vessels in 1846. During the first half of that decade about 160,000 barrels of sperm oil were brought each year to New England's ports (Starbuck 1878). The subsequent decline in sperm whale numbers and competition from coal gas and kerosene led to a rapid decline of the hunt.

Transportation and Construction

The preindustrial evolution of transportation and construction shows a highly uneven pattern of advances and stagnation, or even decline. Ordinary sail ships of the late eighteenth century were greatly superior to the best vessels of classical antiquity, both in their speed and in their ability to sail much closer into the wind. Similarly, well-upholstered coaches sitting on good springs and drawn by efficiently harnessed horses offered an incomparably more comfortable ride than travel on horseback or in unsprung carts. But at the same time, even in the richest European countries typical roads were hardly better, and often much worse, than during the last centuries of the Roman Empire. And the skills of the Athenian architects who designed the Parthenon, or of the Roman masons who finished the Pantheon, were hardly inferior to the abilities of their successors building late Baroque palaces and churches. Everything changed, and rather rapidly, only with the diffusion of a much more powerful prime mover and a superior construction material. The steam engine and cheap cast iron and steel revolutionized transportation as well as construction.

Moving on Land

Walking and running, the two natural modes of human locomotion, have accounted for most of the personal movements in all preindustrial societies. Energy costs, average speeds, and maximum daily distances have always depended primarily on individual fitness and on the prevailing terrain (Smil 2008a). The efficiency cost of walking increases both below and above the optimum speeds of 5–6 km/h, and uneven surfaces, mud, or deep snow will raise the costs of walking on the level by up to 25–35%. The cost of walking uphill is a function of both gradient and speed, and detailed studies show a nearly linear increase in energy needs across a broad range of speeds and inclines (Minetti et al. 2002).

Running requires power outputs mostly between 700 and 1,400 MW, equivalent to 10–20 times the basal metabolic rate. A slowly running 70 kg man will produce 800 W; the power of an accomplished marathoner running the race (32.195 km) in 2.5 hours will average about 1,300 W (Rapoport 2010); and when Usain Bolt set the world record for 100 m at 9.58 seconds, his maximum power (a few seconds into the run, and at time when his speed was only half of the maximum) was 2,619.5 W, that is, 3.5 horsepower (Gómez, Marquina, and Gómez 2013). The energy cost of running for humans is relatively high, but, as already noted (chapter 2), people have a unique capability of virtually uncoupling this cost from speed (Carrier 1984). Arellano and Kram (2014) showed that body weight support and forward propulsion account for about 80% of the total cost of running; leg swinging claims about 7%, and maintaining lateral balance about 2%—but arm swinging cuts the overall cost by about 3%.

Modern record performances in running improved steadily during the twentieth century (Ryder, Carr, and Herget 1976) and they are undoubtedly well above the best historical achievements. But there is no shortage of outstanding examples of long-distance running in many traditional societies. Pheidippides' fruitless run from Athens to Sparta just before the battle of Marathon in 490 BCE is, of course, the prototype of great running endurance. He covered the distance of 240 km in just two days (his average power output, assuming he weighed about 70 kg, would have been about 800 W, slightly more than 1 hp), only to find that the Spartans refused to help.

The domestication of horses not only introduced a new and more powerful and faster means of personal transport, it was also associated with the diffusion of Indo-European languages, bronze metallurgy, and new ways of warfare (Anthony 2007). Horses were ridden for a long time before they were first harnessed; the beginnings of horseback riding have been placed in the Asian steppes around the middle of the second millennium BCE. But Anthony, Telegin, and Brown (1991) concluded that it may have begun much earlier, around 4000 BCE, among the people of Sredni Stog culture in today's Ukraine.

They based the claim on still inconclusive evidence on the difference between the premolars of feral and domestic horses: animals that have been bitted show distinctive fractures and beveling on micrographs of their teeth. Similarly, Outram and co-workers (2009) used the signs of bitting damage (and other evidence) to conclude that the first horse domestication took place among the people of the Botai Culture and that some of those animals were bridled and perhaps ridden. When walking, bitted animals were no faster than humans, but trotting (in excess of 12 km/h) and cantering (up to 27 km/h) speeds easily covered the distance that would have require major human effort. Galloping horses have a great mechanical advantage: their muscular work is halved by storing and returning elastic strain energy in their spring-like muscles and tendons (Wilson et al. 2001).

Experienced riders on a fit animal had no difficulty riding 50–60 km/day, and by changing horses they could cover more than 100 km/day in emergencies. The longest distances ridden routinely in a day during the medieval era were those by the riders of the Mongolian *yam* (message delivery) service (Marshall 1993), and in the modern era William F. Cody (1846–1917) claimed that as a young rider with the Pony Express he covered, after his relief ride was killed, 515 km in 21 hours 40 minutes using 21 horses (Carter 2000). Minetti (2003) showed that the typical performances of long-distance services were carefully optimized. Relay postal systems preferred an average speed of 13–16 km/h and a daily distance of 18–25 km/ animal to minimize the risk of damage to horses, and these optimum performance bands were followed by the ancient Persian service established by

Cyrus between Susa and Sardis after 550 BCE, by *yam* riders of the thirteenth century, and by the Overland Pony Express, which served California before the construction of the telegraph and railway links.

But riding a horse has always been a major physical challenge. Because a horse's fore-end contains about three-fifths of its body weight, the only way for the vertical planes intersecting rider's and animal's center of gravity to coincide is for the rider to sit forward. But an upright forward position leaves the rider's center of gravity much higher than that of the horse. This can produce a rapid lever action by the rider's back when the horse moves forward, jumps, or stops fast. Consequently, the most efficient position requires the rider to put his center of gravity not only forward but also low. The jockey's crouch ("monkey on a stick") is the best way to do it. Curiously, this optimum was irrefutably established only before the end of the nineteenth century by Federico Caprilli (Thomson 1987).

Pfau and co-workers (2009) found that major horse race times and records improved by up to 7% around 1900 when the crouched posture was first adopted. The posture isolates the rider from the movement of his mount: inevitably, the horse supports the rider's body weight but does not have to move the jockey through each cyclical stride path. Maintaining that posture requires substantial exertion, as reflected by the near-maximum heart rates of jockeys during racing. The forward-low position, used in the most exaggerated version in modern showjumping, differs radically from riding styles portrayed in historical sculptures and images. For a variety of reasons riders sat too far back and were too much extended to make the most efficient motion possible. Classical riders were even more disadvantaged because they did not have stirrups. Only the universal adoption of stirrups in early medieval Europe made armored riding, fighting, and jousting possible.

The simplest way of transporting loads is to carry them. Where roads were absent people could often do better than animals: their weaker performance was often more than compensated for by flexibility in loading, unloading, moving on narrow paths, and scrambling uphill. Similarly, donkeys and mules with panniers were often preferred to horses: steadier on narrow paths, with harder hooves and lower water needs they were more resilient. The most efficient method of carrying is to place the load's center of gravity above the carrier's own center of gravity—but balancing a load is not always practical. Poles slung over a shoulder and wooden yokes hung with loads or buckets are preferable to carrying with the hands or in the arms. Long-distance transfers in difficult terrain are best accomplished with backpacks fastened by good shoulder or head straps. Nepali Sherpas, carrying supplies of Himalayan expeditions, are generally acknowledged as the best porters. They can move between 30 and 35 kg (close to half their body weight) up to base camp, and less than 20 kg on steeper slopes in rarer air above it.

As already noted, the Roman saccarii who reloaded Egyptian grain at Ostia harbor from ships to barges carried sacks of 28 kg over short distances. In the light version of the traditional Chinese sedan chair two men carried a single customer, a load prorating to as much as 40 kg per carrier. These loads corresponded to as much as two-thirds of a carrier's body weight, and walking speeds usually did not exceed 5 km/h. In relative terms, people were better carriers than animals. Typical loads were only about 30% of an animal's weight (that is, mostly just 50–120 kg) on the level and 25% in the hills. Men aided by a wheel could move loads far surpassing their body weight. Recorded peaks are more than 150 kg in Chinese barrows where the load was centered right above the wheel's axle. European barrows, with their eccentric front wheel, were usually loaded with no more than 60–100 kg.

Massed applications of human labor, aided by simple mechanical devices, could accomplish some astonishingly demanding tasks. Undoubtedly the most taxing transport tasks in traditional societies were the deliveries of large-sized building stones or finished components to construction sites. Large stones were quarried, moved, and emplaced by every old high culture (Heizer 1966). A few ancient images offer firsthand illustrations of how this work was accomplished. Certainly the most impressive one is depicted in an already mentioned Egyptian painting from the tomb of Djehutyhotep at el-Bersheh, dated to 1880 BCE (Osirisnet 2015). The scene portrays 166 men dragging a colossus on a sledge whose path is lubricated by a worker pouring liquid from a vessel (fig. 4.17). With lubrication cutting the friction by about half, their massed labor, reaching a peak power of over 30 kW, could move a 50 t load. Yet even such efforts were greatly surpassed in a number of preindustrial societies.

Inca builders used enormous irregular stone polygons whose smoothed sides were fitted with amazing precision. Pulling a 140 t stone, the heaviest block at Ollantaytambo in southern Peru, up the ramp required the coordinated force of about 2,400 men (Protzen 1993. The brief peak power of this group would have been around 600 kW, but we know nothing of the logistics of such an enterprise. How were more than 2,000 men harnessed to pull in concert? How were they arranged to fit into the confines of narrow (6–8 m) Inca ramps? And how did the people in ancient Brittany handle the



Moving a massive (6.75 m tall, weighing more than 50 t) alabaster statue of Djehutyhotep, Great Chief of the Hare Nome (Osirisnet 2015). The drawing reconstructs a damaged wall painting in the tomb of Djehutyhotep at the site of el-Bersheh, Egypt (Corbis).

Grand Menhir Brise (Niel 1961), at 340 t the largest stone erected by a European megalithic society?

The superiority of horses could be realized only with a combination of horseshoes and an efficient harness. Performance in land transport also depended on success in reducing friction and allowing higher speeds. The state of roads and the design of vehicles were thus two decisive factors. The differences in energy requirements between moving a load on a smooth, hard, dry road and on a loose, gravelly surface are enormous. In the first case a force of only about 30 kg is needed to wheel a 1 t load, the second instance would call for five times as much draft, and on sandy or muddy roads the multiple can be seven to ten times higher. Axle lubricants (tallow and plant oils) were used at least since the second millennium BCE. Celtic bronze bearings had inner grooves that contained cylindrical wooden rollers during the first century BC (Dowson 1973). Chinese rolling bearings may be of even greater antiquity, but ball bearings are firmly documented for the first time only in early seventeenth-century Europe.

The roads in ancient societies were mostly just soft tracks that seasonally turned into muddy ruts, or dusty trails. The Romans, starting with the Via Appia (Rome to Capua) in 312 BCE, invested a great deal of labor and organization in an extensive network of hard-top roads (Sitwell 1981). Well-built Roman *viae* were topped with gravel concrete, cobblestones, or slabs set in mortar. By Diocletian's reign (285–305) the Roman system of trunk roads, the *cursus publicus*, had grown to some 85,000 km. The overall energy cost of this enterprise was equivalent to at least one billion labordays. This large total prorates to easily manageable requirements over the centuries of ongoing construction (box 4.12) In Western Europe the Roman achievements in road building were surpassed only during the nineteenth century, in the eastern regions of the continent only during the twentieth.

