MULTIPURPOSE ORE MILL powered by a single water wheel at the upper left was illustrated in Georgius Agricola's *De re metallica*, published in 1556. Gold ore was processed in the following steps. First the ore was crushed by a cam-lifted stamp (*c*), just visible to the left of the water wheel. Next the crushed ore was ground to a powder in a pair of millstones to the right of the wheel. Two spare dome-shaped upper millstones (*d, e*) are on the ground on each side of a spare lower millstone; one of the upper millstones is turned upside down to show the hole that admitted the crushed ore. The outlet for the powdered ore (*h*) in the lower millstone deposited the powder into the first of three settling tubs (*o*). The slurry of powdered ore in the tubs was agitated by paddles driven by cogs (*x*) attached to the axle of the wheel. The agitation separated the heavier gold from the lighter dross, which eventually spilled from the last of the settling tubs.

Medieval Roots of the Industrial Revolution

The revolution is generally dated to the arrival of steam power in the 18th and 19th centuries. It is now clear that long before then a significant role was played by water-powered machines

by Terry S. Reynolds

The origins of modern industry are often dated only to the late 18th and early 19th centuries, when manual labor was displaced by steam-powered machines, first in the cotton-textile industry and later in other industries. This period is commonly called the Industrial Revolution, a term strongly suggesting that there had been a sharp break from developments in the preceding centuries.

The history of water power in medieval and early modern Europe presents a different picture. Powered machinery had begun to displace manual labor long before the 18th century, and in some areas of Europe it had done so on a substantial scale and in many industries. In other words, the rise of European industry should more properly be regarded as an evolutionary process going back at least to the eighth or ninth century, when European engineers began to aggressively apply water power to industrial processes.

Although water power can be harnessed by a variety of devices, the commonest device is of course a wheel fitted with blades or buckets. Such a wheel can be mounted either horizontally or vertically. Until the introduction of the water turbine in the 1830's horizontally mounted water wheels were the simpler of the two types. In the early horizontal water mill the lower end of a vertical shaft carried a small horizontal wheel consisting only of blades. The upper end of the axle was linked directly, without gearing, to a rotating millstone. This kind of mill was cheap to build but usually delivered no more power than a donkey or a horse (less than one horsepower). Even that power it generated wastefully, operating at an efficiency of only 5 to 15 percent. The horizontal mill was also not as easily adapted as the vertical one to tasks other than milling grain. Hence it did not play an important role in the early evolution of water-powered industry in Europe.

Vertical water wheels, on the other hand, did. There were two main subtypes of vertical wheel: undershot and overshot. The undershot was the simpler. It had flat radial blades attached to its circumference, and it was energized by the impact of water flowing under the wheel and pushing against the blades. The undershot wheel could work in almost any stream as long as there was enough water flowing at a modest speed, but it worked most effectively in a confined channel. Its typical output was three to five times as great as that of a horizontal wheel (namely about two to three horsepower) and its efficiency was 20 to 30 percent.

With the overshot wheel water was fed over the wheel into "buckets" built into the wheel's circumference. There the weight of the water, rather than its impact, turned the wheel, with each bucket discharging its water at the bottom of the wheel and returning empty to the top to begin the cycle anew. Overshot wheels were usually more expensive to build than undershot or horizontal wheels, since they called for a dam and an elevated water channel, and they could not handle large volumes of water. With a small volume and a head of water ranging from three to 12 meters, however, they were capable of operating at an efficiency of from 50 to 70 percent and delivering anywhere from two to 40 horsepower. (The average was from five to seven horsepower.)

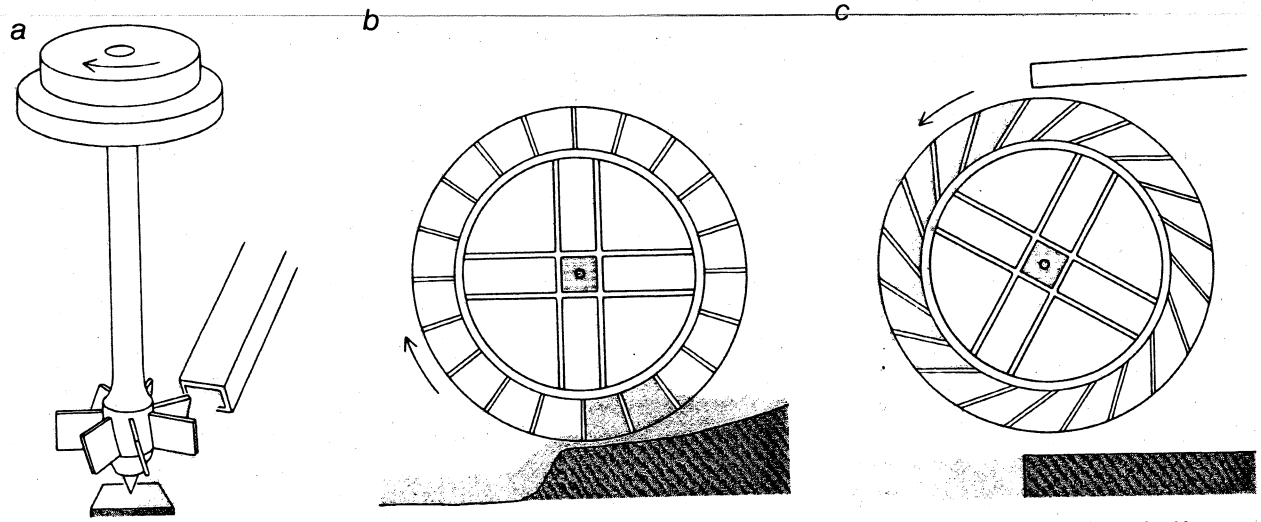
Although ancient engineers devised both undershot and overshot wheels, neither were widely built. For example, in the first century B.C. the Roman engineer Vitruvius described the undershot wheel in a section of his *De architectura* dealing with machines rarely employed. Indeed, there are fewer than a dozen known literary references to the use of water power in all antiquity.