The Muslim world had no roads network comparable to the Roman *cursus publicus*, although it had intense communication (Hill 1984). Its far-flung parts were connected by much-traveled caravan routes, which, technically, were mere tracks. This was the result of pack camels replacing wheeled transport in the arid region between Morocco and Afghanistan. This development, preceding the Muslim conquest, was driven largely by economic imperatives (Bulliet 1975). In comparison with oxen, pack camels are not only more powerful and faster, they also have greater endurance and longevity. They can move over a rougher ground, subsist on inferior forage, and tolerate longer spells of feed and water shortages. These economic advantages were strengthened with the introduction of the North Arabian saddle sometime between 500 and 100 BCE. The saddle provided an excellent riding and carrying arrangement, and allowed

Box 4.12 Energy cost of Roman roads

If we assume that the average Roman road was just 5 m wide and 1 m deep, construction of 85,000 km of trunk roads would have required the emplacement of about 425 Mm³ of sand, gravel, concrete, and stone, after first removing at least some 800 Mm³ of earth and rock for the roadbed, embankments, and ditches. Assuming that a worker handled only 1 m³ of building materials a day, the tasks of quarrying, cutting, crushing, and moving stones, excavating sand for foundations, ditches, and roadbeds, preparing concrete and mortar, and laying the road would have added up to about 1.2 billion labor-days. Even if the maintenance and repair needs would have eventually tripled this requirement, prorating this grand total over 600 years of construction would result in an annual average of six million labor-days, an equivalent of some 20,000 full-time construction workers. This would represent (at 2 MJ/day) an annual energy investment of nearly 12 TJ of labor.

caravans to displace carts in the Old World's arid region before the Arab expansion.

The Incas, consolidating their empire between the thirteenth and fifteenth centuries, built an impressive road network by corvée labor. Its length totaled about 40,000 km, including 25,000 km of all-weather roads crossing culverts and bridges and equipped with distance markers. Of the two main royal roads, the one winding through the Andes was stonesurfaced. Its width ranged from up to 6 m on river terraces to just 1.5 m when cut through solid rock (Kendall 1973). The unsurfaced coastal link was about 5 m wide. Neither road had to support any wheeled vehicles, just caravans of people and pack llamas carrying 30–50 kg per animal and covering less than 20 km/day.

During the Qin and Han dynasties, the Chinese built an extensive road system totaling about 40,000 km (Needham et al. 1971). The contemporary Roman cursus was more extensive, both in its total length and in the road density per unit area, as well as more sturdily built. This is how Statius (Mozley 1928, 220) in his *Silvae* described the building of the Via Domitiana in 90 CE:

The first labour was to prepare furrows and mark out the borders of the road, and to hollow out the ground with deep excavation; then to fill up the dug trench with other material, and to make ready a base for the road's arched ridge, lest the soil give way and a treacherous bed provide a doubtful resting-place for the o'erburdened stones; then to bind it with blocks set close on either side and frequent wedges. Oh! how many gangs are at work together ! Some cut down the forest and strip the mountain-sides, some plane down beams and boulders with iron; others bind the stones together, and interweave the work with baked sand and dirty tufa; others by dint of toil dry up the thirsty pools, and lead far away the lesser streams.

Chinese roads were constructed by tamping rubble and gravel with metal rammers. This provided a more elastic but less durable surface than the best Roman roads. An excellent messenger service survived the decline of the Han dynasty, but the land-borne transport of goods and people generally deteriorated. Only in some parts of the country was this decline more than made up for by the development of efficient canal transportation. Ox-drawn carts and wheelbarrows carried most of the goods. People were moved in two-wheeled carts and in sedan chairs well into the twentieth century. The first documented vehicles come from Uruk around 3200 BCE. They had heavy, solid-disk wheels up to 1 m in diameter made of dowelled and mortised planks. Their subsequent diffusion across different European cultures was remarkably rapid (Piggott 1983). Some early wheels

rotated about a fixed axle; others turned together with it. Subsequent developments were in the direction of much lighter, free-turning spoked wheels (in the early second millennium BCE) and the use of a pivoted front axle in four-wheel vehicles, making sharp turns possible.

Inefficiently harnessed horses moving on poor roads were slow even when pulling relatively light loads. Maximum specifications restricted loads on Roman roads of the fourth century to 326 kg for horse-drawn, and up to 490 kg for slower ox-drawn, post carriages (Hyland 1990). The low speeds of this transport method limited its daily range to 50-70 km for passenger horse carts on good roads, 30–40 km for heavier horse-drawn wagons, and up to half those distances for oxen. Men with wheelbarrows would cover about 10–15 km/day. Of course, much longer distances were covered by messengers on fast horses. Recorded maxima on Roman roads are up to 380 km/day. Low speeds and low capacities of land transport translated into excessive costs, as illustrated by the figures in Diocletian's edictum de pretiis. In 301 CE it cost more to move grain just 120 km by road than to ship it from Egypt to Ostia, Rome's harbor. And after the Egyptian grain arrived at Ostia, just some 20 km away from Rome, it was reloaded onto barges and moved against the Tiber's stream rather than be hauled by ox-drawn wagons.

Similar limitations persisted in most societies well into the eighteenth century. At its beginning it was cheaper to import many goods into England by sea from Europe rather than to carry them by pack animals from the country's interior. Travelers described the state of English roads as barbarous, execrable, abominable, and infernal (Savage 1959). Rain and snow made poorly laid-out soft dirt or gravel roads impassable; in many cases their limited width allowed only pack traffic. Roads in continental Europe were in similarly bad shape, and coach horses harnessed in teams of four to six animals lasted on average less than three years. Fundamental improvements came only after 1750 (Ville 1990). Initially they included widening and better drainage of roads, and later their surfacing with durable finishes (gravel, asphalt, concrete). Heavy European horses could finally demonstrate their great performance in hauling. By the mid-nineteenth century the maximum allowable French load was increased to nearly 1.4 t, about four times the Roman limit.

In urban transportation horses reached the peak of their importance also only during the railway age, between the 1820s and the end of the nineteenth century (Dent 1974). While the railways were taking over longdistance shipments and travel, the horse-drawn transport of goods and people dominated in all rapidly growing cities of Europe and North America. Steam engine had actually expanded the deployment of horses (Greene 2008). Most railway shipments had to be collected and distributed by horsedrawn vans, wagons, and carts. These vehicles also delivered food and raw materials from the nearby countryside. Greater urban affluence brought many more private coaches and hansoms, cabs and omnibuses (first in London in 1829), and delivery wagons (fig. 4.18).

The stabling of the animals in mews and the provision and storage of hay and straw made an enormous demand on urban space (McShane and Tarr 2007). At the end of Queen Victoria's reign, London had some 300,000 horses. City planners in New York were thinking about setting aside a belt of suburban pastures to accommodate large herds of horses between the peak demands of rush-hour transport. The direct and indirect energy costs of urban horse-drawn transport—the growing of grain and hay, feeding and stabling the animals, grooming, shoeing, harnessing, driving, and removal of wastes to periurban market gardens—were among the largest items on the energy balance of the late nineteenth-century cities. This equine dominance ended rather abruptly. Electricity and internal combustion engines were becoming practicable just as the numbers of urban horses rose to record totals during the 1890s. In less than a generation,



Figure 4.18

Engraving from the *Illustrated London News* of November 16, 1872, captures perfectly the high density of horse-drawn traffic (hansom cabs, omnibuses, heavy wagons) in the rapidly industrializing cities of late nineteenth-century Europe.

horse-drawn city traffic was largely displaced by electric streetcars, automobiles, and buses.

Curiously, it was also only during that time that European and American mechanics came up with a practical version of the most efficient humanpowered locomotive vehicle, the modern bicycle. For generations bicycles were clumsy, even dangerous, contrivances that had no chance of mass adoption as vehicles of convenient personal transport. Rapid improvements came only during the 1880s. John Kemp Starley and William Sutton introduced bicycles with equal-sized wheels, direct steering, and a diamond-shaped frame of tubular steel (Herlihy 2004; Wilson 2004; Hadland and Lessing 2014), and these designs have been closely followed by virtually all twentieth-century machines (fig. 4.19). The evolution of the modern bicycle was largely complete with the addition of pneumatic tires and the back-pedal brake in 1889.

Improved bicycles equipped with lights, various load carriers, and tandem seats became common for commuting, shopping, and recreation in a number of European nations, most prominently the Netherlands and Denmark. Later diffusion throughout the poor world multiplied European totals. The history of Communist China has been particularly closely connected with a massive use of the machine. Until the early 1980s there were no private cars in China, and until the late 1990s most commuters rode bicycles even in the country's large cities. The subsequent construction of subways in all major cities and a surge in car ownership reduced urban bicycle use (a shift that has been only partially offset by the rising popularity of e-bikes), but rural demand remains strong, and China is still the world's largest producer of bicycles, with more than 80 million units a year, of which more than 60% are exported (IBIS World 2015).

Oared Ships and Sail Ships

Human-powered waterborne movement achieved much higher power ratings than animate transport on land. Oared vessels were ingeniously designed to integrate the efforts of tens and even hundreds of oarsmen. Naturally, prolonged strenuous pulling of heavy oars required very hard labor, and when done in confined quarters below the deck it was extremely exhausting. Our admiration of the complex design and organizational mastery of large oared ships must be tempered by the realization of the human suffering exacted by their speedy motion. Ancient Greek oared ships have been particularly well studied (Anderson 1962; Morrison and Gardiner 1995; Morrison, Coates, and Rankov 2000). The vessels that took the Greek



The development of the bicycle started surprisingly late and advanced rather slowly. Riders had to push themselves on Baron von Drais's 1816 clumsy draisine. Pedals were first applied to the axle of the drive wheel in 1855, an advance leading to the velocipedes of the 1860s. Subsequent design regression led to huge front wheels and plenty of accidents. Only the late 1880s brought the safety, efficiency, and simplicity of the modern bicycle. Adapted from Byrn (1900).

troops to Troy, *penteconteres* with 50 oarsmen, could receive briefly useful power inputs of up to 7 kW.

Triple-tiered *trieres* (Roman triremes), the best-performing warships of the classical era, were powered by 170 rowers (fig. 4.20). Strong oarsmen could propel them with more than 20 kW of power, enough to produce maximum speeds of close to 20 km/h. Even when moving at more common top speeds of 10–15 km/h, the highly maneuverable triremes were powerful fighting machines. Their bronze ram could hole the hulls of enemy ships with devastating effect. One of the decisive battles of Western history, the defeat of a larger Persian fleet by a smaller Greek force at Salamis (480 BCE), was won in this fashion by triremes. They were also the most important



Side view, partial plan, and cross section of the reconstructed Greek trireme *Olympias*. Six files arranged in a V shape accommodate 170 rowers, and the topmost oars have their pivots on outriggers. Based on Coates (1989).

warships of republican Rome. A full-scale reconstruction was finally accomplished during the 1980s (Morrison and Coates 1986; Morrison, Coates, and Rankov 2000).

Larger ships—quadriremes, quinquiremes, and so on—followed in rapid succession after Alexander's death in 323 BCE. As there is no indication that any of these ships had more than three tiers, two or more men presumably powered a single oar. The end of this progression was reached with the construction of *tessarakonteres* during Ptolemaios Philopator's reign (222–204 BCE). The 126 m long ship was to carry more than 4,000 oarsmen and nearly 3,000 troops, and could theoretically be propelled with over 5 MW of power. But its weight, including the heavy catapults, made it virtually immovable, a costly shipbuilding miscalculation.

In the Mediterranean, large oared vessels retained their importance well into the seventeenth century: at that time the largest Venetian galleys had 56 oars, each crewed by five men (Bamford 1974; Capulli 2003). Large Maori dugout canoes were oared by almost as many warriors (up to 200). The general limits of aggregate human power in sustained rowing applications were thus between 12 and 20 kW. There were also ships powered by pedaling or stepping on treadmills. During the Sung dynasty the Chinese built increasingly larger paddle-wheel warships powered by up to 200 men treading pedals (Needham 1965). In Europe, smaller tugs powered by 40 men turning capstans or treadmills appeared in the middle of the sixteenth century. Animate power was also the principal prime mover for moving goods and people by canal boats and barges (box 4.13).

Canals were particularly important catalysts of economic development in the core area of the Chinese state (in the lower basin of the Huang He and on the North China Plain) beginning in the Han dynasty (Needham et al. 1971; Davids 2006). By far the longest and most famous of these transport arteries is *da yunhe*, the Grand Canal. Its first section was opened in the early seventh century, and its completion in 1327 made it possible to move barges from Hangzhou to Beijing. This is a latitudinal difference of 10° and an actual distance of nearly 1,800 km. Early canals used inconvenient double slipways on which oxen hauled boats to a higher level. The invention of the canal pound-lock in 983 made it possible to raise boats safely and without wasting water. A progression of locks raised the Grand Canal's highest point to just over 40 m above sea level. Chinese canal boats were pulled by gangs of laborers or by oxen or water buffaloes.

In Europe, canals reached their greatest importance during the eighteenth and nineteenth centuries. Horses or mules moving on adjoining tow paths pulled the barges with speeds of about 3 km/h when loaded, and up to 5 km/h when empty. The mechanical advantages of this form of transport are obvious. On a well-designed canal a single heavy horse could pull a load of 30–50 t, an order of magnitude more than a horse could manage on the best hard-top road. Steam engines gradually replaced bargetowing animals, but many horses still worked on smaller canals during the 1890s.

Box 4.13 Ancient canal transportation

The earliest description of their sluggish progress (snoring waterman, grazing mule) was left by Horace (Quintus Horatius Flaccus, 65–8 BCE) in his *Satires* (Buckley 1855, 160):

While the waterman and a passenger, well-soaked with plenty of thick wine, vie with one another in singing the praises of their absent mistresses: at length the passenger being fatigued, begins to sleep; and the lazy waterman ties the halter of the mule, turned out a-grazing, to a stone, and snores, lying flat on his back. And now the day approached, when we saw the boat made no way; until a choleric fellow, one of the passengers, leaps out of the boat, and drubs the head and sides of both mule and waterman with a willow cudgel. At last we were scarcely set ashore at the fourth hour. The European construction of transportation canals, an unmistakable import from China, started in North Italy during the sixteenth century. The 240 km long French Canal du Midi was completed by 1681. The longest continental and British links came only after 1750, and the German canal system actually postdated railroads (Ville 1990). Canal barges moved large quantities of raw materials and import commodities for expanding industries and growing cities, and they also took out their wastes. They handled a large share of European traffic just before the introduction of railways and for a few decades afterward (Hadfield 1969).

In contrast to canal shipping and to warships, the long-distance seaborne transport of goods and people was dominated by sail ships from the very beginning of high civilizations. The history of sail ships may be understood primarily as a quest for the better conversion of the kinetic energy of the wind into the efficient motion of vessels. Sails alone could not do this, but they were obviously the key to nautical success. They are basically fabric aerofoils (as they are inflated by wind they form a foil shape) designed to maximize lift force and minimize drag (box 4.14). But this force from the sail's foil shape must be combined with the balancing force of the keel; otherwise the vessel will drift downwind (Anderson 2003).

Square sails set at right angles across the ship's long axis were efficient energy converters only with the wind astern. Roman ships pushed by the northwesterlies could make the Messina-Alexandria run in just 6–8 days, but the return could take 40–70 days. Irregular sailings, substantial seasonal differences, and the cessation of all travel during winter (shipping between Spain and Italy was closed between November and April) make it almost impossible to say what speeds were typical (Duncan-Jones 1990). Longer voyages against the wind were primarily the result of lengthy course changes. All ancient ships were rigged with square sails, and there was a long interval before the introduction and widespread diffusion of radically different designs (fig. 4.21).

Ships with fore-and-aft rigging had sails aligned with the vessel's long axis, and their masts were pivots for the sails to swing around and to catch the wind. They could change direction much more easily by simply turning into the wind and proceeding on a zig-zag course. The earliest fore-and-aft rigging most likely came from Southeast Asia in the form of a rectangular canted sail. Modifications of this ancient design were eventually adopted both in China and, through India, in Europe. The characteristic battenstrengthened Chinese lug sails were in use since the second century BCE. The canted square sail became common in the Indian Ocean during the

Box 4.14 Sails and sailing near the wind

When wind strikes a sail, the difference in pressure generates two forces: lift, whose direction is perpendicular to the sail, and drag, which acts along the sail. With wind astern, the lift force will obviously be much stronger than the drag force, and a ship will make good progress. With wind on the beam, or slightly ahead it, the force pushing the vessel sideways is obviously stronger than the force propelling it forward. If the ship were to try to steer even closer to the wind, the drag would surpass the lift and the vessel would be pushed backward. The maximum capabilities for sailing near the wind have advanced by more than 100° since the beginning of sailing. Early Egyptian square-sailed ships could manage only a 150° angle, while medieval square rigs could proceed slowly with the wind on their beam (90°), and their post-Renaissance successors could move at an angle of just about 80° into the wind. Only the use of asymmetrical sails mounted more in line with the ship's long axis and capable of swiveling around their masts made sailing closer to the wind possible.

Ships combining square sails with triangular mizzens could manage 60°, and fore-and-aft rigs (including triangular, lug, sprit and gaff sails) could come as close as 45° to the wind. Modern yachts come very close to 30°, the aerody-namic maximum. The only way to circumvent the earlier limits was to proceed under the best manageable angle and keep changing the course. Square-rigged ships had to resort to wearing, or making a complete downwind turn. Ships with fore-and-aft sails tried tacking, turning their bows into the wind, and eventually catching the wind on the opposite side of the sail.

third century BCE, a clear precursor of the triangular (lateen) sails that were so typical of the Arab world after the seventh century.

Viking expansion (which eventually reached as far west as Greenland and Newfoundland) was made possible by the deployment of a large number of massive rectangular or square woolen sails. Production of those large sails was very labor-intensive (a single 90 m² one-ply sail took one craftsman, using vertical warp and horizontal weft, up to five years to produce), and the need to convert land for pasture and to maintain extensive sheep herds in order to produce enough wool for large Norse fleets were likely based on slave labor (Lawler 2016). After the Viking voyages ended, large woolen sails were used in the Northeastern Atlantic (between Iceland and Scandinavia, including the Hebrides and the Shetlands) until the nineteenth century (Vikingeskibs Museet 2016).



Principal types of sails. Square sails, straight (a) or flared (b), are the oldest types. Triangular sails include the Pacific boom (d), and lateens without or with a luff edge (e, f). Sprit sails (h) were common in Polynesia, Melanesia (i), the Indian Ocean (j), and Europe (k, l). Masts and all supporting structures (booms, sprits, gaffs) are drawn with thicker lines, and the sails are not shown to scale. Based on Needham and coworkers (1971) and White (1984).

In Europe, only the late medieval combination of square rigging and triangular sails made sailing close to the wind possible. Gradually, these ships were rigged with a larger number of loftier and better adjustable sails (fig. 4.22). Better and deeper hull designs, a stern-post rudder (in use in China since the first century CE, in Europe only a millennium later), and a magnetic compass (in China after 850, in Europe around 1200) turned them into uniquely efficient wind energy converters. This combination was made almost irresistibly powerful by the addition of accurate heavy guns. The gunned ship, developed in Western Europe during the fourteenth and fifteenth centuries, launched the era of unprecedented long-distance expansion. In Cipolla's (1965, 137) apt characterization, the ship



Evolution of sail ships. Ancient Mediterranean societies used square-rigged sails. Before they were adopted by Europeans, triangular sails were dominant in the Indian Ocean. A large seagoing junk from Jiangsu typifies efficient Chinese designs. Columbus's *Santa Maria* had square sails, a foretopsail, a lateen on mizzen, and the spritsail under the bowsprit. *Flying Cloud,* a famous mid-nineteenth-century record-breaking U.S. clipper, was rigged with triangular jibs fore, a spanker aft, and lofty main royal and skysails. Simplified outlines are based on images in Armstrong (1969), Daumas (1969), and Needham and co-workers (1971) and are drawn to scale.

was essentially a compact device that allowed a relatively small crew to master unparalleled masses of inanimate energy for movement and destruction. The secret of the sudden and rapid European ascendancy was all there.

These ships reached their largest sizes and became equipped with an increasing number of guns during the late eighteenth and the early nine-teenth centuries. The French-British naval rivalry eventually ended in a clear British maritime supremacy, but it was an original French design of a large two-decked battleship (about 54 m long at the gun deck, with 74 guns and crew of 750 men) that became the dominant class of sailing vessels

before being displaced by steam-powered ships. The British Royal Navy eventually commissioned nearly 150 of those large ships (Watts 1905; Curtis 1919), and they ensured the country's naval dominance before and after the Napoleonic age. Starting in the early fifteenth century the simplest ships of this innovative design carried the audacious Portuguese sailors on longer voyages (box 4.15).

In 1492 the Atlantic was crossed to America by three Spanish ships captained by Christopher Columbus (1451–1506). In 1519 Ferdinand Magellan (1480–1521) traversed the Pacific, and after his death in the Philippines his *Victoria* was captained by Juan Sebastián Elcano (1476–1526), who completed the first circumnavigation of the world. Rich historical records enable us to chart the progress in tonnages and speeds of both typical and best sail ships used during the colonial expansion and for the rising volume of maritime trade (Chatterton 1914; Anderson 1926; Cipolla 1965; Morton 1975; Casson 1994; Gardiner 2000). Although the Romans built ships with capacities of more than 1,000 t, their standard cargo vessels carried less than 100 t.

More than a millennium later, Europeans embarked on their explorations with ships nearly as small. In 1492 Columbus's *Santa Maria* had a capacity of 165 t, and the *Trinidad*, Magellan's ship, had a mere 85 t. A century later vessels of the Spanish Great Armada (sailing in 1599) averaged

Box 4.15

Portuguese voyages of discovery

Portuguese sailors advanced first southward, along the western coast of Africa: the mouth of the Senegal Rover was reached in 1444, the equator was crossed in 1472, today's Angola was sighted in 1486, and in 1497 Vasco da Gama (1460–1524) rounded the Cape of Good Hope and crossed the Indian Ocean to India (Boxer 1969; Newitt 2005). Luís de Camões (1525–1580), in his great epic poem *Os Lusíadas*, published in 1572 and cited here in Richard Burton's translation (Burton 1880, 11), captured their progress:

They walked the water's vasty breadth of blue, parting the restless billows on their way; fair favouring breezes breathed soft and true, the bellying canvas bulging in their play: The seas were sprent with foam of creamy hue, flashing where'er the Prows wide open lay the sacred spaces of that ocean-plain where Proteus' cattle cleave his own domain. 515 t. By 1800 British ships in the Indian fleet had capacities of about 1,200 t. And while Roman cargo ships could not go faster than 2–2.5 m/s, the best mid-nineteenth-century clippers could surpass 9 m/s. In 1853 the Bostonbuilt and British-crewed *Lightning* logged the longest daily run under sail: its 803 km prorate to an average speed of 9.3 m/s (Wood 1922). And in 1890 the *Cutty Sark*, perhaps the most famous tea clipper, ran 6,000 km in 13 consecutive days, averaging 5.3 m/s (Armstrong 1969).