In medieval Europe social and economic conditions increased the need for such power and initiated the trend toward replacing manual labor with powered machines. One of the most critical elements in the changing technological climate of western Europe was the monastic system, based on the rules laid down early in the sixth century by St. Benedict. These rules had two features that encouraged the introduction of water power. First, monks were to devote certain rigidly regulated periods to manual labor, to reading and study and to spiritual duties such as meditation and prayer. Second, the monastery was to be self-sufficient and to isolate itself from worldly influences.

These rules provided an incentive for the development of water power because only by harnessing power for time-consuming manual tasks such as grinding grain could the monastery ever become self-sufficient or give the monks time for study and prayer. The monastic order that was perhaps the most aggressive in developing water power was the Cistercian. By 1300 there were more than 500 Cistercian monasteries. Virtually all of them had a water mill, and many had five or more mills.

One other social class contributed to the diffusion of water power in the medieval West. It was the feudal nobility. The nobles saw in the introduction of water power an additional means of getting revenue from the peasantry. In a number of areas of Europe lords imposed on their serfs the obligation to bring their grain for grinding only to the lord's mill. That milling monopoly, at first limited to grain mills, was sometimes extended to other water-powered processes, for example fulling: the finishing of wool cloth. Thus in western Europe two major groups—the clergy and the landed nobility—developed an interest in expanding water power. They were later joined by a third group: the merchant class, which saw in milling a way to make a profit.

Other economic pressures in medie-



MEDIEVAL WATER WHEELS rotated either horizontally on a vertical axle (*a*) or vertically on a horizontal axle (*b*, *c*). The horizontal wheel, an ancestor of the turbine, was called a Norse mill; it was inefficient and was not widely used for anything but flour milling. **The earliest vertical wheel (*b*) is known as an undershot wheel because the water passes under it; its chief virtue is its low cost and simplicity of installation. The overshot wheel (*c*) usually requires either a substantial fall of water (three meters or more) or a dam to provide such a fall.**

val Europe contributed to the extension of water power. By the seventh century the labor surplus that had plagued the Roman Empire at its height and may have discouraged the adoption of water power had completely disappeared. The ensuing labor shortage encouraged the adoption of laborsaving devices such as the water wheel. Europe's geography may also have contributed to the development. The heart of medieval European civilization lay in the drainage basins of rivers that flowed into the Bay of Biscay, the English Channel and the North Sea. In this region were hundreds of small to middle-size streams with a fairly regular flow, which was convenient for the development of water power. The heart of Classical civilization, on the other hand, was in the Mediterranean basin, where because of the dry climate stream flow tended to be erratic and seasonal.

As a result of these social, economic and geographic factors the use of water power in Europe steadily grew, particularly from the ninth century on. By 1500 water wheels were in operation throughout Europe. At some sites the concentration of powered machines was quite comparable to that in the factories of the 18th- and 19th-century Industrial Revolution. Let us look at three elements of medieval water-wheel technology: growth in numbers, growth in applications and concentrations of power.

The best source of data for the number of water mills in any part of medieval Europe is William the Conqueror's late-11th-century census of his newly acquired English domain. The areas of England under Norman rule in the late 11th century had 5,624 water mills at more than 3,000 locations. This amounted to one mill for approximately every 50 households. Moreover, in some areas the mills were close together: as many as 30 mills might be found along 16 kilometers of the same stream. Whether these mills had horizontal, undershot or overshot wheels and what work they did was not recorded. Most of them probably ground grain, a tedious task that if done by hand would have consumed from two to three hours of each housewife's day.

Even figures as incomplete as these do not exist for other European countries of the same period. Presumably some of those areas were technologically ahead of England. Later evidence, however, indicates the substitution of water power for manual labor must have been growing at a rate at least comparable to that in England. For example, in 1694 the Marquis de Vauban, a French military engineer, estimated that France had 80,000 flour mills, 15,000 industrial mills and 500 iron mills and metallurgical works. This is a total of more than 95,000 mills, although some of them, particularly the flour mills, were powered not by water but by wind.

Even in industrially backward regions of Europe, such as Russia and Poland, water wheels were common before the introduction of steam power. A 1666 survey of the northern tributaries of the Dnieper River in Russia, from the Sula River to the Vorskla River, lists 50 dams and 300 water wheels. One of these tributaries alone, the Udai River, had 72 water mills. By late in the 18th century the part of Poland under Austrian occupation had more than 5,000 water mills.

The steady numerical growth of water wheels was accompanied by a steady geographic diffusion. By the 13th century water wheels were turning throughout Europe: from the Black Sea to the Baltic, from Britain to the Balkans, from Spain to Sweden.

Ancient engineers had applied the rotary motion of the water wheel in only two ways: in the flour mill and in what was called a noria, a wheel to raise water. In the noria the motion was harnessed directly; it was not transformed by any kind of gearing. In the flour mill, however, right-angle gearing at one end of the wheel's axle changed the speed of rotation and transformed the wheel's motion in the vertical plane into motion in the horizontal plane in order to turn a millstone. Beyond this ancient engineers evidently did not go, although one poem of the fourth century Roman poet Ausonius suggests the possibility of wheel-driven saws.

Beginning in the ninth century millwrights started to extend the developments of antiquity. For example, medieval European millwrights applied the vertical water wheel to several processes that, like water-raising with the noria, called for rotary motion in the same plane as the wheel itself. One was the grinding and polishing of metals in cutlery mills. These mills are first mentioned in documents dating from early in the 13th century. In such mills gears were installed not to alter the plane of rotation but to step up the rotational speed of the water-wheel axle and in some instances to shift the direction of the plane of rotation to grindstones mounted on shafts set at right angles to the water-wheel axle.

Other examples of new applications of water power that harnessed the rotary motion of vertical water wheels in the same plane were lathes (the earliest evidence of the use of water power for this purpose was in the 14th century), pipe borers (in the 15th century), rollers for producing metal sheets and rotary cutters for cutting the sheets (also in the 15th century), fans for mine ventilation, mine hoists and ball-and-chain mine pumps (all in the 16th century).

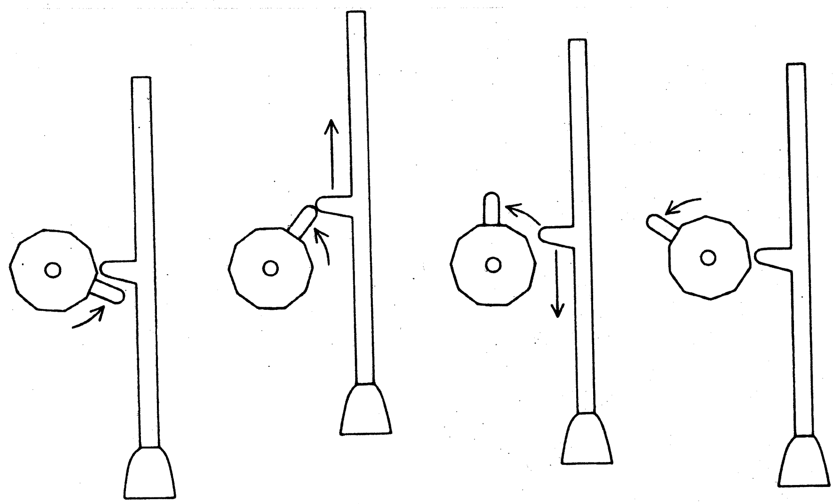
In a similar way medieval engineers extended the combination of the water wheel and vertical-to-horizontal plane gearing. As early as the ninth century in France traditional water-powered flour mills were modified to turn millstones not for grinding wheat into flour (the only Roman use of the combination of gearing and the water wheel) but for grinding malt for beer mash. Later vertical-to-horizontal plane gearing was applied in order to replace manual labor in such activities as grinding metal ores into powder.

By the 11th century vertical-to-horizontal gearing arrangements had been further developed to turn millstones set on edge, which crushed rather than ground. Water mills with such edge-rolling stones may have served to crush oil out of olives as early as the 11th century and were definitely serving this purpose and others by the 12th century. Early in the latter century the mills were adopted by the tanning industry: they reduced oak bark to powder preparatory to the leaching process that extracted the tannin. Water-powered edge rollers may also have been used to crush sugarcane in Sicily as early as the 12th century. Later such mills served to crush mustard seed (the earliest evidence of the application of water power for this purpose is in the 13th century), poppy seed (also in the 13th century) and dyeing substances (in the 14th century).

Although the rotary motion of water wheels—speeded up, slowed down or translated into another plane of rotation—could be applied to many tasks, other tasks called not for rotary motion but for linear motion. For example, many industries employed pummeling or hammering actions. They included washing wool cloth, crushing ore for a smelter, forging iron and separating the fiber from flax plants. Medieval technicians between the 10th and the 15th centuries devised two solutions to the problem of transforming rotary motion into the linear motion needed to actuate hammers: the cam and the crank.

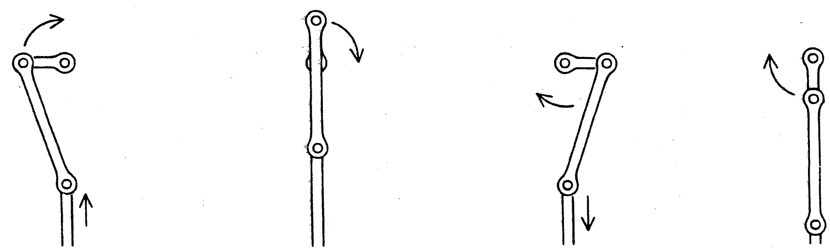
The cam was the earlier of the two devices and was long the more widely applied. It was a simple device, basically a small projection fixed on an axle. Not a medieval invention, it had appeared in small-scale mechanisms in antiquity but had never been applied to large-scale production devices. It came of age in medieval Europe, and in conjunction with water wheels it served mostly to actuate hammers. By 1500 European engineers had developed two forms of water-actuated hammer: the vertical stamp and the recumbent stamp. In the vertical stamp a cam on a horizontal shaft rotated against a similar projection on a vertical rod with a hammerhead at its lower end. As the cam rotated it lifted the rod until contact was lost; the rod then dropped, delivering the hammer blow. With the recumbent stamp the cam was rotated against the hammer end of a horizontal rod pivoted at the other end, first lifting the hammer and then, as the rotation continued, dropping it.