Too many questionable assumptions would have to be made to calculate the total energy needed to move either individual ships on long voyages or harnessed annually by a nation's merchant or military fleets. According to Unger (1984), the contribution of sail ships to the nationwide energy use during the Dutch Golden Age was about equal to the output of all Dutch windmills—but that was equivalent to less than 5% of the country's huge peat consumption (box 4.16). While it may be elusive to quantify aggregate energies in sailing, there is no doubt that an expansion of shipping

Box 4.16

Contribution of sail ships to Dutch energy use

Information on tonnages and speeds that would allow us to calculate the energies needed to move individual ships on long voyages, or to come up with the aggregate annual contributions of wind power harnessed by merchant or military fleets, is inadequate. Critical variables—hull designs, sail areas and cuts, cargo weights, and utilization rates—are far too heterogeneous to allow for estimation of meaningful averages. Still, Unger (1984) made a set of assumptions to calculate the contribution of sail ships to the Dutch nation's energy use during the Dutch Golden Age and ended up with an annual total of roughly 6.2 MW during the seventeenth century. For comparison, this is almost exactly equal to the total power of all Dutch windmills as estimated by De Zeeuw (1978)—but it was only a small fraction (<5%) of the country's huge peat consumption.

But such quantitative comparisons are misleading: no amount of peat would have made the trips to the East Indies possible; useful energy gained from the peat was most likely less than a quarter of its gross heat value; and, of course, there is the fundamental contrast in comparing limited and nonrenewable (or not renewable on a historical time scale) deposits of a young fossil fuel and an abundant and renewable resource constantly recharged by differences in atmospheric pressure. Comparisons of aggregate power thus make no greater sense than those of specific conversion efficiencies (in this case, contrasting the efficiency of a sail with the performance of a peat stove). (preceding that of the economy as a whole) and its rising productivity were critical contributions to Europe's economic growth between 1350 and 1850 (Lucassen and Unger 2011).

Buildings and Structures

The enormous variety of building styles and ornaments can be reduced to only four fundamental structural members: walls, columns, beams, and arches. Only human labor aided by a few simple tools was needed to create them from the three basic building materials of the preindustrial world, timber, stone, and bricks, either sun-dried or kiln-burned. Trees could be cut and roughly shaped with axes and adzes. Stone could be quarried with only hammers and wedges and shaped with chisels. Sun-dried bricks could be made with readily available alluvial clays. Shortages of large trees limited the use of timber in many regions, and the expensive transport of stone restricted its choice largely to local varieties. Subsequent, and often very elaborate, fine shaping and surface detailing of timber and stone could greatly increase the energy cost of using these building materials.

Sun-dried mud bricks, common throughout the Middle East and Mediterranean Europe, were the least energy-intensive building blocks. Their output reached prodigious quantities even in the earliest settled societies. This how the Sumerian capital Uruk is described in the Sumerian epic Gilgamesh, one of the first preserved literary documents, from before 2500 BCE (Gardner 2011): "One part is city, one part orchard, and one part claypits. Three parts including the claypits make up Uruk." They were made from loams or clays, water, and chaff or chopped straw, sometimes with the addition of dung and sand; the mixture was compacted, rapidly shaped in wooden molds (up to 250 pieces per hour), and left to dry in the sun. Dimensions ranged from chunky square Babylonian pieces ($40 \times 40 \times$ 10 cm) to slimmer, oblong $(45 \times 30 \times 3.75 \text{ cm})$ Roman bricks. Mud bricks are poor heat conductors, helping to keep buildings cool in hot arid climate. They also had an important mechanical advantage: building a mud-brick vault requires no wooden beams for support (Van Beek 1987). With suitable clays and requisite labor they could be produced in prodigious quantities.

Burned bricks were used in ancient Mesopotamia, and later became common in both the Roman Empire and Han China. For centuries, most of the firings were in unenclosed piles or pits, resulting in a great waste of fuel and uneven baking. Later, firing in regular mounds or stacks could reach temperatures up to 800°C, yielding a more uniform product with a much higher efficiency. Completely enclosed horizontal kilns ensured better
consistency and a higher combustion efficiency. They had properly spaced flues, and the rising hot gases were reflected downward from domed roofs but they needed wood or charcoal for their operation. In Europe, these needs increased during the sixteenth century when bricks started to replace wattle-and-daub or timber studding, and when they began to be more commonly used for foundations as well as for walls.

Regardless of their principal materials, preindustrial structures demonstrate a skillful integration of large numbers of men (including some experienced builders), or men and animals, accomplishing tasks that appear extraordinarily demanding even by the standards of today's mechanized world. All quarrying was done by hand. Animal teams transported quarried stone to a site, and animals were sometimes used to power hoisting machines used to lift heavy pieces to a higher elevation, but otherwise traditional construction relied solely on human labor. Craftsmen used saws, axes, hammers, chisels, planes, augers, and trowels and worked compound pulleys or cranes and treadwheels for lifting timber, stones, and glass (Wilson 1990).

Cranes powered by men turning capstans or windlasses or treading drums could do that task readily, if slowly, and some machines—including Filippo Brunelleschi's (1377–1446) ox-powered hoist, used to raise masonry materials for building the spectacular cupola of the Cathedral of Santa Maria del Fiore in Florence, and a rotary crane to set the lantern top (Prager and Scaglia 1970)—were designed for specific demanding tasks (box 4.17). Some projects were completed speedily: the Parthenon in just 15 years (447–432 BCE), the Pantheon in about eight (118–125 CE), and Constantinople's Hagia Sophia, a high-vaulted Byzantine church later converted into a mosque, in less than five years (527–532).

Several types of large construction projects stand out. By far the best known are various ceremonial structures, above all funerary monuments and places of worship. The most remarkable structures in the first group, pyramids and tombs, are distinguished by their massiveness, while temples and cathedrals combine monumentality with complexity and beauty. Among the preindustrial utilitarian structures I would single out aqueducts because of their length and the combination of canals, tunnels, bridges, and inverted siphons. No accurate energy accounts can be prepared for the construction of any ancient structures, and even the energy cost of building medieval projects is not easy to estimate. But approximate calculations reveal substantial differences in total energy requirements, and even greater differences in average power flows.

Box 4.17 Brunelleschi's ingenious machines

Filippo Brunelleschi's work on the Cathedral of Santa Maria del Fiore is a perfect demonstration of the roles played by ingenious inventions in deploying the needed amount of energy in a suitable manner. Draft animals and laborers were readily available to supply the requisite power, but the record size of the cathedral's cupola (an inner span of 41.5 m in diameter) and, even more, the unprecedented manner of its construction (without any ground-based scaffolding) could not have been accomplished without Brunelleschi's new ingenious machines (Prager and Scaglia 1970; King 2000; Ricci 2014). Those machines were dismantled once the construction ended, but fortunately, their drawings have been preserved in Buonaccorso Ghiberti's *Zibaldone*.

They included ground-supported and elevated cranes and a reversible hoist, a rotary crane used in the construction of the lantern, elaborate winches, and, perhaps the most ingenious machine of all, a load positioner (not necessarily Brunelleschi's original invention but certainly an excellent execution of the idea). Materials for the cupola were lifted by a central (ox-powered) hoist. Bricks were easily moved to masons building the ascending curved structure, but the heavy stone blocks used for the tie rings (needed to arrest any spreading of the structure) could not be moved from the central elevated location to their precisely predetermined sites by pulling or pushing: the task was done by the load positioner with two horizontal screw-actuated slideways mounted on a vertical rod and using a counterweight.

Impressive funerary or religious structures requiring huge and sustained energy flows—long-range planning, outstanding organization, and large-scale labor mobilization—were built by every preindustrial high culture (Ching, Jarzombek, and Prakash 2011). These tombs and temples express the universal human striving for permanence, perfection, and transcendence (fig. 4.23). I would very much like to say something definite about the construction process and energy requirements of building the Egyptian pyramids, the grandest structures of the ancient world. We know that their construction required a meshing of long-range planning, efficient grand-scale logistics, effective supervision and servicing, and admirable, though nearly completely obscured, technical skills.

The largest pyramid, the pharaonic tomb of Khufu of the Fourth Dynasty, best embodies all these qualities. Built of nearly 2.5 million stones weighing on average about 2.5 t, this mass of over 6 Mt within a volume of 2.5 Mm³ was assembled with remarkable precision, and with admirable speed. From



ANURADHAPURA

ELAM

Figure 4.23

Khufu's pyramid at Giza, Pyramid of the Sun at Teotihuacan, the Jetavana stupa at Anuradhapura, and the Choga Zanbil ziggurat at Elam. Detailed information about these structures is available in Bandaranayke (1974), Tompkins (1976), and Ching, Jarzombek, and Prakash (2011).

the orientation of the Great Pyramid (using the alignment of two circumpolar stars, Mizar and Kochab) we can narrow the beginning of its construction to between 2485 and 2475 BCE (Spence 2000), and the structure was completed in 15–20 years. Egyptologists concluded that core stones were quarried at the Giza site, that the facing stones had to be brought from Tura quarries across the Nile, and that the most massive granite blocks, those forming the corbel roof inside the pyramid (the heaviest one weighing nearly 80 t), had to be shipped from southern Egypt (Lepre 1990; Lehner 1997).

All of that seems quite intelligible. Ancient Egyptians mastered the craft of stone quarrying, in terms of both the mass output of similarly seized blocks and extracting massive monoliths. They could also move heavy objects on land and on boats. A well-known painting shows how a 50 t colossus from a cave at el-Bersheh (1880 BCE) was moved by 127 men (developing peak useful power of over 30 kW) on a sledge whose friction was reduced by a worker pouring water from a vessel. And that very large stones were transported on boats is attested by a unique image from Deir el-Bahari: two 30.7 m long Karnak obelisks were carried on a 63 m long barge pulled by about 900 oarsmen in 30 boats (Naville 1908).

But beyond quarrying and moving stones to the building site, all is conjecture; we still do not know how the largest pyramids were actually built (Tompkins 1971; Mendelssohn 1974; Hodges 1989; Grimal 1992; Wier 1996; Lehner 1997; Edwards 2003). The Egyptian hieroglyphic and pictorial record, so rich in many other aspects, provides no contemporaneous depictions or descriptions. The most common modern assumptions specify the use of clay, brick, and stone ramps, with no consensus about their form (a single inclined plane, multiple planes, an encircling ramp?) or slope (with suggested ratios as high as 1:3 and as low as 1:10). But such disagreements do not matter as it is highly unlikely that any construction ramps were used (Hodges 1989).

A single inclined plane would have to be completely rebuilt after every layer of stonework was finished, and with a manageable slope of 10:1 its volume would have far surpassed that of the pyramid itself. Ramps encircling the pyramid would have been narrow; quite difficult to build, buttress, and maintain under heavy use; and perilous if not impossible to negotiate. Pivoting ropes at right angles around corner posts was suggested as a solution, but we have no proof that Egyptians could do that or that it would actually work. In any case, there are no remnants of vast volumes of the ramp-building rubble anywhere on the Giza Plateau.