Water-actuated trip hammers could

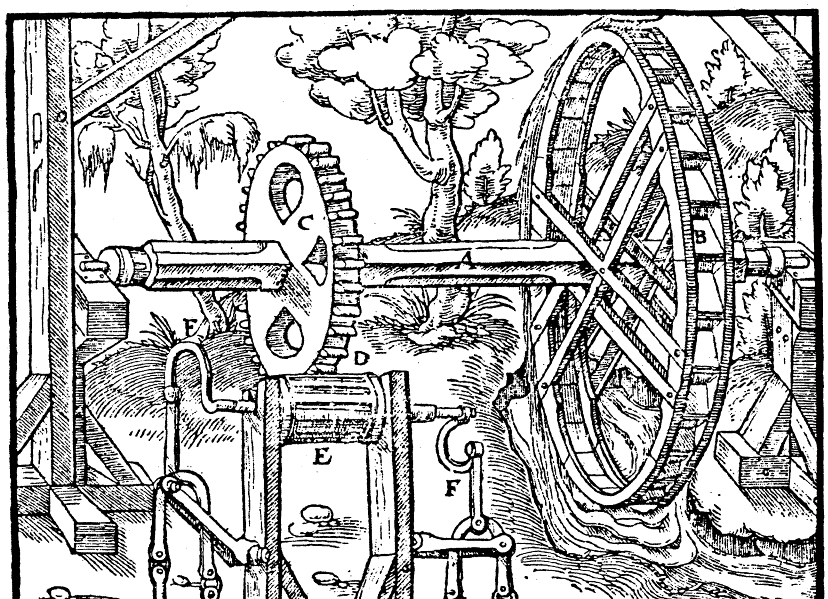


TRANSFORMATION OF ROTARY MOTION into linear motion can be achieved by having a cam on the axle of the wheel. The rotating cam engages a matching cam on a stamp shaft; as the shaft turns, the stamp is first raised and then dropped to deliver a powerful impact.

CAM PRINCIPLE WAS APPLIED in a rock-crushing mill illustrated in *De re metallica.* Cams on the axle engage and then release a tappet (*g*) attached to each of the iron-shod stamps.



ROTARY MOTION WAS ALSO TRANSFORMED into linear motion by the crank. This one requires a flexible joint between the shaft being raised and lowered and the driven shaft.



PAIR OF CRANKS driven by an overshot wheel rotating a two-gear train are converting rotary motion into linear motion in this illustration from *De re metallica*. The linear motion is being conveyed to pistons of two pairs of mine pumps. The lower pump of each pair lifts water from the mine shaft to a trough in the foreground for further raising by the upper pumps.

have been used instead of modified millstones in the beer mills of the ninth century, but the first industries to definitely take up hydraulic hammers were the fulling and hemp industries of the 10th and 11th centuries. After wool has been woven into cloth it must be pounded or pummeled in a cleansing solution. This action serves three purposes. First, it washes the cloth and removes much of the remaining sheep's grease from it. Second, it shrinks the wool so that it can be safely sewn to size afterward. Third, it felts the wool fibers, strengthening the weave.

In antiquity and on into early medieval times fulling had been done by hand. The water wheel and the cam-actuated trip hammer mechanized the process beginning in the 11th century. By the 13th century mechanized fulling was done over much of western Europe. In England, for example, the earliest water-powered fulling mill recorded dates from 1185. By 1327 there were 130 such mills, and before the end of the century the English woolens industry had shifted almost entirely to sites where water power was available.

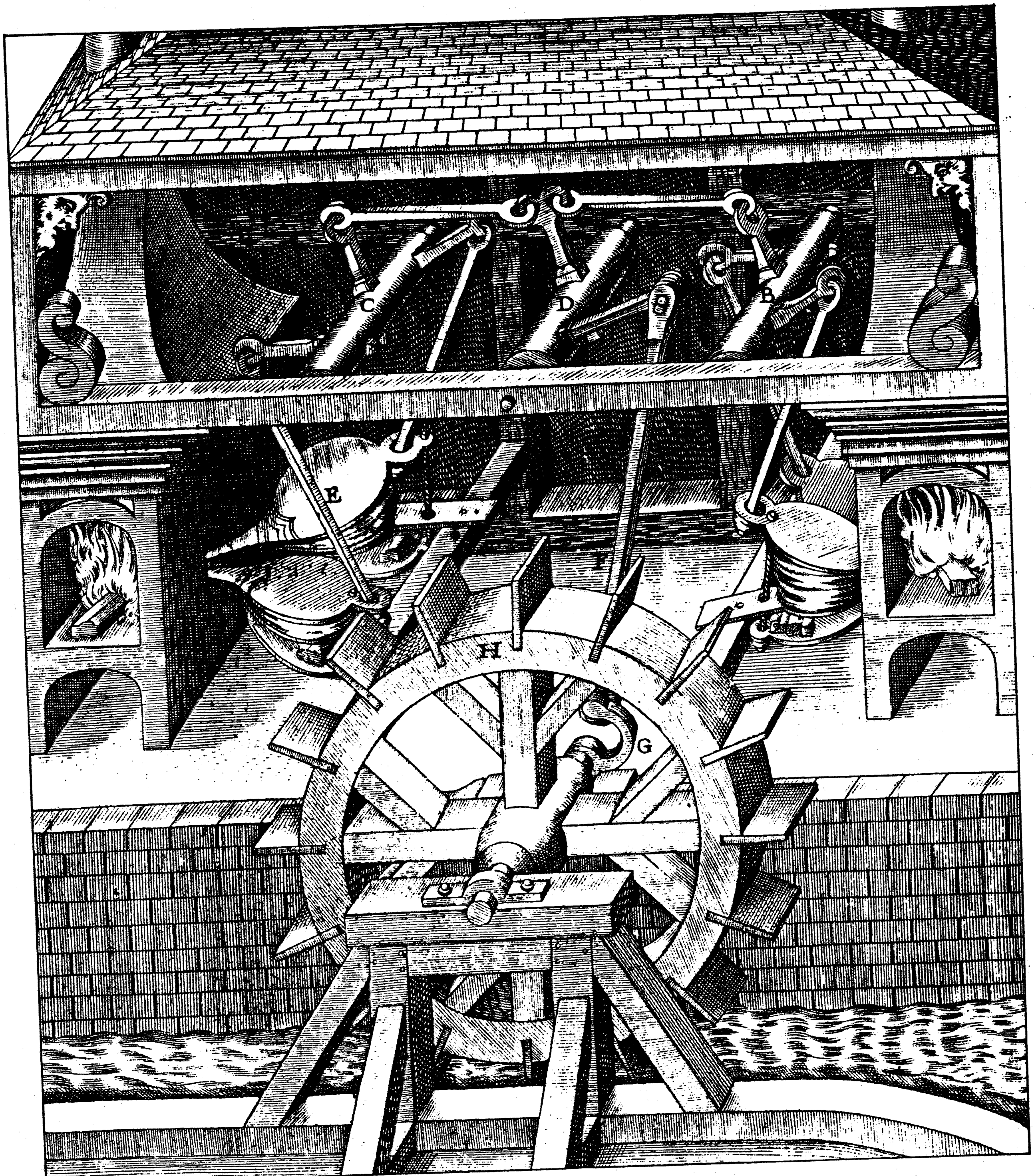
The hemp industry was also among the first industries to adopt the mechanized trip hammer. Traditionally hemp fibers, which are formed into rope and cord, had been separated from the woody plant tissue by being pounded and picked by hand. Water-powered hammers were substituted for this manual labor in Alpine France late in the 10th century and early in the 11th. By the 12th century there were water-powered hemp mills throughout France.

As time passed many other tasks were taken over by water-powered hammers. Ever since paper had been invented in Asia the pulp for making it had been produced by manually pounding rags in water. Western Europeans learned how to make paper only at the beginning of the 12th century. By the late 13th century European papermakers had taken a step that Chinese and Arabic ones never had: they substituted the water-powered trip hammer for the manual hammering. By the early 17th century England alone had 38 water-powered paper mills. By 1710 the number was 200 and by 1763 it was 350.

One of the most important European industries to be partially mechanized by the combination of the vertical water wheel and the cam was the iron industry. Early in the Middle Ages, European ironmasters smelted ore in a small furnace with air supplied to the burning mixture of charcoal and ore by a hand- or foot-powered bellows. The process did not yield temperatures high enough to liquefy iron. Thus almost daily the ironmaster had to shut his furnace down and take it apart to remove the sponge-like mass known as bloom, consisting of a porous mixture of metallic iron and slag. In order to get a usable form of iron the ironworkers had to heat and hammer the bloom repeatedly, with each cycle further consolidating the iron and eliminating the slag. The bloom, like the ore, was heated in a furnace with a draft that was supplied by a manually operated bellows.

The introduction of water power significantly affected both processes. Water-powered hammers in iron forges may have appeared as early as the 11th century; they were certainly in service by the 13th century, and they were commonplace in the 14th. Cam-actuated bellows, powered by water wheels, were operating in forges by early in the 13th century and were common in the 14th.

By late in the 14th century the combi-



SIXTEENTH-CENTURY SMITHY had bellows driven by an undershot wheel to achieve high furnace temperature. Again a crank converted rotation of the shaft into reciprocating motion. The plate is in Agostino Ramelli's *Le diverse et artificiose machine*, dated 1588.

nation of a vertical water wheel and a cam-actuated bellows had moved from the forge to the smelting furnace and iron production underwent an even more radical change. Larger and more powerful bellows, made possible by water power, enabled ironmasters to get higher temperatures in their smelters, so that the iron was liquefied. The bottom of the smelting furnace could be tapped, and the liquid metal would run out to solidify in "pigs." Shutting down and taking apart the furnace to get the bloom came to an end, and iron production was transformed from a batch process into at least a semicontinuous one, with significant reductions in labor requirements. This new application of water power spread rapidly. For example, in the Siegen area of Germany all 38 pig-iron works and steelmaking forges were relying on water power by 1492.

Still other industries were transformed by the combination of the water wheel and the cam. In water-powered sawmills the cam served to pull down a ripsaw; the saw was pulled back up by a spring pole. Mills of this kind are first mentioned in documents of the early 13th century. Apparently the practice spread rapidly. In 1304 deforestation in the area of Vizille in southeastern France was being blamed in part on the proliferation of water-powered sawmills. Two centuries later the water wheel and the cam were being employed to lift hammers for the crushing of ore and to operate piston pumps for mine drainage.