The earliest description of pyramid building was written by Herodotus (484–425 BCE) two millennia after their completion. During his Egyptian travels he was told that

for the making of the pyramid itself there passed a period of twenty years; and the pyramid is square, each side measuring eight hundred feet, and the height of it is the same. ... This pyramid was made after the manner of steps, which some call "rows" and others "bases": and when they had first made it thus, they raised the remaining stones with machines made of short pieces of timber, raising them first from the ground to the first stage of the steps, and when the stone got up to this it was placed upon another machine standing on the first stage, and so from

this it was drawn to the second upon another machine; for as many as were the courses of the steps, so many machines there were also, or perhaps they transferred one and the same machine, made so as easily to be carried, to each stage successively, in order that they might take up the stones; for let it be told in both ways, according as it is reported. However that may be, the highest parts of it were finished first, and afterwards they proceeded to finish that which came next to them, and lastly they finished the parts of it near the ground and the lowest ranges.

Might this be the description of the actual construction method? Proponents of lifting think so, and they have offered many solutions as to how the work could have been done with the help of levers or simple but ingenious machines. Hodges (1989) argued for the simplest method of using wooden levers to lift stone blocks and then rollers to emplace them. Objections to this process rest above all on the large number of vertical transfers required for every block placed in higher rows and on the need for constant vigilance and accuracy to prevent accidental falls during the manipulation of stones weighing 2–2.5 t.

Construction specifics aside, first principles allow us to quantify the total energy required to build the Great Pyramid and hence to estimate the required labor force: my calculations (erring on a generous side rather than assuming theoretical minima) show that it could have been as low as 10,000 people (box 4.18). One of the few certainties regarding the pyramid construction is that order-of-magnitude-higher claims of required labor force are indefensible exaggerations. Feeding very large numbers of workers, most of them concentrated on the Giza Plateau, might have been a factor as limiting as or even more limiting than delivering and lifting the stones.

Other ancient structures that required a long-term labor commitment included the Mesopotamian stepped temple towers (ziggurats) built after 2200 BCE, and stupas (or *dagobas*), monuments built to honor Buddha and often housing relics (Ranaweera 2004). Falkenstein (1939) calculated that the construction of the Anu ziggurat near Warqa in Iraq required at least 1,500 men working 10 hours a day for five years, adding up to embodied energy of nearly 1 TJ. And Leach (1959) estimated that Jetavanaramaya, the largest Anuradhapura stupa (122 m tall, built with about 93 million roughly laid baked bricks), needed about 600 laborers for100 days a year for 50 years, or just over 1 TJ of useful energy (see fig. 4.23).

Mesoamerican pyramids, especially those at Teotihuacan (built during the second century CE) and Cholula, are also quite imposing. Teotihuacan's flat-topped Pyramid of the Sun was the tallest, probably just over 70 m, including the temple (see fig. 4.23). Its construction was much easier than the building of the three stone structures at Giza. The pyramid's core is

Box 4.18 Energy cost of the Great Pyramid

The Great Pyramid's potential energy (required to lift the mass of 2.5 Mm^3 of stones) is about 2.5 TJ. Wier (1996) got that total right, but his assumption of 240 kJ/day of average useful work was too low. These are my conservative assumptions. To cut 2.5 Mm^3 of stone in 20 years (the length of Khufu's reign) would require 1,500 quarrymen working 300 days per year and producing 0.25 m^3 of stone per capita by using copper chisels and dolerite mallets. Even assuming that three times as many stonemasons were needed to square and dress the stones (although many interior blocks were only rough-hewn) and to move them to the construction site, the total labor force supplying the building material would be on the order of 5,000 men.

With net daily inputs of useful energy at 400 kJ/capita, lifting the stones would have required about 6.25 million workdays, and prorated over 20 years and 300 workdays per year it could have been accomplished by about 1,000 workers. If the same number were needed to emplace the stones in the rising structure, and even if that number were doubled, reflecting the additional labor needed as organizers and overseers and for transport, repair of the tools, delivery of food, cooking of meals, and washing of clothes, the grand total would still be fewer than 10,000 men. During the peak labor periods pyramid workers at the Giza site were investing collectively at least 4 GJ of useful mechanical energy every hour, that is, an overall power of 1.1 MW, and to maintain this effort they consumed every day an additional 20 GJ of food energy, the equivalent of nearly 1,500 t of wheat.

Wier (1996) calculated the maximum of 13,000 pyramid builders for the 20-year period. Hodges (1989) calculated that 125 teams could have jacked up all the stones into position during 17 years of work, and that the numbers would add up to only about 1,000 permanent workers for stone lifting; he also allowed three years for the dressing of casing stones in place, proceeding from the top. In contrast, Herodotus was told of 100,000 men working for three months a year for 20 years, while Mendelssohn (1974) estimated the total at 70,000 seasonal laborers and perhaps as many as 10,000 permanent masons. Both of these are indefensible exaggerations.

made up of earth, rubble, and adobe bricks, and only the exterior was faced with cut stone, which was anchored by projecting catches and plastered with lime mortar (Baldwin 1977). Still, its completion could have required the work of up to 10,000 laborers for more than 20 years.

In contrast to our conjectures about the construction of the largest pyramids, there is little mystery about the way such classical structures as the Parthenon or the Pantheon were built (Coulton 1977; Adam 1994; Marder and Jones 2015). The Pantheon's remarkable design is often cited as an ingenious use of concrete, but the often repeated claim that the Romans were the first builders to use this material is inaccurate. Concrete is a mixture of cement, aggregates (sand, pebbles), and water, and cement is produced by high-temperature processing of a carefully formulated and finely ground mixture of lime, clay, and metallic oxides in an inclined rotating kiln—and there was no cement in the Roman *opus caementicium* used to build the Pantheon or in any other building until the 1820s (box 4.19).

We know that massive architraves (such as those at the Parthenon, weighing almost 10 t) had to be lifted by a crane (and could be rolled to the site encased in circular frames), and very similar crane designs were used nearly two millennia later in building cathedrals, the most elaborate

Box 4.19 Rome's Pantheon

The Roman *opus caementicium* was a mixture of aggregates (sand, gravel, stones, often also broken bricks or tiles) and water, but its bonding agent was not cement (as it is in concrete) but lime mortar (Adam 1994). The mixture was prepared on a building site, and the unique combination of slaked lime and volcanic sand—excavated near Puteoli (modern-day Pozzuoli, just a few kilometers west of Mount Vesuvius) and known as *pulvere puteolano* (later as *pozzolana*)—made a sturdy material that could harden even under water. Although inferior in comparison with modern concrete, the pozzolanic aggregate and a high-quality lime produced material that was strong enough not only for massive and durable walls but also for large vaults and domes (Lancaster 2005).

The Roman use of *opus caementicium* reached its design apogee in the Pantheon, whose construction was completed in 126 CE during Hadrian's rule. The large dome, 43.3 m in diameter (the structure's interior could fit into a sphere of the same diameter), was never topped by any preindustrial builders, although Saint Peter's dome, designed by Michelangelo and completed in 1590, came close, at 41.75 m (Lucchini 1966; Marder and Jones 2015). Besides its obvious visual appeal, the dome's most remarkable property is its vertically decreasing specific mass: the five rows of square coffered ceiling not only diminish in size as they converge on the central oculus but are built of progressively thinner layers of masonry using lighter aggregates, from travertine at the bottom to pumice at the top (MacDonald 1976). The entire dome weighs about 4,500 t.

structures of the European Middle Ages. Their builders included many experienced craftsmen and required the use of many special tools (Wilson 1990; Erlande-Brandenburg 1994; Recht 2008; Scott 2011). Much of the labor was seasonal, but a typical need would be an equivalent of hundreds of full-time workers—lumbermen, quarrymen, wagon drivers, carpenters, stonemasons, glass workers—engaged for one to two decades. The total energy investment was thus two orders of magnitude smaller than in pyramid building, with peak labor flows only a few hundred kilowatts.

Although some cathedrals were completed quickly (Chartres took only 27 years, the original Notre-Dame de Paris took 37), construction was commonly interrupted by epidemics, labor disputes, regime changes, money shortages, and intra- and international conflicts. As a result, the building of a cathedral usually lasted several generations, and in some cases even centuries were needed for the completion: Prague's Saint Vitus cathedral, begun by Charles IV in 1344, was abandoned in the early fifteenth century, and the unfinished (and provisionally walled-off) structure was completed (with the erection of two Gothic spires) only in 1929 (Kuthan and Royt 2011).

Extensive waterworks, including dams, canals, and bridges, are well documented from Jerusalem, Mesopotamia, and Greece. But Roman achievements are certainly the best-known examples of bold engineering solutions to an urban water supply. Virtually every sizable Roman town had a wellplanned water supply. This accomplishment was surpassed only by industrializing Europe. Roman aqueducts were especially impressive (fig. 4.24). Pliny in his *Historia Naturalis* called them "the most remarkable achievement anywhere in the world."

Starting with the Aqua Appia in 312 BCE, the water supply system eventually comprised 11 lines, totaling almost 500 km (Ashby 1935; Hodge 2001). By the end of the first century CE the total daily water supply was just above 1 Mm³ (1 GL)/day, averaging more than 1,500 L/capita, while by the end of the twentieth century Rome (with a population of about 3.5 million) averaged (including all industrial use) about 500 L/capita (Bono and Boni 1996). Equally impressive was the scale of Rome's underground sewage canal system, with *cloaca maxima* arches about 5 m in diameter.

Throughout the Roman Empire, aqueducts consisted of a number of common structural elements (fig. 4.24). Starting from springs, lakes, or artificial impoundments, water channels had a rectangular cross section and were built of stone slabs or concrete lined with fine cement. Channels with the usual gradient of no less than 1:200 followed slopes in order to avoid tunneling whenever possible. Where an underground course was



Figure 4.24

Roman aqueducts carried water from rivers, springs, lakes, or reservoirs by combining at least two or three of the following structures (from the top): shallow rectangular channels running on a foundation, tunnels accessible by shafts, embankments pierced by arches, single- or double-tiered arched bridges, and inverted lead-pipe siphons to take water across deep valleys. Rome's aqueducts, supplying about 1 Mm³/ day of water, formed an impressive system built over a period of more than 500 years. Based on Ashby (1935) and Smith (1978). Aqueduct slope is exaggerated.

unavoidable, the channel could be accessed from above by shafts. Only in valleys too long to skirt or too deep for simple embankments did the Romans resort to bridges. No more than about 65 km of Rome's aqueducts were carried on (sometimes shared) arches. The Augustan bridges at Gard (more than 50 m high), Merida, and Taragona are the finest examples of this art. The cleaning and repair of channels, tunnels, and bridges, which were often threatened by erosion, was a continuous task.

If crossing a valley would have required a bridge taller than 50–60 m, Roman engineers opted for an inverted siphon. Its pipes connected a header tank on one side of the valley with a slightly lower-lying receiving tank on the opposite side (Hodge 1985; Schram 2014). Crossing the stream at the valley bottom still required building a bridge. The high energy cost of these structures primarily reflected the large amounts of lead needed for highpressure pipes—they could withstand up to 1.82 MPa (18 atmospheres) and the cost of transporting the metal over often considerable distances from its smelting centers. For example, the total amount of lead for nine siphons in the Lyon water supply was about 15,000 t.

Metallurgy

The beginnings of all old high cultures are marked by the use of color (nonferrous) metals. Besides copper, early metallurgists also recognized tin (which was combined with copper to make bronze), iron, lead, mercury, and the two precious elements, silver and gold. Mercury is a liquid at ambient temperatures, while gold's relative scarcity and softness precluded its use beyond the minting of coins and ornamental items. Although much more abundant, silver was also too rare for mass-produced items. The softness of lead and tin limited their unalloyed uses largely to pipes and food containers. Only copper and iron were relatively abundant and possessed, especially when alloyed, great tensile strength and hardness. The combination of their abundance and their properties made them the only two practical choices for the mass production of durable items. Copper and bronze dominated the first two millennia of recorded history, while iron and its alloys (an enormous variety of steels) are now dominant more than ever.

Charcoal fueled the smelting of both nonferrous and iron ores, as well as the subsequent refining and finishing of crude metals and metallic objects. Hard human labor did all ore mining and crushing, tree cutting and charcoal making, furnace building and charging, casting, refining, and repeated forging. In many societies, ranging from sub-Saharan Africa to Japan, metallurgy remained solely manual until the introduction of modern industrial methods. In Europe and later in North America, animals and above all water power took over such repetitive, exhausting tasks as ore crushing, water pumping from mines, and metal forging. The availability of wood, and later also the accessibility and reliability of water power resources needed to energize larger bellows and hammers, were thus the key determinants of metallurgical progress.

Nonferrous Metals

Copper tools and weapons bridged the stone and the iron eras of human evolution. The first copper uses, datable to the sixth millennium BCE, did not involve any smelting. Pieces of naturally pure metal were merely shaped by simple tools or worked by annealing, alternating heating and hammering (Craddock 1995). The earliest evidence of exploiting native metal (in the form of beads of malachite and copper in southeastern Turkey) goes as far back as 7250 BCE (Scott 2002). Smelting and casting of the metal became common after the middle of the fourth millennium BCE in a number of regions with rich and relatively accessible oxide and carbonate ores (Forbes 1972). Numerous copper objects—rings, chisels, axes, knives, and spears were left behind by the early Mesopotamian societies (before 4000 BCE), predynastic Egypt (before 3200 BCE), the Mohenjodaro culture in the Indus valley (2500 BCE), and the ancient Chinese (after 1500 BCE).

The copper-mining centers of antiquity included most notably Egypt's Sinai peninsula, North Africa, Cyprus, today's Syria, Iran, and Afghanistan, the Caucasus region, and Central Asia. Italy, Portugal, and Spain later became production regions. Because of the metal's relatively high melting point (1083°C), the production of pure copper was fairly energy-intensive. Ore reduction was done with wood or charcoal, first just in clay-lined pits and later in simple, low shaft clay furnaces with a natural draft. The first clear evidence of bellows use comes from Egypt of the sixteenth century BCE, but their use is almost certainly older than that. Impure metal was refined by heating in small crucibles, after which it was cast into stone, clay, or sand molds. Castings were fashioned into utilitarian or ornamental products by hammering, grinding, piercing, and polishing.

Much higher technical skills were necessary for producing the metal from abundant sulfide ores (Forbes 1972). They had to be first crushed and roasted in heaps or furnaces to remove sulfur and other impurities (antimony, arsenic, iron, lead, tin, and zinc), which would change the metal's properties. For millennia, the crushing of ores was done by hand hammering, a practice common in Asia and Africa until the twentieth century. In Europe, waterwheels and horses harnessed to whims gradually took over this work. The roasting of crushed ores needed relatively little fuel. The smelting of roasted ores in shaft furnaces was followed by smelting of the coarse metal (only 65–75% of copper) and its resmelting to produce nearly pure (95–97%) blister copper. This product could be further refined by oxidation, slagging, and volatilization. The sequence added up to high fuel requirements.

Calculating the annual and cumulative fuel demand of ancient smelting operations is an inherently uncertain exercise, strongly influenced by the estimates of total slag mass and by assumptions about the length of the extraction and the energy intensity of smelting. All these uncertainties are perfectly illustrated by the ancient world's largest smelting concentration, Rio Tinto, in southwestern Spain, less than 100 km west of Seville (box 4.20). In any case, the extent of Roman smelting operations remained unsurpassed for another 1,500 years. Summaries of the late medieval metallurgical expertise (Agricola 1912 [1556]; Biringuccio 1959 [1540]) describe copper smelting in ways that hardly differ from the Rio Tinto practices.

Box 4.20

Fuelwood needs for Roman copper and silver smelting at Rio Tinto

The first mapping of Rio Tinto's enormous slag heaps resulted in estimates of 15.3 Mt of slag from lead and silver mining and 1 Mt of slag from copper mining; these estimates led Salkield (1970) to conclude that the Romans had to cut down 600,000 mature trees a year to fuel the smelting, an impossible total for southern Spain. New mapping (based on extensive drilling) ended with about 6 Mt of slag, and although copper was the main product during the Roman era, there was an extensive pre-Roman smelting of silver (Rothenberg and Palomero 1986). With a 1:1 slag:charcoal ratio and a 5:1 wood:charcoal ratio, the production of 6 Mt of slag would have needed 30 Mt of wood, or 75,000 t/ year during 400 years of large-scale operations.

Supplying this fuel by cutting down natural forest (storing no more than 100 t/ha) would have required clearing annually about 750 ha of forest, the equivalent of a circle with a radius of about 1.5 km: that would have been a major but manageable undertaking, and one resulting in extensive deforestation. Similarly, centuries of copper smelting on Cyprus (starting around 2600 BCE) left behind more than 4 Mt of slag. Clearly, ancient smelting was a major cause of deforestation in the Mediterranean region, as well as in Transcaucasia and Afghanistan, and local wood shortages eventually limited the extent of smelting.

From the very beginning of copper smelting some of the metal was incorporated into bronze, the first practical alloy, chosen by Christian Thomsen for his now classical division of human evolution into Stone, Bronze, and Iron Ages (Thomsen 1836). This is a highly generalized division. Some societies, most notably Egypt before 2000 BCE, went through a pure copper era, while others, above all in sub-Saharan Africa, moved directly from the Stone Age to the Iron Age. The first bronzes came out of the inadvertent smelting of copper ores containing tin. Later they were produced by cosmelting of the two ores, and only after 1500 BCE were they made by smelting two metals together. With its low melting point of a mere 231.97°C, tin was produced with relatively little charcoal from its crushed oxide ores. The total energy cost of bronze was thus lower than that of pure copper, but it was an alloy with superior properties.

As the shares of tin varied anywhere between 5% and 30% (and, consequently, the melting points ranged between 750°C and 900°C), it is impossible to speak of a typical bronze. An alloy preferred for casting guns, composed of 90% copper and 10% tin, had both the tensile strength and hardness about 2.7 times higher than the best cold-drawn copper (Oberg et al. 2012; box 4.21). The availability of bronze thus brought the first good metallic axes, chisels, knives, and bearings, as well as the first reliable swords, of both cutting and thrusting type. Bronze bells usually were 25% tin.

Brass has been the other historically important copper alloy combining the element (<50% up to about 85% of the total) with zinc. As with bronze,

Metal or alloy	Tensile strength (MPa)	Hardness (Brinell scale)
Annealed	220	40
Cold drawn	300	90
Bronze (90% Cu, 10% Sn)	840	240
Brass (70% Cu, 30% Zn)	520	150
Cast iron	130-310	190–270
Steel	650->2,000	280->500

its production needs less energy than the smelting of pure copper (zinc's melting point is only 419°C). A higher zinc content improves the alloy's tensile strength and hardness. For a typical brass they are about 1.7 times higher than for cold-drawn copper, but there is no reduction of the alloy's malleability and corrosion resistance. The first uses of brass date to the first century BCE. The alloy became widely used in Europe only during the eleventh century, and became common only after 1500.

Iron and Steel

The replacement of copper and bronze by iron proceeded slowly. Small iron objects were produced in Mesopotamia during the first half of the third millennium BCE, but ornaments and ceremonial weapons became more common only after 1900 BCE. The extensive use of iron dates only to after 1400 BCE, and the metal became truly abundant after 1000 BCE. Egypt's iron era dates from the seventh century BCE, China's from the sixth. African iron making is also ancient, but the metal was never smelted by any New World society. Iron smelting was necessarily bound up with the large-scale production of charcoal. Iron melts at 1535°C; an unaided charcoal fire can reach 900°C, but a forced air supply can raise its temperature close to 2000°C. Charcoal thus fueled all iron ore smelting in every traditional society except China (where coal was also used since the Han dynasty), but the efficiency of its production and of its metallurgical use had gradually improved.

The development of iron making began with fires enclosed in shallow, and often clay- or stone-lined, pits where crushed iron ore was smelted with charcoal. These primitive hearths were commonly located on hilltops to maximize the natural draft. Later a few narrow clay tubes (tuyères) were used to deliver a blast into the hearth, first from small hand-operated leather bellows, then from larger bellows driven by a treadle or a rocking bar, and throughout Europe eventually powered by waterwheels. Simple clay walls were erected to contain the smelting: they were just a few decimeters to more than a meter tall, but in some parts of the Old World (including Central Africa) they eventually reached more than 2 m (van Noten and Raymaekers 1988).

Archaeologists have unearthed thousands of these temporary structures throughout the Old World, from the Iberian peninsula to Korea and from northern Europe to Central Africa (Haaland and Shinnie 1985; Olsson 2007; Juleff 2009; Park and Rehren 2011; Sasada and Chunag 2014). The temperature inside these small charcoal-fueled furnaces reached no more than 1100–1200°C, high enough to reduce iron oxide but far below iron's

melting point (pure Fe liquefies at 1535°C): their final product was a bloom (whose typical medieval mass was just 5–15 kg, later 30–50 kg or even more than 100 kg), a spongy mass of iron, and an iron-rich slag full of nonmetal-lic impurities (Bayley, Dungworth, and Paynter 2001).

This bloomery iron contained 0.3–0.6% carbon and had to be repeatedly reheated and hammered to produce a lump of tough and malleable wrought iron containing less than 0.1% carbon. Wrought iron was used in making objects and tools ranging from nails to axes. The European demand for bloomery iron began to rise in the eleventh century thanks to the adoption of iron mail and the increased production of hand weapons and helmets, as well as of common tools and implements ranging from sickles and hoes to hoops and horseshoes. Metal bands were also used in the building of cathedrals, and the new papal palace, the Palais des Papes, in Avignon, whose construction began in 1252, required 12 t of the construction metal (Caron 2013).

Han dynasty (207 BCE–220 CE) Chinese were the first craftsmen to produce liquid iron. Their furnaces, built with refractory clays and often strengthened by vine cables or heavy timbers, eventually reached just over 5 m. They could take a charge of nearly 1 t of iron ore, and produced cast iron in two tappings a day. The high phosphorus content, which lowered the iron's melting point, and the invention of double-acting bellows, which delivered a strong air blast, were critical ingredients of this early success (Needham 1964). Later came the use of coal packed around the batteries of tubelike crucibles containing the ore and the powering of larger bellows by waterwheels. Casting into interchangeable molds was used commonly to mass produce iron tools, thin-walled cooking pots and pans, and statues before the end of the Han dynasty (Hua 1983). There were few subsequent substantial improvements, and China's small blast furnaces did not start the lineage of today's huge structures.