The alternative to the cam for converting rotary motion into linear motion was the crank (or crankshaft). Known in China by the second century A.D., the crank appeared in Europe somewhat later. Cranks may have been used to rotate millstones by hand late in Classical times; they appear in mature form in Europe only in the ninth century, when the Utrecht Psalter depicts a crank attached to a hand-powered grindstone. Late in the medieval period the crank was combined with the water wheel and began to replace the cam for certain tasks. The double action provided by the crank was more advantageous than the single action of the cam in water-powered pumps, sawmills and bellows. The crank was also combined with manually operated grippers and drawplates in wire-drawing mills, which emerged in the 14th or 15th century.

PAPER MILL relied on an undershot wheel with cams (*c*) to lift and drop hammers (*d, e*) that reduced rags to pulp. Thereafter the process was manual: the pulp was transferred to a vat (*g*), dipped out with a seive and formed into a sheet in a press (*f*). The sheets were hung on racks to dry. The plate is from Georg Andreas Böckler's *Theatrum machinarum novum* of 1662.

By the 16th century at least 40 different industrial processes in Europe had come to depend on water power. The trend continued in the ensuing centuries. As one example, water power was first applied to spinning silk sometime between 1300 and 1600. In the silk mills water-powered spindles twisted individual silk fibers into thread. By 1700 there were 100 silk mills in northeastern Italy alone. The large silk mill erected early in the 1700's by Thomas Lombe at Derby in England, powered by the River Derwent, was a multistoried structure with a work force of 300.

Between 1550 and 1750 water power was applied to other processes as well. It was harnessed to bore the barrels of cannons and muskets, to thresh grain (with rotary flails), to agitate mixtures of ore and water and to pulverize the raw materials of glassmaking. Edge rollers were applied to such new activities as the preparation of snuff, cement, potter's clay and gunpowder. By 1692 there were 22 gunpowder mills in France, some on a scale matching the British textile mills of the late 18th and early 19th centuries. By the middle of the 18th century water-actuated hammers had been applied to the crushing of bone for fertilizer and of chalk for whitewash, and complex water-driven transmission systems, including cranks, had mechanized glass polishing.

Just as the water-powered trip hammer had mechanized the hemp industry by the 12th century, so it had penetrated the linen industry before the middle of the 18th century. The making of linen had been completely dependent on manual labor. After the flax plants for the linen had been harvested the stems were put in water to rot. The stems were then beaten to separate their fibers. When the fibers had been spun into thread and the thread had been woven into cloth, the cloth was washed and then beaten with light wood hammers to toughen the weave and give the cloth a sheen.

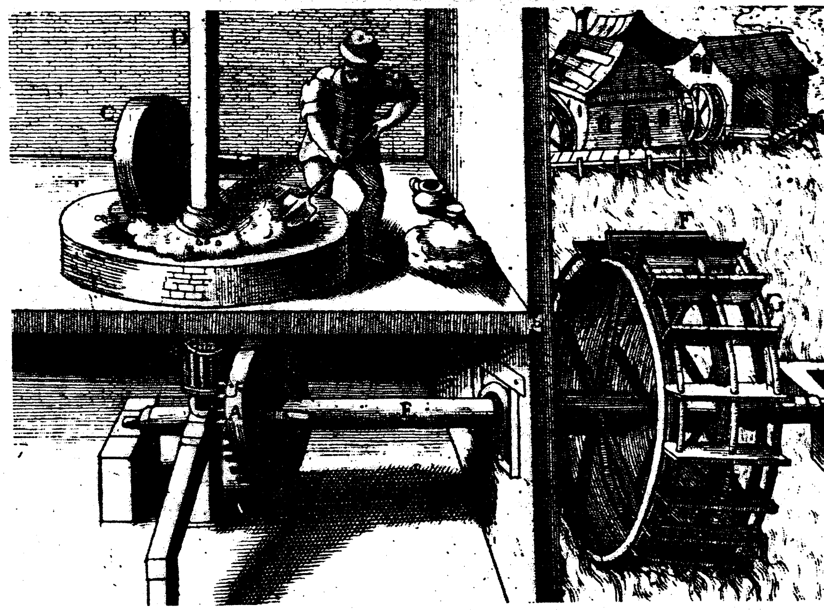
Late in the 17th century and early in the 18th European technicians mechanized several of these steps. Water-powered scutching mills relied on wood blades, rather like fan blades, to separate the fibers from the rotted flax stems. Linen-washing mills harnessed the combination of a water wheel and a cam or a crank to drive scrubbing boards of corrugated wood, through which the wet linen was drawn. Beetling mills then used water-actuated wood hammers to toughen and give a sheen to the linen cloth as it was drawn over large wood rollers. In Ulster alone more than 200 water-powered linen plants were established between 1700 and 1760.

The traditional beginnings of the Industrial Revolution in the late 18th century are dated to the early English cotton-textile mills. It is true that no cotton-textile production had been mechanized with water power before the 1770's. Nevertheless, water power not only had mechanized many nontextile industries but also had affected several processes in the production of textiles other than those of cotton. As we have seen, the fulling of wool, the spinning of silk and several stages of linen production had been taken over by water-powered machinery well before 1770.

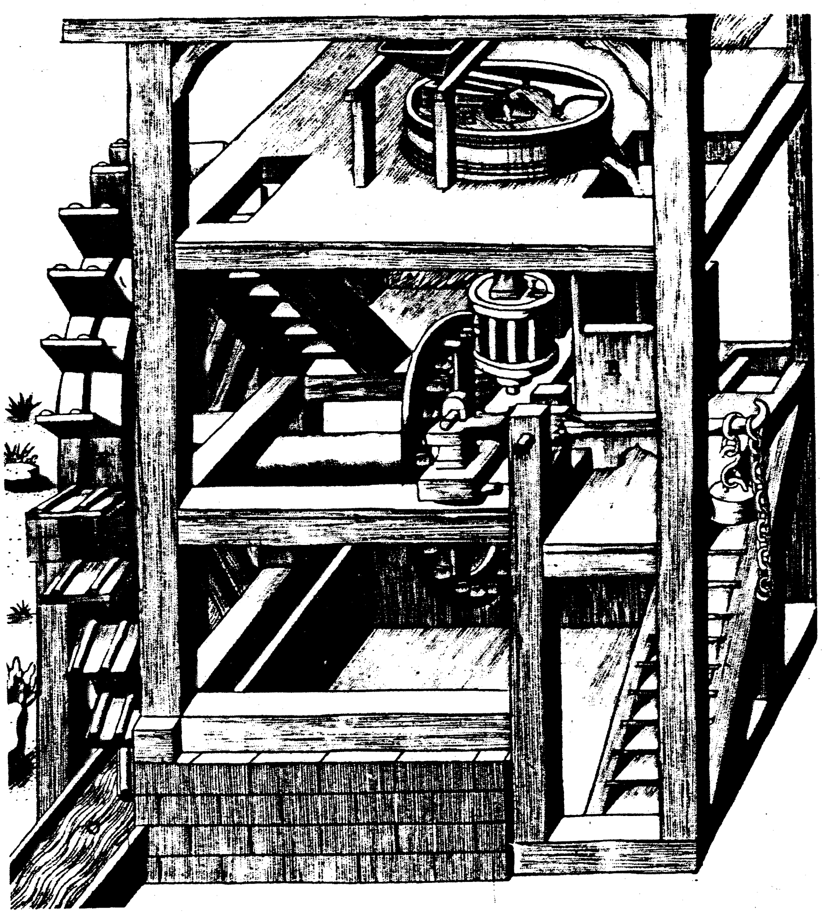
By the same token, the cotton-textile mills of the late 18th century were not unique in replacing manual labor with powered machinery. Neither were they unique in the amount of power they concentrated in a single location. Most of the early mechanized cotton mills had available perhaps 10 to 20 horsepower. The replacement in these mills of water power by steam power, beginning in the 1790's, made little difference at first because until well into the 19th century the average power of the steam engines was less than 20 horsepower. Even as late as 1835 the average mechanized cotton mill had available no more than about 35 horsepower. Concentrations of that much energy were not at all unknown in water-powered mills between the ninth century and the middle of the 18th.

Precise data on the power output of water wheels do not exist before 1700. In the period between 1700 and 1800, however, before the traditional wood wheel was replaced by iron wheels, water turbines and the steam engine, widely scattered sources provide enough information to allow an approximate calculation of the power output of some of the traditional wheels. I have collected data on 40 wheels, of both the undershot and the overshot type, from scattered millwright manuals, engineering texts, encyclopedias and other sources. They indicate that the average power output at the shaft was between five and seven horsepower. Thus the concentration of three or four wheels of average size at a single site would represent a power concentration roughly equal to that of the mechanized English cotton mills.

Concentrations of this kind, although



EDGE-ROLLER MILL differed from the mills that ground flour in that the top stone rolled over the bottom one instead of rubbing against it. Introduced in the 11th or 12th century, such mills were applied to crushing olives for the extraction of oil or pressing sugarcane for the extraction of sugar. Plate is from Vittorio Zonca's *Novo teatro di machine,* published in 1607.



LARGE UNDERSHOT WHEEL powers two gears that transform vertical rotation into horizontal rotation in this illustration of a 16th-century flour mill from Ramelli. The millstones are installed in the top story of the building; the flour falls into a bin below, beside the gears.

not commonplace, certainly existed. Monasteries provide some examples. For instance, as early as the ninth century the abbey of Corbie, near Amiens, had water mills with as many as six wheels. The monastery of Royaumont, near Paris, had a tunnel two and a half meters in diameter and 32 meters long in which there were mounted separate water wheels for grinding grain, tanning, fulling and working iron. In 1136 the abbey of Clairvaux, near Troyes, had wheels that ground grain, fulled cloth and tanned leather.

Similar concentrations of power existed elsewhere. In the 14th century the millers of Paris operated 13 water mills under the Grand Pont. Even earlier, late in the 12th century, the millers of Toulouse built three dams across the Garonne River; the largest of them, the Bazacle dam, was 400 meters long. These dams served 43 horizontal water mills. By the 13th century a division of capital and labor characteristic of the early British cotton mills had emerged at Toulouse: the mills were owned by investors and the millers were employees.