These originated in the slow evolution of European shaft furnaces, from the simple Catalan forge to the rock-lined osmund furnaces of Scandinavia to the *Stuckofen* of Styria. Higher stacks and better shapes lowered fuel consumption. Higher temperatures and longer contact between the ore and the fuel produced liquid iron. European blast furnaces originated most likely in the lower Rhine valley region just before 1400. Blast furnaces produce cast, or pig, iron, an alloy with 1.5–5% of carbon that cannot be directly forged or rolled. Its tensile strength is no higher than copper's (and it can be up to 55% weaker) but it is two to three times harder (Oberg et al. 2012; box 4.21). The number of blast furnaces grew steadily during the sixteenth and seventeenth centuries. Perhaps the most notable improvement of that time was the introduction of larger leather bellows. Their tops and bottoms were made of wood, their sides of bull hides. After 1620 came double bellows operated alternatively by the cams on the waterwheel axle, as well as a gradual elongation of the stack. Both these trends soon ran into limits imposed by the maximum power of waterwheels and by charcoal's physical properties. By 1750 the largest waterwheels were delivering up to 7 kW of useful power. But during the summer smelting campaigns there often was not enough water to generate the maximum output. Charcoal's main disadvantage is its high friability: it crushes under heavier loads, and its use limited the mass of charged ore and limestone and hence the height of blast-furnace stacks to less than 8 m (Smil 2016; fig. 4.25). Before 1800 both of these limits were removed, the first one by Watt's steam engine, the other one by the use of coke.

Medieval bloomery hearths needed 3.6–8.8 times more fuel than the mass of the charged ore (Johannsen 1953). Even with ores containing about 60% Fe, bloomeries would have needed at least 8 and as much as 20 kg of charcoal per kilogram of hot metal. By the end of the eighteenth century typical charcoal/metal ratios were around 8:1; they fell to just around



Figure 4.25

Charcoal-fueled blast furnace of the mid-eighteenth century, with bellows powered by an overshot waterwheel. Reproduced from the *Encyclopédie* (Diderot and d'Alembert 1769–1772).

1.2 by 1900, and to 0.77 in Swedish charcoal furnaces (Campbell 1907; Greenwood 1907). A good late nineteenth-century charcoal-fueled furnace thus needed only about one-tenth the energy of its medieval counterpart. The high energy requirements of pre-1800 charcoal-fueled smelting inevitably caused extensive deforestation around furnace sites. A typical early eighteenth-century English furnace needed about 1,600 ha of trees for a sustainable supply (box 4.22).

The total national wood requirements of charcoal-based iron making can be fairly well estimated for England of the early 1700s, before the industry began to adopt coke-based smelting: a sustainable supply would have required harvesting coppiced or natural wood growth from about 1,100 km² of wood groves or forests (box 4.22). A century later the United States had no problems energizing its iron ore smelting with charcoal made from wood from its rich natural forests, but by the beginning of the twentieth century it would have been impossible, and only the use of coke allowed the country to become the world's larger producer of pig iron (box 4.23).

Not surprisingly, during the wooden era communities surrounded by traditional iron mills and forges found themselves in a desperate situation. Already in 1548 anguished inhabitants of Sussex wondered how many towns were likely to decay if furnaces continued working: they would have no wood to build houses, water mills, wheels, barrels, piers, and hundreds

Box 4.22

Fuel needs of an eighteenth-century English blast furnace

Early eighteenth-century English blast furnaces worked only from October to May, and during that time their average output was just 300 t of pig iron (Hyde 1977). Assumptions of as little as 8 kg of charcoal per kilogram of iron and 5 kg of wood per kilogram of charcoal translate into annual requirements of some 12,000 t of wood for a single furnace. After 1700, nearly all accessible natural forest growth was gone, and the wood was cut in 10- to 20-year rotations from coppicing hardwoods, whose annual harvestable increment would be between 5 and 10 t/ha. A medium productivity of 7.5 t/ha would have required about 1,600 ha of coppicing hardwoods for perpetual operation. For comparison, a much less efficient, large seventeenth-century English furnace in the Forest of Dean needed about 5,300 ha of coppice growth, while the smaller Wealden ironworks needed around 2,000 ha for each furnace-forge combination (Crossley 1990).

Box 4.23

Energy needs in British and American iron production

In 1720, 60 British furnaces produced about 17,000 t of pig iron, requiring, with 40 kg of wood per kilogram of metal, about 680,000 t of wood. Forging the metal to produce 12,000 t of bars added, with 2.5 kg of charcoal per kilogram of bars, another 150,000 t, for a total annual consumption of some 830,000 t of charcoaling wood. With an average productivity of 7.5 t/ha, this would have required about 1,100 km² of forests and coppiced growth for sustainable harvests.

For the United States, the earliest available pig iron total is for the year 1810, when about 49,000 t of the metal needed (assuming 5 kg of charcoal, or at least 20 kg of wood per kilogram of hot metal) about 1 Mt of wood. At that time, all that wood could come from clear-cutting natural old-growth hardwood forests, rich ecosystems that stored around 250 t/ha (Brown, Schroeder, and Birdsey 1997), and if all aboveground phytomass were used in charcoaling, an area of about 4,000 ha (a square with a side of 6.3 km) would have to be cleared every year to sustain that level of production. The rich U.S. forests could support an even higher rate, and by 1840 all U.S. iron was still smelted with charcoal, but after a subsequent rapid switch to coke energized nearly 90% of iron production by 1880 and future increases in iron production could not be based on charcoal: in 1910—with an iron output at 25 Mt, and even with much reduced charges of 1.2 kg of charcoal and 5 kg of wood per kilogram of hot metal—the country would have required 125 Mt of wood a year.

Even when assuming a high average increment of 7 t/ha in secondarygrowth forests, a sustainable supply of that wood would have required annual harvests from nearly 180,000 km² of forest, an area equal to Missouri (or a third of France), represented by a square whose side would reach from Philadelphia to Boston or from Paris to Frankfurt. Obviously, even a forest-rich America could not afford to energize its iron ore smelting with charcoal.

of other necessities—and they asked the king to close down many of the mills (Straker 1969; see also Smil 2016). The limiting role of energy in traditional iron smelting was thus unmistakable. When a single furnace could strip each year a circle of forest with a radius of about 4 km, it is easy to appreciate the cumulative impact of scores of furnaces over a period of many decades.

This effect was necessarily concentrated in wooded mountainous regions. There the radius of animal-drawn charcoal transport could be kept to a minimum (a restriction further aggravated by the fuel's fragility), and

the need to power furnace and forge bellows was readily satisfied by installing waterwheels. Proximity to the ore was also important, but because the ore charge was only a fraction of charcoal's weight, it was easier to transport. Deforestation was the inevitable environmental price paid for making nails, axes, and horseshoes, as well as mail shirts, lances, guns, and cannonballs. The early expansion of iron making and the limited supply of domestic wood led to a clear energy crisis in Britain during the seventeenth century. That situation was further aggravated by the high timber demand in the country's burgeoning shipbuilding industry.

While iron was relatively abundant in many preindustrial societies, steel was available only for special uses. Like cast iron, steel is also an alloy, but one containing only between 0.15% and 1.5% of carbon and often also small amount of other metals (mainly nickel, manganese and chromium). The metal is superior to cast iron or to any copper alloys: the best tool steels have a tensile strength an order of magnitude higher than either copper or iron (Oberg et al. 2012; box 4.21). Some simple ancient smelting techniques could produce directly relatively high-quality steel, but only in small amounts. Traditional East African steelmakers used low (< 2 m), circular, cone-shaped charcoal-fueled slag and mud furnaces built over a pit of charred grass. Eight men operating goatskin bellows connected to ceramic tuyères were able to achieve temperatures above 1800°C (Schmidt and Avery 1978). This method, apparently known since the early centuries of the Common Era, made it possible to produce directly small amounts of good-quality medium carbon steel.

But preindustrial societies usually followed one of the two effective ancient routes toward steel: either by carburizing wrought iron or by decarburizing cast iron. The first, older technique entailed prolonged heating of the metal in charcoal, resulting in gradual inward diffusion of carbon. Without further forging this method produced a hard steel layer over a core of softer iron. This was a perfect material for plowshares—or for body armor. Repeated forging distributed the absorbed carbon fairly evenly and produced excellent sword blades. Decarburization, the removal of carbon from cast iron by oxygenation, was done in China already during the Han dynasty and produced the metal for such exacting applications as chains for suspension bridges.

The spreading availability of iron and steel gradually led to a number of profound social changes. Iron saws, axes, hammers, and nails sped up house construction and improved its quality. Iron kitchenware and a variety of other utensils and objects, ranging from rings to rakes, from grates to graters, made it easier to cook and run a household. Iron horseshoes and plowshares were instrumental in advancing the intensification of cropping. On the destructive side, warfare was revolutionized first by flexible chain-mail suits, helmets, and heavy swords, later by guns, iron cannonballs, and more reliable firearms. These trends were greatly accelerated with the introduction of coke-based iron smelting and the emergence of the steam engine.

Warfare

Armed conflicts have always had a formative role in history: they require the mobilization of energy resources (often on an extraordinary scale, be it by marshalling masses of foot soldiers equipped with simple weapons or by producing highly destructive explosives and machines and laying down supplies for prolonged wars), and they have repeatedly resulted in the most concentrated and the most devastating releases of destructive power. Moreover, the basic energy supplies, whether of food or fuel, of populations exposed to armed conflicts are affected not only during the conflict's duration (through the acquisition of food for roaming armies, the destruction of crops, or the interruption of normal economic activities with the mobilization of young males and the damage inflicted on settlements and infrastructures) but often for years after its end.

All historical conflicts have been fought with weapons, but weapons are not the prime movers of war: two exceptions aside, until the invention of gunpowder the only prime movers of wars were human and animal muscles. The first exception was the use of incendiary materials; the second, of course, was the use of wind-powered sails to speed up and facilitate naval maneuvers. Traditional mechanical weapons—handheld (daggers, swords, lances) and projectile (spears, arrows, heavy weights discharged by catapults and trebuchets)—were designed to maximize physical damage through the sudden release of kinetic energy. Only the invention of gunpowder introduced a new, and much more powerful, prime mover. The explosive reaction of chemicals could propel projectiles faster and farther and increase their destructive impact. For centuries this impact was limited by the clumsy designs of personal weapons (front- and breach-loading rifles), but gunpowder gained ever greater importance as the propellant of cannonballs.

Animate Energies

All prehistoric land warfare and all conflicts of ancient and early medieval eras were powered solely by human and animal muscles. Warriors wielded

daggers, axes, and swords in close combat, on foot or on horseback. They used spears and lances, and they drew bows and much more powerful crossbows (both the Chinese and the Greeks used them since the fourth century BCE) to shoot arrows whose impact would injure and kill unprotected enemies as far as 100–200 m away. The antiquity of archery warfare is attested by the fact that the Egyptian hieroglyph for soldier is a man kneeling on his left knee, bow in his outstretched right arm and a quiver on his left shoulder (Budge 1920). Animate energies also wound winches of massive catapults and took advantage of leveraged gravity to hurl massive weights by trebuchets in order to breach city walls and destroy castle fortifications.