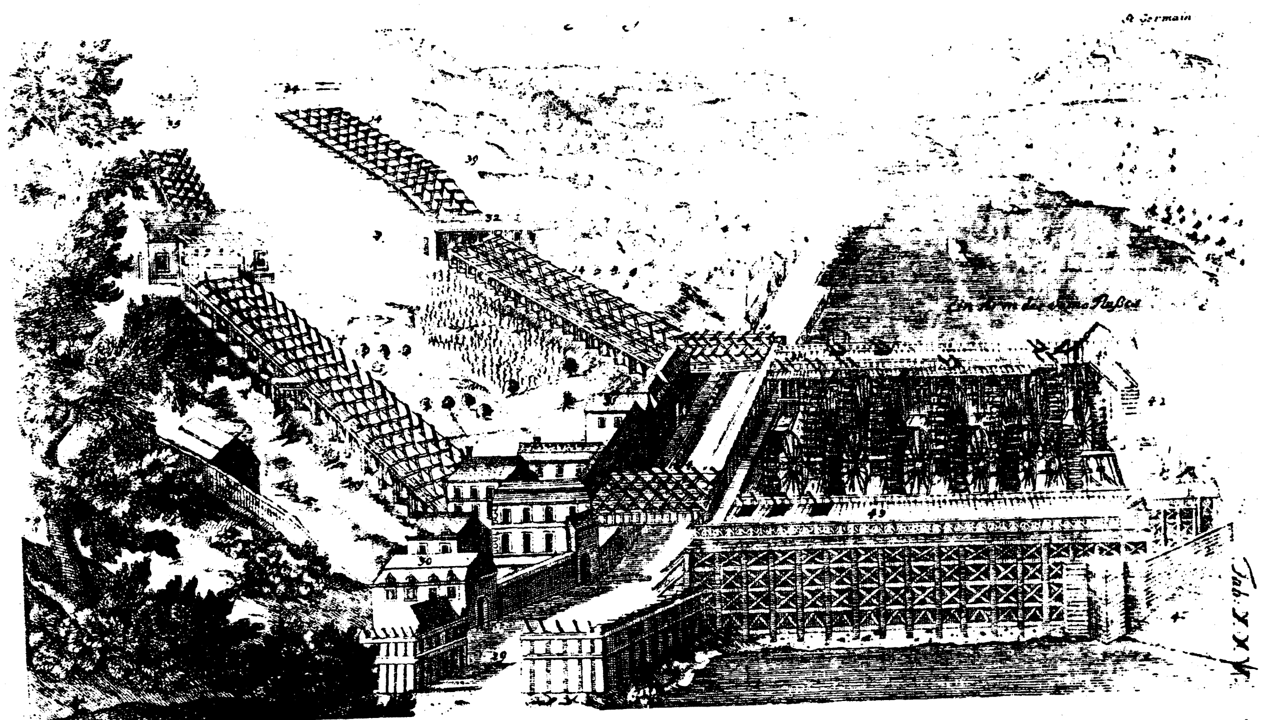
Elaborate water-power installations are also to be found in early modern Europe. For example, in the 1680's a Flemish engineer, Rennequin Sualem, designed and built for Louis XIV an elaborate water-powered complex at Marly-le-Roi on the Seine. There a dam diverted water to a set of 14 undershot wheels, each wheel 11 meters in diameter and 2.3 meters wide. The wheels drove 221 pumps at three levels by means of a complex linked set of cranks, rocking beams and connecting rods and lifted the river water 153 meters to an aqueduct a kilometer away. The transmission system was so cumbersome and inefficient, however, that the 14 wheels yielded only 150 horsepower.

Roughly contemporary with the Marly works was the Grand Rive mill, a paper plant in the Auvergne region with seven water wheels and 38 sets of hammers. In the 1720's Russian engineers built a large dam at Ekaterinburg in the Urals; an industrial complex powered by water from the dam consisted of 50 water wheels that drove 22 hammers, 107 bellows and 10 wire-drawing mills. By 1760 the British Royal Gunpowder Factory at Faversham in Kent included 11 water wheels. At about the same time engineers in Cornwall built what was known as the tower engine; it had 10 overshot wheels, mounted one above the other, linked by connecting rods to two large mine pumps.

Some pre-1800 power concentrations were regional rather than confined to a single site. For example, in the Harz Mountain region of Germany mining engineers began constructing a complex network of dams, reservoirs and canals to turn wheels that powered mine pumps, wire-drawing engines, ore-washing plants, ore-crushing mills and the bellows of furnaces and forges in about 1550. By 1800 this system included 60 dams and reservoirs, all within a four-kilometer radius of Clausthal, the center of the mining district. The largest dam in the system, the masonry Oderteich dam, built between 1714 and 1721, was 145 meters long, 18 meters high and 47 meters thick at the base. The dams eventually fed water to 225 wheels through a network of 190 kilometers of canals. The aggregate power of the system almost certainly exceeded 1,000 horsepower.

Water power also spread to the New World. Near Potosí in the Bolivian Andes, Spanish engineers exploiting rich silver deposits began in 1573 to build a system of dams, reservoirs and canals to bring water to ore-crushing mills. By 1621 the system included 32 dams. A main canal five kilometers long carried water to 132 ore-crushing mills near the city. The system generated more than 600 horsepower.

Hence it is clear that the mechanized cotton mills of England in the late 18th and early 19th centuries represented no radical break with the past, either in the replacement of manual labor with machines or in the concentration of large amounts of power. The substitution of water-powered machinery for manpower and the concentration of water-powered industry were trends well under way before that time. The British textile mills were simply the culmination of an evolutionary process that had its origins in medieval Europe and even in the Classical Mediterranean.



ARRAY OF 14 WHEELS on the Seine at Marly-le-Roi, 14 kilometers west of Paris, was erected in the 1680's. Developing from 300 to 500 horsepower at the shaft but only from 80 to 150 horsepower after losses in the pumps and the mechanical transmission are taken into account, the wheels pumped water to an aqueduct 153 meters above the river. It was carried to several of Louis XIV's palaces.