Handheld weapons could cause grievous injuries, and well-aimed cuts or thrusts could kill instantly, but they required a commingling of fighting forces, and their power was obviously limited by the capabilities of a warrior's muscles. Bows and arrows allowed the separation of fighting forces, and master archers achieved admirable accuracy over relatively long distances, but archery battles wasted too many arrows through inaccurate targeting and the relatively low kinetic energy of light arrows (box 4.24), and the time needed to reset the arrows between successive discharges limited the magnitude and frequency of injuries that could be inflicted by these weapons. The limits of human performance also determined the daily range of advancing armies, and even if well-rested and well-fed men were able to

Box 4.24

Kinetic energy of swords and arrows

Even heavy medieval swords weighed no more than 2 kg, usually less than 1.5 kg. Kinetic energy increases with the square value of speed: it is only 9 J for a 2 kg sword clumsily wielded at just 3 m/s, 75 J for a 1.5 kg Japanese katana the (traditional Japanese curved, slender, 60–70 cm long single-edged sword) swung by an expert swordsman at 10 m/s. This appears to be rather low, but the impact of a slashing cut was highly concentrated, aimed at a narrow part of a body (neck, shoulder, arm), while the piercing thrust penetrated deeply into soft body tissues. A typical lightweight arrow weighing just 20 g and launched by a good archer from a compound bow would fly at up to 40 m/s (Pope 1923) and its kinetic energy would be 16 J. Again, this may seem low, but the projectile's impact is basically punctiform and hence deeply penetrating: flint- or metal-tipped arrows could easily penetrate a coat of mail when shot from distances of up to 40–50 m and, when well aimed, could kill unprotected men from more than 200 m away.

move swiftly, the army's progress was often limited by the speed of its supply train, made up of slow-moving animals.

The two most powerful military machines of antiquity and the early Middle Ages relied on the mechanical advantage of levers. Catapults were large-scale mechanized bows powered by a sudden release of the elastic deformation of twisted ropes or sinews (fig. 4.26). They were in use from the fourth century BCE (Soedel and Foley 1979; Cuomo 2004). They could shoot arrows or throw objects; mangonel catapults, used in city sieges, were third-class levers: their base was a fulcrum, force was provided by tension bands, and the load was thrown with a speed unattainable by the direct deployment of human muscles. Typical medieval catapults throwing stones of 15–30 kg could do only limited damage to city walls, however.

In contrast, trebuchets, invented in China before the third century BCE, were first-class levers with beams that pivoted around an axle and a projectile loaded at the end of the throw arm that was four to six times the length of the short arm (Hansen 1992; Chevedden et al. 1995). The earliest, smaller trebuchets were operated by men pulling ropes attached to the short arm; later large machines had massive counterweights and were able to throw objects weighing hundreds of kilograms (with record weights around or even surpassing 1 t) farther than the range of early medieval artillery. They were also used in defense against sieges, with trebuchets positioned on the high ramparts of castles or city walls, ready to hurl massive stones at any siege construction within their reach.

Animals in preindustrial warfare had two distinct roles: as the enablers of rapid and long-distance thrusts and as an indispensable means of transportation, making it possible to field larger armies whose supplies were carried by pack or draft beasts. In the earliest recorded depictions horses were harnessed to light chariots with spoked wheels (first used around 2000 BCE). No other traditional military innovation preceding the use of gunpowder was as consequential, owing to the combination of speed and the possibility of rapid tactical adjustments, as archers on horseback. Riding small horses and shooting arrows with powerful compound bows, mounted archers (first Assyrians and Parthians, later Macedonians and Greeks) were a formidable and highly mobile fighting force centuries before the introduction of stirrups (Drews 2004).

These simple pieces of metal providing footholds for a rider were first used in China in the early third century CE and then diffused westward; they gave riders unprecedented support and stability in the saddle (Dien 2000). Without them a fighter clad in armor could not even mount a larger (and sometimes also partially armored) horse, and would have been unable to fight effectively with a lance or a heavy sword while on its back. This



Figure 4.26 Roman catapults (Corbis).

does not mean that riders equipped with stirrups enjoyed easy supremacy in battle. Asian riders, unarmored and with small but extraordinarily hardy horses, created especially effective fighting units: they could move with high speed and enjoyed superior maneuverability.

This combination brought the Mongolian horsemen from eastern Asia to the center of Europe between 1223 and 1241 (Sinor 1999; Atwood 2004; May 2013) and enabled several empires of the steppes to survive in Central Asia until the early modern era (Grousset 1938; Hildinger 1997; Amitai and Biran 2005; Perdue 2005). The most spectacular series of long-distance forays by armored riders brought the Crusaders from many European countries to the eastern Mediterranean, where they established (between 1096 and 1291) temporary rule over fluctuating coastal and interior areas of what is now Israel and parts of Jordan, Syria, and Turkey (Grousset 1970; Holt 2014).

The importance of horses, both in cavalry units and harnessed to heavy wagons and field artillery, persisted in all major Western conflicts of the early modern era (1500–1800), as well in the epoch-defining Napoleonic Wars. Large armies projected far from their home base had to rely on animals to move their supplies: pack animals (donkeys, mules, horses, camels, llamas) were used in difficult terrain; draft animals (mostly oxen, in Asia also elephants) pulled heavy supply wagons and increasingly heavier field guns. The mass requirements of large military campaigns relying on draft power are well illustrated by the list of provisions and animals that occupied Prussia agreed to supply to Napoleon's armies for their invasion of Russia in 1812 (box 4.25). Without oxen—44,000 of them—pulling the supply wagons, the army could not have advanced.

Western armed conflicts fought after 1840 would use the first modern inanimate prime mover, the steam engine, to mobilize troops and animals and move them to the front lines by trains (or, in the case of troops sent to colonial wars on other continents, to embarkation ports to be loaded on steamships), but movement on the battlefield was still solely powered by human and animal muscles. And although World War I saw the first deployment of new inanimate mechanical prime movers (internal combustion engines powering trucks, tanks, ambulances and airplanes) in or near combat zones, horses remained indispensable.

By late 1917 the British armies on the Western front relied on 368,000 horses (with two-thirds of them engaged in transporting supplies, the rest in cavalry units), and although the Wehrmacht's advances in France (in spring 1940) and Russia (in summer 1941) are often cited as textbook examples of rapid mechanized tank-led warfare, Germany mobilized 625,000

Box 4.25

Prussian supplies and animals for the Russian invasion

Opening the road to Russia to Napoleon: that is how Philip Paul, comte de Ségur (1780–1873), one of Napoleon's young generals and perhaps the most famous chronicler of the disastrous Russian invasion, described the Prussian contribution:

By this treaty, Prussia agreed to furnish two hundred thousand quintals of rye, twenty-four thousand of rice, two million bottles of beer, four hundred thousand quintals of wheat, six hundred and fifty thousand of straw, three hundred and fifty thousand of hay, six million bushels of oats, forty-four thousand oxen, fifteen thousand horses, three thousand six hundred waggons, with harness and drivers, each carrying a load of fifteen hundred weight; and finally, hospitals provided with everything necessary for twenty thousand sick. (Ségur 1825, 17)

horses for its invasion of Russia, and by the war's end the Wehrmacht had about 1.25 million animals (Edgerton 2007). Similarly, the Soviet armies deployed hundreds of thousands of horses in their advance from Moscow and Stalingrad to Berlin (fig. 4.27). Hay and oats thus remained in the category of strategic matériel until the end of World War II.

Explosives and Guns

The only inanimate energies used in the pregunpowder warfare were incendiary materials prepared by combining sulfur, asphalt, petroleum, and quicklime and either fastened to arrowheads or hurled at targets across moats and walls from catapults and trebuchets. Gunpowder's origins stem undoubtedly from the long experience of Chinese alchemists and metallurgists (Needham et al. 1986; Buchanan 2006). They worked with the three ingredients—potassium nitrate (KNO₃, saltpeter), sulfur, and charcoal—long before they started to combine them. The first incipient gunpowder formula comes from the mid-ninth century; clear directions for preparing gunpowders were published in 1040. The early mixtures consisted of only about 50% saltpeter and were not truly explosive. Eventually the mixtures capable of detonation settled at 75% saltpeter, 15% charcoal, and 10% sulfur.

Unlike in ordinary combustion, where oxygen must be drawn from the surrounding air, ignited KNO₃ readily provides its own oxygen, and the gunpowder rapidly produces a roughly 3,000-fold expansion of its volume in gas. When appropriately confined and directed in rifled gun barrels, a small amount of gunpowder can impart to bullets kinetic energy an order



Figure 4.27

Soviet cavalry in Red Square, Moscow, on November 7, 1941, a week before the start of the German offensive to reach Moscow (Corbis).

of magnitude greater than that of a heavy crossbow arrow used to propel heavy projectiles, and larger charges can propel heavy projectiles from field artillery. Not surprisingly, the diffusion and perfection of firearms and cannons followed rather rapidly after their initial introduction.

Artillery developments started with Chinese fire-lances of the tenth century. These bamboo, and later metal, tubes ejecting bits of materials evolved first into simple bronze cannons inaccurately hurling loosely fitting stones. The first true guns were cast in China before the end of the thirteenth century, with Europe only a few decades behind (Wang 1991; Norris 2003). The pressures of frequent armed conflicts led to rapid rates of innovation, resulting in more powerful and more accurate guns. Already by 1400 the longest guns measured 3.6 m with a 35 cm caliber; the Mons Meg cannon, built in France in 1499 and donated to Scotland, was nearly 4.06 m long, could fire a 175 kg shot, and weighed 6.6 t (Gaier 1967). The destructive power increased with the general replacement of stone balls by iron projectiles.

The strategic implications of gunpowder-powered warfare were immense, both on the land and on the seas. There was no need to mount prolonged and often desperate sieges of seemingly impregnable castles. The combination of accurate artillery and iron cannonballs, whose higher density made them much more destructive than their stone predecessors, made them indefensible. Attackers able to destroy sturdy stone structures from far beyond the range of archers put an end to the defensive value of traditionally built castles and walled cities, and the medieval practice of building relatively compact fortresses with thick stone walls was superseded by new designs of low spreading star-shaped polygons with massive earthen embankments and huge water ditches.

These projects consumed enormous amounts of materials and energy. The fortifications of Longwy in northeastern France, the largest project of the famous French military engineer Sebastien Vauban (1633–1707), required moving 640,000 m³ of rock and earth (a volume equal to about a quarter of Khufu's pyramid) and emplacement of 120,000 m³ of masonry (M. S. Anderson 1988). But they, too, went out of fashion with the more mobile warfare of the eighteenth century when sieges became much less common. During the Napoleonic Wars light Gribeauval guns (including a 12-pounder model firing 5.4 kg projectiles, and weighing, including carriage, just below 2 t, compared to nearly 3 t for British guns) made faster maneuvers easier (Chartrand 2003).

On the seas, gunned ships (once equipped with two other Chinese innovations, compasses and good rudders) became the principal carriers of European technical supremacy, the tools of aggressive expansion to distant locations during all but the closing decades of the expansive colonial era: their dominance ended only with the introduction of naval steam engines, a process that began only in the 1820s. In the continent's waters, long-range guns gave the English captains a decisive advantage over the Spanish Armada in 1588 (Fernández-Armesto 1988; Hanson 2011). A century later large men-of-war were fitted with up to 100 guns, and the British and Dutch ships engaged during the battle of La Hogue in 1692 carried a total of 6,756 guns (M. S. Anderson 1988). The concentrated discharges of destructive energy reached levels that were not surpassed until the middle of the nineteenth century with the introduction of nitrocellulose-based powders (during the 1860s) and dynamite (patented by Alfred Nobel in 1867).